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Analysis of Land Use Change: Theoretical and Modeling Approaches

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Introduction

1.1. Overview of Issues Related to Land Use Change

Land is the stage on which all human activity is being conducted and the source of the materials needed for this conduct. Human use of land resources gives rise to "land use" which varies with the purposes it serves, whether they be food production, provision of shelter, recreation, extraction and processing of materials, and so on, as well as the bio-physical characteristics of land itself. Hence, land use is being shaped under the influence of two broad sets of forces – human needs and environmental features and processes. Neither one of these forces stays still; they are in a constant state of flux as *change* is the quintessence of life. Changes in the uses of land occurring at various spatial levels and within various time periods are the material expressions, among others, of environmental and human dynamics and of their interactions which are mediated by land. These changes have at times beneficial, at times detrimental impacts and effects, the latter being the chief causes of concern as they impinge variously on human well-being and welfare. Lay and scientific interest on land use change has a long history as there have been no instances in which people used land and its resources without causing any harm. Ancient writers, philosophers, scientists and the like but also lay people have left records of the unwanted consequences of changes in the uses of land in the form of pieces of literature, philosophy, science and folklore.

The magnitude of land use change varies with the time period being examined as well as with the geographical area. Moreover, assessments of these changes depend on the source, the definitions of land use types, the spatial groupings, and the data sets used. A few indicative figures are given here to show salient changes in major uses of land. Table 1.1a contains data on global and regional land use and population change in the last 300 years for three main land use types.

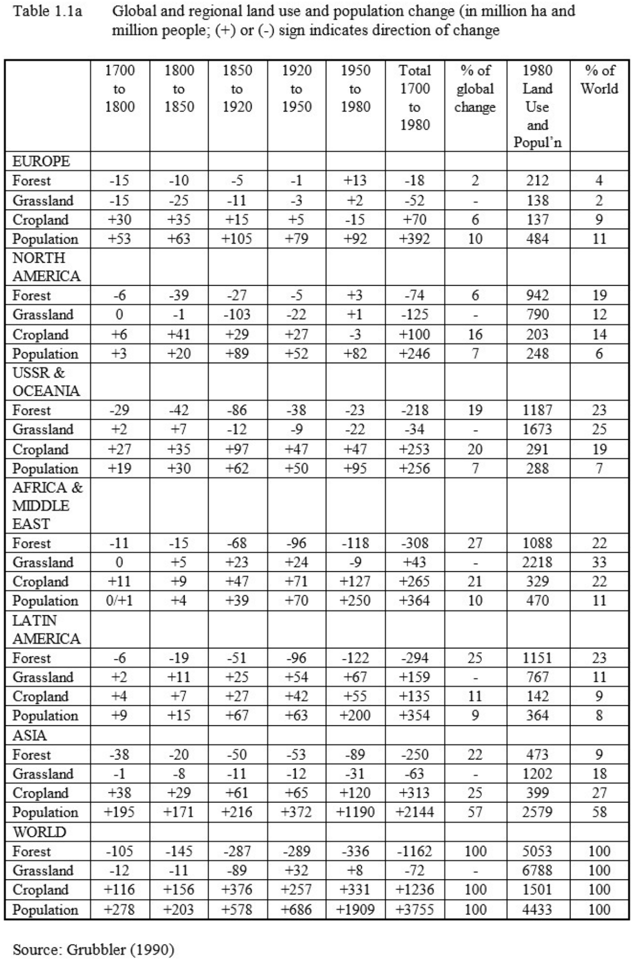


Table 1.1a Global and regional land use and population change (in million ha and million people; (+) or (-) sign indicates direction of change

	1700 to 1800	1800 to 1850	1850 to 1920	1920 to 1950	1950 to 1980	Total 1700 to 1980	% of global change	1980 Land Use and Popul'n	% of World
EUROPE									
Forest	-15	-10	-5	-1	+13	-18	2	212	4
Grassland	-15	-25	-11	-3	+2	-52	-	138	2
Cropland	+30	+35	+15	+5	-15	+70	6	137	9
Population	+53	+63	+105	+79	+92	+392	10	484	11
NORTH AMERICA									
Forest	-6	-39	-27	-5	+3	-74	6	942	19
Grassland	0	-1	-103	-22	+1	-125	-	790	12
Cropland	+6	+41	+29	+27	-3	+100	16	203	14
Population	+3	+20	+89	+52	+82	+246	7	248	6
USSR & OCEANIA									
Forest	-29	-42	-86	-38	-23	-218	19	1187	23
Grassland	+2	+7	-12	-9	-22	-34	-	1673	25
Cropland	+27	+35	+97	+47	+47	+253	20	291	19
Population	+19	+30	+62	+50	+95	+256	7	288	7
AFRICA & MIDDLE EAST									
Forest	-11	-15	-68	-96	-118	-308	27	1088	22
Grassland	0	+5	+23	+24	-9	+43	-	2218	33
Cropland	+11	+9	+47	+71	+127	+265	21	329	22
Population	0/+1	+4	+39	+70	+250	+364	10	470	11
LATIN AMERICA									
Forest	-6	-19	-51	-96	-122	-294	25	1151	23
Grassland	+2	+11	+25	+54	+67	+159	-	767	11
Cropland	+4	+7	+27	+42	+55	+135	11	142	9
Population	+9	+15	+67	+63	+200	+354	9	364	8
ASIA									
Forest	-38	-20	-50	-53	-89	-250	22	473	9
Grassland	-1	-8	-11	-12	-31	-63	-	1202	18
Cropland	+38	+29	+61	+65	+120	+313	25	399	27
Population	+195	+171	+216	+372	+1190	+2144	57	2579	58
WORLD									
Forest	-105	-145	-287	-289	-336	-1162	100	5053	100
Grassland	-12	-11	-89	+32	+8	-72	-	6788	100
Cropland	+116	+156	+376	+257	+331	+1236	100	1501	100
Population	+278	+203	+578	+686	+1909	+3755	100	4433	100

Source: Grubbler (1990)

Figures 1.1a, 1.1b, 1.1c, 1.1d, 1.1e, 1.1g depict these changes.

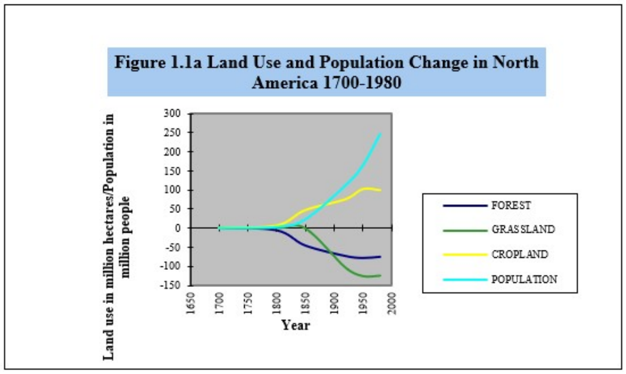


Figure 1.1a Land Use and Population Change in North America 1700-1980

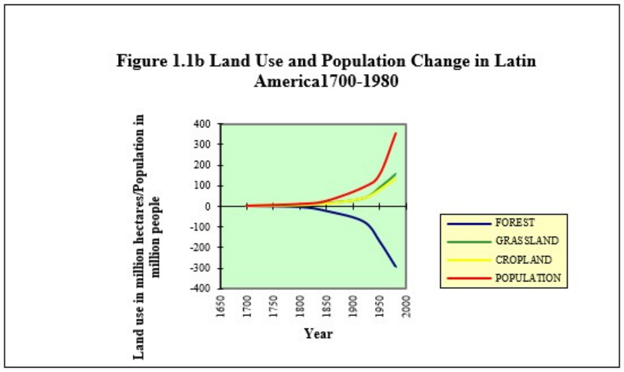


Figure 1.1b Land Use and Population Change in Latin America1700-1980

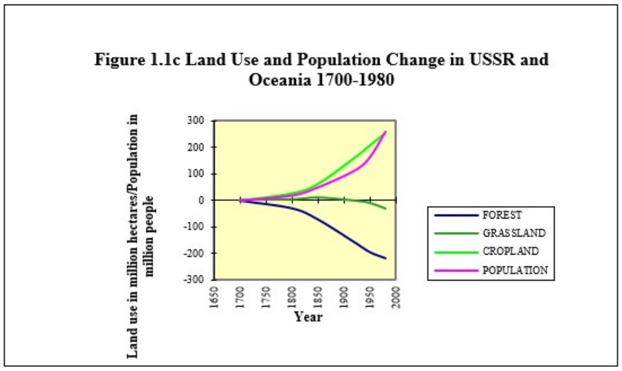


Figure 1.1c Land Use and Population Change in USSR and Oceania 1700-1980

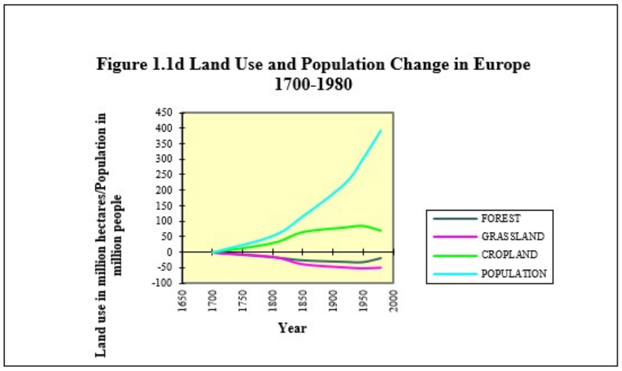


Figure 1.1d Land Use and Population Change in Europe 1700-1980

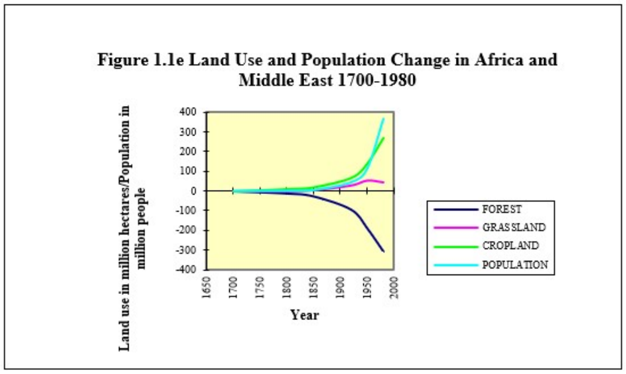


Figure 1.1e Land Use and Population Change in Africa and Middle East 1700-1980

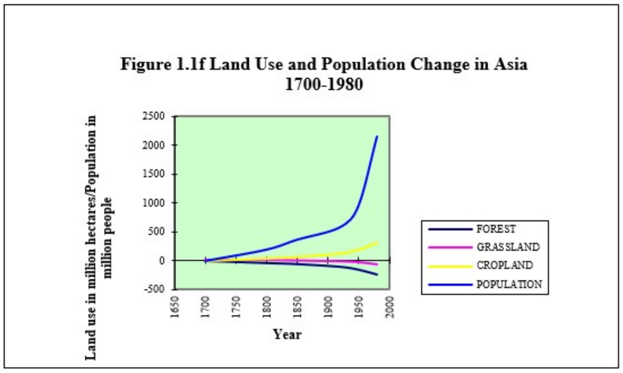


Figure 1.1f Land Use and Population Change in Asia 1700-1980

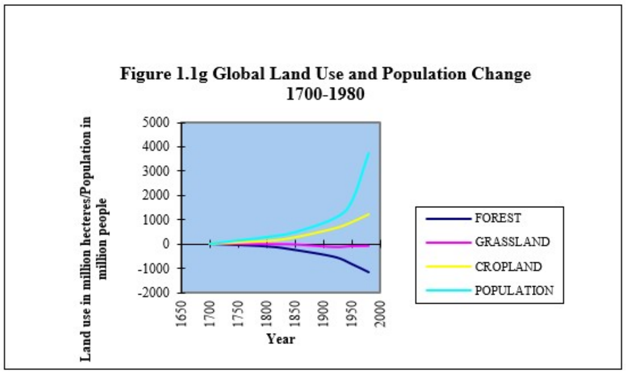
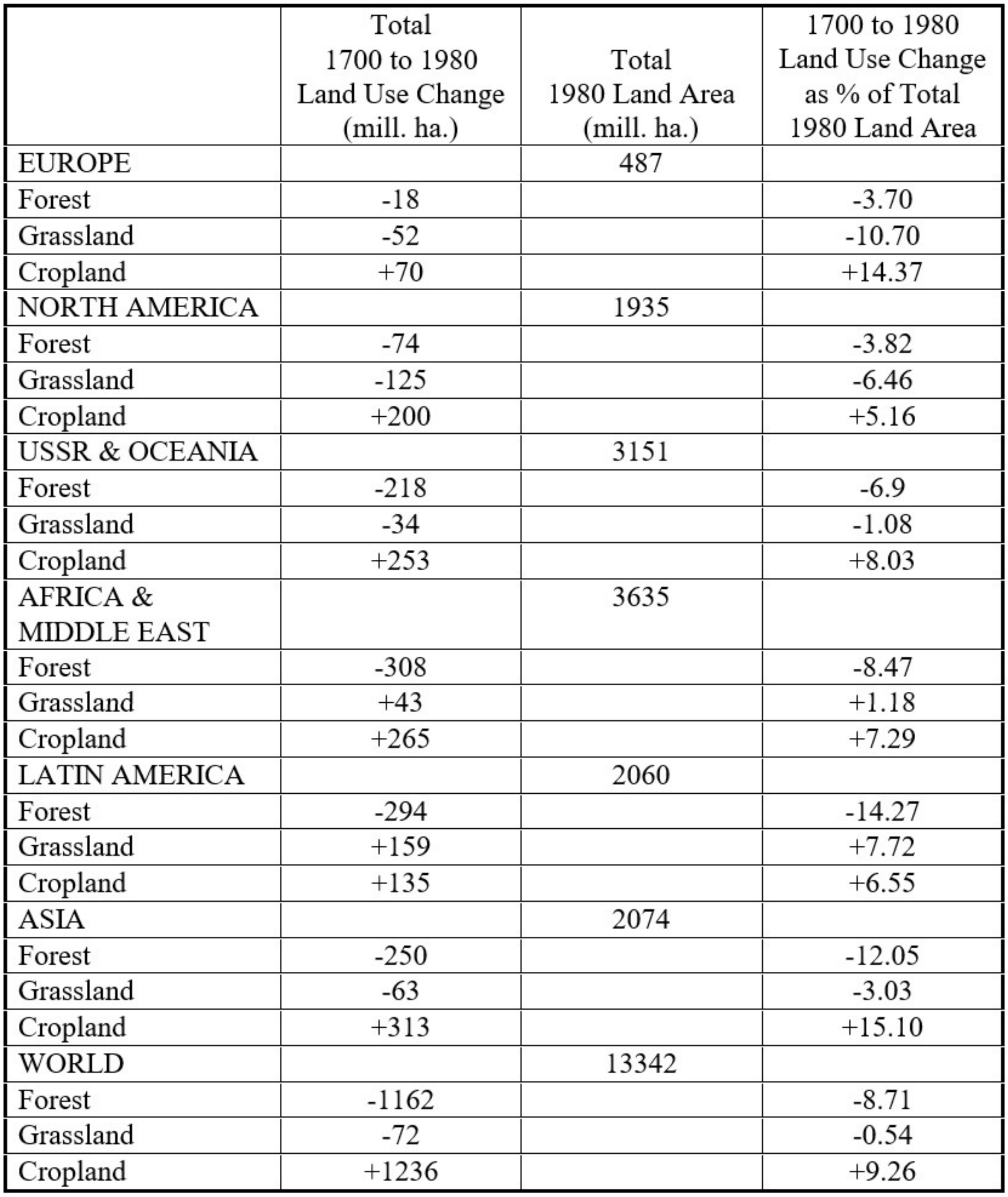


Figure 1.1g Global Land Use and Population Change 1700-1980

Table 1.1b presents the magnitude of change in each of the three major land use types distinguished in Table 1.1a as percent of total 1980 land area of each regional grouping and for the world as a whole.

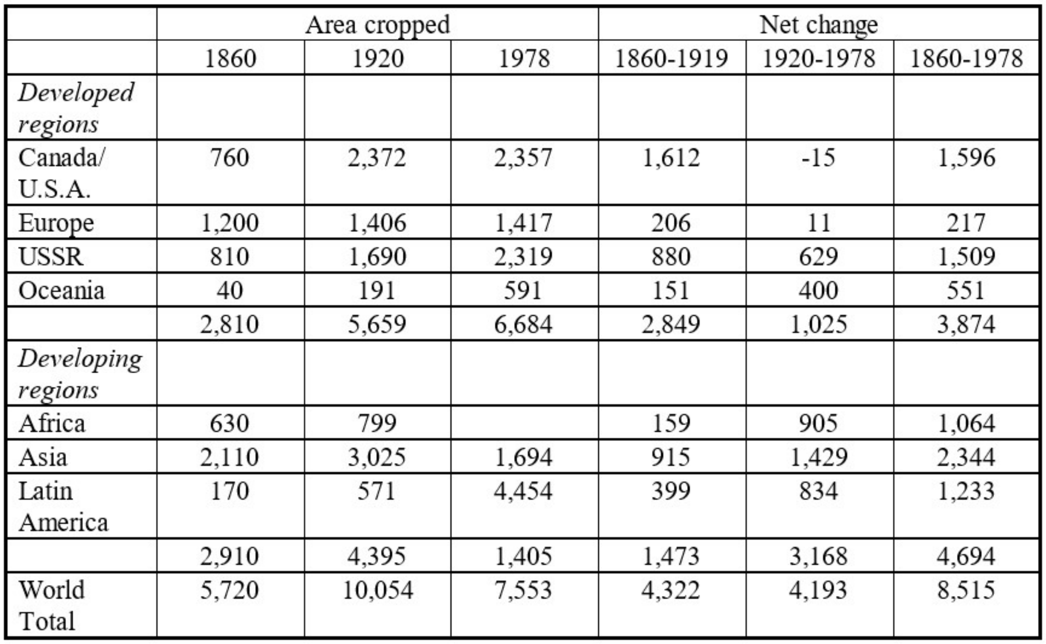
Table 1.1b 1700-1980 Land Use Change as Percent of Total 1980 Land Area of Each Regional Grouping



	Total 1700 to 1980 Land Use Change (mill. ha.)	Total 1980 Land Area (mill. ha.)	1700 to 1980 Land Use Change as % of Total 1980 Land Area
EUROPE		487	
Forest	-18		-3.70
Grassland	-52		-10.70
Cropland	+70		+14.37
NORTH AMERICA		1935	
Forest	-74		-3.82
Grassland	-125		-6.46
Cropland	+200		+5.16
USSR & OCEANIA		3151	
Forest	-218		-6.9
Grassland	-34		-1.08
Cropland	+253		+8.03
AFRICA & MIDDLE EAST		3635	
Forest	-308		-8.47
Grassland	+43		+1.18
Cropland	+265		+7.29
LATIN AMERICA		2060	
Forest	-294		-14.27
Grassland	+159		+7.72
Cropland	+135		+6.55
ASIA		2074	
Forest	-250		-12.05
Grassland	-63		-3.03
Cropland	+313		+15.10
WORLD		13342	
Forest	-1162		-8.71
Grassland	-72		-0.54
Cropland	+1236		+9.26

What is important to note in these Tables and the associated Figures is the variability of changes among the major land use types as well as the geographical variability of land use changes within and between land use types. Population change is used as a proxy measure of changes in the area of human settlements especially in urban areas. These latter changes are difficult to assess unambiguously as they are haunted by definitional and data problems (Douglas 1994). Changes in the uses of land which cause major concern are associated with conversion to and from cropland as well as with forest clearance. Table 1.1c. and Table 1.1d present data on global land areas converted to regular cropping and global areas of different ecosystems converted to cropping, respectively.

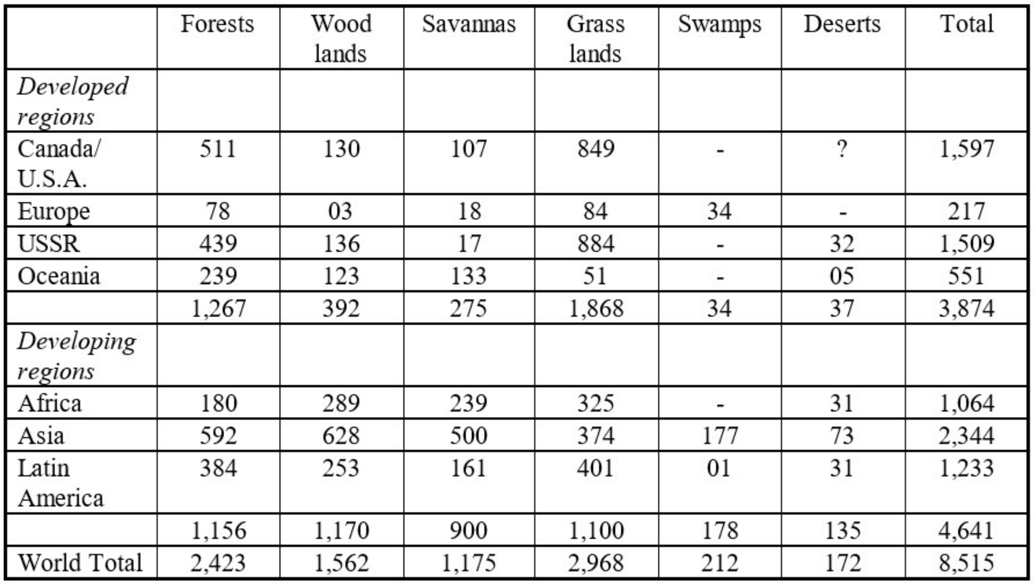
Table 1.1c Global land areas converted to regular cropping, 1860, 1920, 1978 (×10,000km²)



	Area cropped			Net change		
	1860	1920	1978	1860-1919	1920-1978	1860-1978
Developed regions						
Canada/ U.S.A.	760	2,372	2,357	1,612	-15	1,596
Europe	1,200	1,406	1,417	206	11	217
USSR	810	1,690	2,319	880	629	1,509
Oceania	40	191	591	151	400	551
	2,810	5,659	6,684	2,849	1,025	3,874
Developing regions						
Africa	630	799		159	905	1,064
Asia	2,110	3,025	1,694	915	1,429	2,344
Latin America	170	571	4,454	399	834	1,233
	2,910	4,395	1,405	1,473	3,168	4,694
World Total	5,720	10,054	7,553	4,322	4,193	8,515

Source: Williams (1990)

Table 1.1d Global land areas of different ecosystems converted to regular cropping, 1860-1978 (×10,000km²)

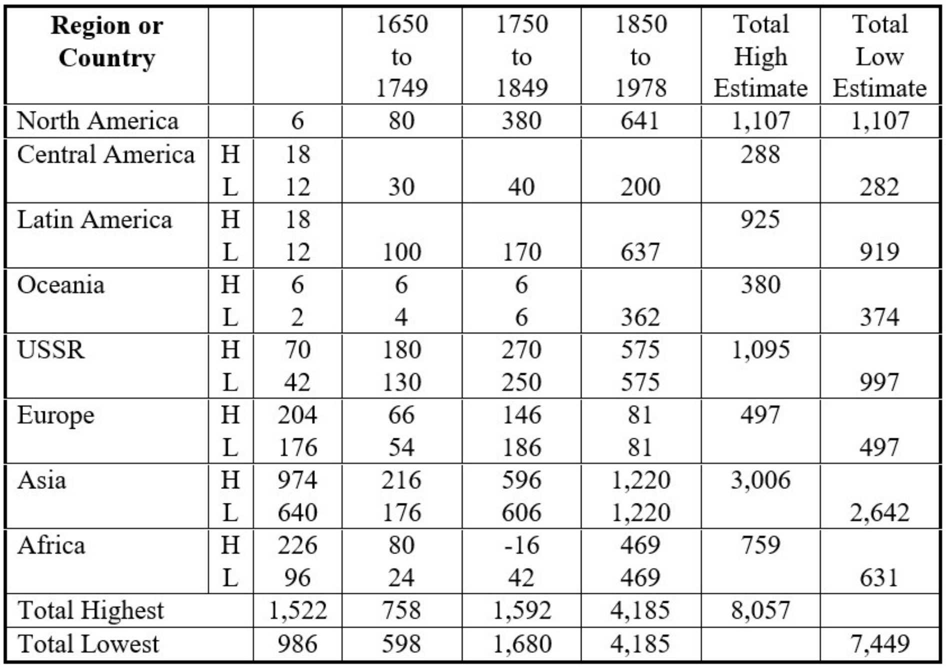


	Forests	Wood lands	Savannas	Grass lands	Swamps	Deserts	Total
Developed regions							
Canada/ U.S.A.	511	130	107	849	-	?	1,597
Europe	78	03	18	84	34	-	217
USSR	439	136	17	884	-	32	1,509
Oceania	239	123	133	51	-	05	551
	1,267	392	275	1,868	34	37	3,874
Developing regions							
Africa	180	289	239	325	-	31	1,064
Asia	592	628	500	374	177	73	2,344
Latin America	384	253	161	401	01	31	1,233
	1,156	1,170	900	1,100	178	135	4,641
World Total	2,423	1,562	1,175	2,968	212	172	8,515

Source: Williams (1990)

Table 1.1e presents data on estimated area cleared over time.

Table 1.1e Estimated Area Cleared 1650-1978 (×000km^2)



Region or Country			1650 to 1749	1750 to 1849	1850 to 1978	Total High Estimate	Total Low Estimate
North America		6	80	380	641	1,107	1,107
Central America	H	18				288	
	L	12	30	40	200		282
Latin America	H	18				925	
	L	12	100	170	637		919
Oceania	H	6	6	6		380	
	L	2	4	6	362		374
USSR	H	70	180	270	575	1,095	
	L	42	130	250	575		997
Europe	H	204	66	146	81	497	
	L	176	54	186	81		497
Asia	H	974	216	596	1,220	3,006	
	L	640	176	606	1,220		2,642
Africa	H	226	80	-16	469	759	
	L	96	24	42	469		631
Total Highest		1,522	758	1,592	4,185	8,057	
Total Lowest		986	598	1,680	4,185		7,449

Source: Williams (1990)

Conversion of cropland andforest land to urban uses is another important type of land use change because of its serious socio-economic and environmental implications. The interested reader may find additional material on estimates of land use changes in, among others, Turner *et al.* (1990), Meyer and Turner (1994), Brouwer *et al.* (1991), various editions of the FAO Production Yearbook, the United Nations Statistical Yearbooks, the World Bank's World Development Reports, EUROSTAT's yearbooks.

In the last 300 years the impacts of land use change have increasingly assumed from significant to threatening proportions. What is most important, however, is that, with few exceptions, it is human and not nature's agency which brings about these changes and which is responsible for their magnitude and severity. Simply consider these major environmental problems: **desertification**, **eutrophication**, **acidification**, climate change, **eustatic sea-level rise**, greenhouse effect, biodiversity loss. In all of them and in myriad other less publicized and less visible, land use change caused by human activities is implicated to a greater or lesser extent. The impacts of these environmental problems are serious both in the short and in the long term. In the short term, food security, human vulnerability, health and safety are at stake; in the longer term, the viability of earth is being threatened. Hence, the impetus to study global environmental change in general and land use change in particular. As regards the former, the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme (IHDP) are the main scientific initiatives undertaken at the international level. Under the auspices of these two programmes and following a period of deliberations, the Land Use and Cover Change (LUCC) Core Project/Research Programme came into life in 1993 (for more information the reader is referred to Turner *et al.* 1995 and LUCC's web site listed in Appendix 1.B).

The scientific study of the determinants and impacts of land use change is not confined, however, to the international level. The subject has engaged scientists in most countries of the world as, in almost all cases, the control of land use and the directing of its change towards particular types were of immediate concern to public authorities and individuals on such matters as quality of drinking water, availability of water for agriculture, flood and other natural hazards, fresh and sea water pollution, atmospheric pollution. This diversity of concerns is associated inevitably with a diversity of disciplines being involved in these studies. But the earth and life sciences are not the only and exclusive territories of scientific activity on land use change. The social sciences and the humanities have long explored various facets of the nature-society interactions from the level of the individual to the level of social groups, particular societies, and "society" as a whole (to whatever the latter may refer). While such a diversity of perspectives and disciplinary "encounters" on particular subjects are always welcome, the general impression a student of land use change gets is that of a polyphony of meanings and of approaches which express particular points of view, definitions of the issue of land use change, and, consequently, proposed solutions. The gap between the life/earth sciences, on the one hand, and the humanities/social sciences, on the other, is particularly visible, intense, and frustrating. Despite mutual acknowledgment of the close interconnections between the bio-physical and socio-economic dimensions of land use change, there is still considerable lack of communication between them and, hence, limited opportunities for essential integration of their different worlds. Researchers working on related subjects seem to have limited, inadequate, or no knowledge and awareness of what each other are doing and how they are studying particular aspects of the same *indivisible* entity; land, its uses and their changes.

There would be no immediate concern and urgency for such an integration was it not for the critical need to address the issues associated with land use change comprehensively and holistically; i.e. in an interdisciplinary or, better, in a transdisciplinary way – a term of a rather recent usage, a successor of the terms multi- and interdisciplinary. Bridging the natural and the social sciences worlds is expected to provide those necessary theoretical and modeling frameworks and tools which will assist in the comprehensive conceptualization and operationalization of the broad repertoire of land use change issues. A prerequisite to this quest for integration and synthesis of the various theoretical and modeling approaches to land use change is a thorough stock-taking of all attempts to date towards this purpose originating in diverse areas of the terrain of scientific knowledge. The present is a modest attempt to present systematically and evaluate critically representative approaches to land use change. It builds on several noteworthy past attempts as well as on the more recent activities undertaken in the context of the LUCC research program. It is intended to provide, on the one hand, the ground for a more comprehensive and in-depth account of extant and evolving approaches and, on the other, the ground for the much desired synthesis into useful spatial (land use) decision support systems. Given the present high interest on the subject and the continuous (and speedy) accumulation of knowledge in terms of both theories and models, this is an open-ended endeavor. Several of the issues which are presented and discussed in this first attempt at compilation are awaiting for further analysis and enrichment in the course of time.

Reviewing and presenting systematically the extant literature on the subject was not an easy task for a variety of reasons the most important of which are mentioned here only. The first is, as usual, conceptual/definitional and a matter of nomenclature. The same concept is defined differently not only in different but, sometimes, in the same discipline or in its fields and, usually, is given different names. Or, the same word is used with differing meanings in the same or in different contexts. Both conceptualizations and definitions may overlap also making analysis even more troublesome. An example which is further analyzed in this chapter is the definition of "land use" which sometimes is used synonymously with that of "land cover" especially on aggregate spatial levels. Similarly, the term "spatial change" is used frequently to denote land use change although spatial change has a much broader meaning as its use in a variety of other contexts reveals. This example brings us to the second reason why this review was not easy which is the fact that land use change is studied explicitly or implicitly in broader contexts dealing with spatial change and, more frequently, with environmental change. In these contexts, theorizing on and modeling of land use change was not always straightforward or did not constitute the principal object (or, purposes) of study although land use was and always is the inevitable intermediary in the nature-economy-society (or, any pair of them) interactions. Hence, the study of land use change is masked by the study of other types of changes in which land use is unavoidably implicated. The third reason, which draws from the previous one, is that theories of land use change may appear as derivatives of theories of broader socio-economic and environmental changes. Similarly, models of land use change may be either simplistic or land use change is modeled "residually" in the context of larger models; i.e. the emphasis is on modeling of micro- or macro- socio-economic or environmental change and land use change is simply assessed as a consequence of these changes by using simple proportionality coefficients. Lastly, a considerable number of important theories and models are essentially aspatial, i.e. they take no account of the material and geographic surroundings and constituents of human activities or they reduce them to certain uniform, geometric characteristics that bear a remote or no relationship to the physical characteristics of land. In this case, there is no direct way to study land use and its changes.

For these reasons, certain decisions were made about what to include and what not to include in this study from the broad spectrum of theoretical and modeling approaches which relate, in one way or another, to land use and its change. The general rule applied was that priority is given to those theories and models which treat land use and, more importantly, its change explicitly. The exact meaning of "explicitly" is clarified in chapters 3 and 4. Secondarily, theories and models which have an easy identifiable link to land use change were included. Certain theories and models – of the aspatial variety – which bear importantly on land use change, as they concern its determinants (or, *drivers* as they are called in the pertinent literature), are briefly mentioned. Finally, although several of the theoretical and modeling approaches which are included here are used (or, originate) in planning – especially, physical, land use and spatial planning, in general – a host of other theories and models which are relevant in the context of planning are not included explicitly. With this, a last, important point is made. Land use change is driven by a variety of forces which relate differently to one another in different spatial and temporal settings. Holistic theories of land use change need to draw on a variety of theories relating to the drivers of this change, first, to offer realistic and meaningful accounts of land use change, second, to provide rigorous theoretical bases for modeling this change, and, third, to guide action in problem solving (i.e. planning) situations. More importantly, however, this blending and synthesis of theories – if it is ever achieved - may dissolve the present thematic boundaries (industrial change, spatial change, institutional change, etc.) and reveal a unified theory, a meta-theory of change.

The present work is organized in five chapters. This first chapter, the Introduction, discusses alternative purposes for which analysis of land use change is undertaken, defines the terms land, land cover, land use, land cover change and land use change, introduces briefly the bio-physical and socio-economic drivers of land use change as well as its environmental and socio-economic impacts, and closes with a presentation of selected land use and land cover classification systems. The second chapter is devoted to a brief historical overview of the study of land use change over time and in various quarters. It draws parallels to changes or differences in socio-cultural values, technology, economic organization, magnitude of environmental problems associated with land use change, as well as changes in the theorizing and modeling traditions of the disciplines of the natural and the social sciences that engage in the study of land use change. The third chapter presents and evaluates selected theories of land use change classified according to the main **theorization traditions** to which they belong. The fourth chapter presents and evaluates a selection of models of land use change classified according to the modeling tradition to which they belong. An understanding of the majority of models presented is facilitated by solid knowledge of statistics, calculus, and operations research methods. Lastly, the fifth chapter summarizes the main issues pertaining to theories and models of land use change, discusses selected issues in of a more general concern in the context of the analysis of land use change and outlines future research directions.

1.2. The Purpose of the Analysis of Land Use Change

The approaches taken for the analysis of land use change are determined critically by the analyst's objectives. The definitions and land use classification systems used, the theoretical schemata adopted and the models employed all depend on the main questions and the user needs the analysis seeks to address; i.e. on its purpose. Characteristic purposes of analysis are briefly discussed in this section grouped into six main categories: description, explanation, prediction, impact assessment, prescription and evaluation.

Descriptive studies of land use change are almost indispensable in any analytical endeavor as a first step towards more refined analyses. Description of land use change documents changes from one type of land use to another over a given time period and within a given spatial entity. Changes in both the qualitative as well as the quantitative characteristics of land use are described, the level of detail conditioned by the spatial level of analysis and the availability of requisite data. Descriptive studies of land use change have provided the impetus for more thorough investigations of the "why" of these changes as well as for taking actions (policies) to counteract the negative impacts of the changes identified.

Description alone, however detailed and thorough it may be, is not enough to provide the basis for understanding the observed land use changes or to guide policy and decision making towards effective ways to cope with the adverse implications of these changes. Explanatory analyses attempt to fill this gap.

Explanation attempts to address the question of "why" these changes have occurred (or, are occurring) and to uncover the factors or forces that bring about these changes directly or indirectly, in the short or the longer run. The level of explanation offered by any study is a matter of the chosen spatial and temporal level of analysis. Macro-analyses necessarily refer to global changes and take into account global explanatory factors or determinants of land use change. As the analysis moves towards lower spatial levels, explanation moves deeper into the social and psychological dynamics that underlie observed human behavior and, consequently, land use change. Similarly, explanatory analyses over long time periods attempt to reveal the macro-forces that induce land use changes such as social, cultural and technological change. On the contrary, short-term explanatory analyses necessarily seek for more immediate factors affecting human behavior that leads to land use change although the influence of the larger macro-forces can be taken into account as conditioning the shorter-term phenomena. Explanatory studies employ more or less specific theoretical schemata that account for the main determinants of land use change and their intricate interrelationships.

In addition to describing and explaining land use change, an important purpose for conducting such analyses is to predict future changes in land use. Predictions may be unconditional or conditional. Unconditional predictions, also called trend extrapolations, provide future images of the land use patterns in an area that will exist if past trends continue into the future. Unconditional predictions may be mechanistic extrapolations of past land use change or, if they are informed by theory, they may be more thorough projections of past trends in the determinants and the resulting land use change into the future. Conditional predictions of land use change produce alternative land use futures of an area under hypothetical conditions or scenarios. Some analyses are conducted with the purpose of predicting land use changes caused by climatic change or by changes in future population, food and other habits and so on. Conditional predictions, based usually on scenario analysis, are frequently used in the context of policy making on issues of global change (e.g. climate change, biodiversity loss, **desertification**). In both unconditional and conditional predictions, the critical issues are again the spatial and temporal level of analysis.

Another important purpose of the analysis of land use change is impact assessment. The contemporary interest is not so much on land use change itself as is on its various environmental and socio-economic impacts at all spatial levels. In addition, as policies are designed to address several of the environmental and socio-economic problems in which land use change contributes in one way or another, policy impact assessment has emerged as a significant scientific activity. The recent policy interest, specifically, is on the broader issue of **sustainability** of development as it is impacted by land use change triggered by proposed or implemented policies. Land use changes with adverse impacts – such as land degradation, **desertification**, depopulation, etc. – contribute negatively to the achievement of long term sustainability as they reduce the natural, economic, human, and social capital available to future generations.

In a normative perspective, the analysis of land use change may seek to address the question of "what should be"; in other words, the purpose is to prescribe land use configurations that ensure the achievement of particular goals. Presently, these goals come under the broad search for "sustainable land use solutions". The purpose of this type of analysis is to indicate those patterns of land use (and, consequently, to prescribe the necessary change from past patterns) which are associated with environmental preservation, economic prosperity and welfare and social equity (that hopefully ensures their acceptability).

Finally, analysis of land use change may be undertaken for evaluating either past, present or future (policy-driven) changes in patterns of land use in terms of certain criteria such as environmental deterioration (or improvement), economic decline (or growth), or social impoverishment; or, more generally, against the criterion of **sustainability** . The results of these evaluations may be used to suggest land use alternatives (i.e. changes over those on which the evaluation was based) that would contribute to the attainment of these goals. Prescriptive and evaluative analyses of land use change are not discussed – except in particular instances – in the present study as they are beyond its scope.

Regardless of its purpose, a reliable and consistent analysis of land use change requires that certain prerequisites are satisfied; namely, that the basic terms used in the analysis are clearly defined, land use classification systems compatible with the purpose of the analysis are used, valid theories frame the analysis, and the analytical techniques used can represent realistically the particular land use change issues under consideration. The rest of this chapter first clarifies the terms "land", "land cover", "land use", "land cover change" and "land use change"; then, it discusses the drivers and impacts of land use change; and, finally, it presents selected available land use classification systems used in related analyses.

1.3. Defining Land, Land Cover, Land Use, Land Cover Change and Land Use Change

Studies of land use change do not always employ similar definitions of the principal terms land, land use and land use change. Definitions and descriptions of these terms vary with the purpose of the application and the context of their use. It is, thus, necessary to look at alternative definitions and descriptions of these terms that are more frequently used in these studies, especially those offered by official sources of land and land use data.

1.3.1. Land

The Food and Agriculture Organization (FAO) defines *land* as an area of the Earth's surface (FAO 1996). However, FAO (1995) gives a more refined and holistic definition which was used also in the documentation for the Convention to Combat Desertification (FAO 1995, 6 citing UN 1994):

"*Land* is a delineable area of the earth's terrestrial surface, encompassing all attributes of the biosphere immediately above or below this surface, including those of the near-surface climate, the soil and terrain forms, the surface hydrology (including shallow lakes, rivers, marshes, and swamps), the near-surface sedimentary layers and associated groundwater reserve, the plant and animal populations, the human settlement pattern and physical results of past and present human activity (terracing, water storage or drainage structures, roads, buildings, etc.)". (FAO 1995, 6).

Wolman (1987) cites Stewart's (1968) definition of *land*: "the term *land* is used in a comprehensive, integrating sense.....to refer to a wide array of natural resource attributes in a profile from the atmosphere above the surface down to some meters below the land surface. The main natural resource attributes are climate, land form, soil, vegetation, fauna and water" (Wolman 1987, 646).

Hoover and Giarratani (1984, 1999) state that *land* "first and foremost denotes space..... The qualities of land include, in addition, such attributes as the topographic, structural, agricultural and mineral properties of the site; the climate; the availability of clean air and water; and finally, a host of immediate environmental characteristics such as quiet, privacy, aesthetic appearance, and so on" (Hoover and Giarratani 1984, 131).

FAO (1995) cites Chapter 10 of Agenda 21 (UNCED 1993) which states that "the definition of land used to be "a physical entity in terms of its topography and spatial nature; this is often associated with an economic value, expressed in price per hectare at ownership transfer" (FAO 1995, 6).

It is worth noting that all definitions of land, although in general similar, differ as to the priority given to the attributes that characterize land. The natural sciences (FAO 1995, Wolman 1987) start from and detail the natural characteristics of land while the social sciences, more specifically economics (Hoover and Giarratani 1984, 1999), start from the mere element of space and refer more abstractly to the natural features of a segment of space. These differences in the definition of land show up in the next chapters of this study in the ways different disciplines theorize on and model land use change.

1.3.2. Land Use and Land Cover

The terms land use and land cover are not synonymous and the literature draws attention to their differences so that they are used properly in studies of land use and land cover change.

"*Land cover* is the biophysical state of the earth's surface and immediate subsurface" (Turner *et al.* 1995, 20). In other words, *land cover* "describes the physical state of the land surface: as in cropland, mountains, or forests" (Meyer 1995, 25 cited in Moser 1996, 247). Meyer and Turner (1994) add: "it embraces, for example, the quantity and type of surface vegetation, water, and earth materials" (Meyer and Turner 1994, 5). Moser (1996) notes that: "The term originally referred to the type of vegetation that covered the land surface, but has broadened subsequently to include human structures, such as buildings or pavement, and other aspects of the physical environment, such as soils, biodiversity, and surfaces and groundwater" (Moser 1996, 247).

"*Land use* involves both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation – the purpose for which the land is used" (Turner *et al.* 1995, 20). In a similar vein, Meyer (1995) states that "*land use* is the way in which, and the purpose for which, human beings employ the land and its resources" (Meyer 1995, 25 cited in Moser 1996, 247). Briefly, *land use* "denotes the human employment of land" (Turner and Meyer 1994, 5). Skole (1994) expands further and states that "*Land use* itself is the human employment of a land-cover type, the means by which human activity appropriates the results of net primary production (NPP) as determined by a complex of socio-economic factors" (Skole 1994, 438). Finally, FAO (1995) states that "*land use* concerns the function or purpose for which the land is used by the local human population and can be defined as the human activities which are directly related to land, making use of its resources or having an impact on them" (FAO 1995, 21).

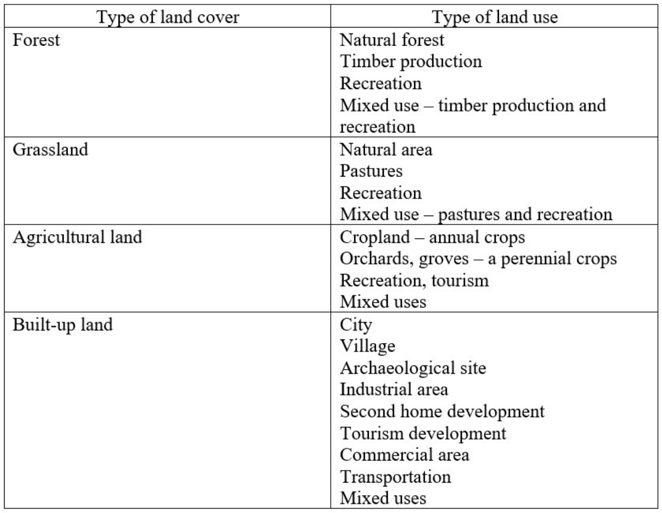
While the above definitions of land use refer mostly to larger, territorial scales, at the urban scale, interest focuses on other aspects of the term. In the words of Chapin and Kaiser (1979): "At territorial scales involving large land areas, there is a strong predisposition to think of land in terms of yields of raw materials required to sustain people and their activities. At these scales, 'land' is a resource and 'land use' means 'resource use'. In contrast, at the urban scale, instead of characterizing land in terms of the production potential of its soils and its submineral content, the emphasis is more on the use potential of the land's surface for the location of various activities" (Chapin and Kaiser 1979, 4). This connotation of the term "land use" is implicit in several other texts dealing with land use in the context of urban and regional analysis and planning (see, for example, Hoover and Giarratani 1984, 1999, Ch. 6).

As it was the case with the definition of the term "land" above, different definitions of "land use" are employed at various levels of analysis and, most of the time, by different disciplines, a fact that inhibits more holistic and integrated approaches to the analysis of land use and its change in general. Wolman (1987) cites Clawson (1982, 111) noting "… the difference in the perception the city planners and the agricultural experts have of land use" (Wolman 1987, 647).

The description of land use, at a given spatial level and for a given area, usually involves specifying the mix of land use types, the particular pattern of these land use types, the areal extent and intensity of use associated with each type, the land tenure status (Bourne 1982, Skole 1994). More detailed natural and physical characteristics are recorded for each land use type for a complete description of land use (see, for example, Chapin and Kaiser 1979 for the case of urban land use studies; Meyer and Turner 1994 for regional and higher level studies).

It will have become apparent by now from the above discussion that land use and land cover are not equivalent although they may overlap. The distinction is schematically depicted in Table 1.2.

Table 1.2: Types of land cover and associated types of land use



Type of land cover	Type of land use
Forest	Natural forest Timber production Recreation Mixed use – timber production and recreation
Grassland	Natural area Pastures Recreation Mixed use – pastures and recreation
Agricultural land	Cropland – annual crops Orchards, groves – a perennial crops Recreation, tourism Mixed uses
Built-up land	City Village Archaeological site Industrial area Second home development Tourism development Commercial area Transportation Mixed uses

Meyer and Turner (1994) state that “By *land cover* is meant the physical, chemical, or biological categorization of the terrestrial surface, e.g. grassland, forest, or concrete, whereas *land use* refers to the human purposes that are associated with that cover, e.g. raising cattle, recreation, or urban living” (Meyer and Turner 1994, x). Land use relates to land cover in various ways and affects it with various implications. As Turner and Meyer (1994) state: “A single land use may correspond fairly well to a single land cover: pastoralism to unimproved grassland, for example. On the other hand, a single class of cover may support multiple uses (forest used for combinations of timbering, slash-and-burn agriculture, hunting/gathering, fuelwood collection, recreation, wildlife preserve, and watershed and soil protection), and a single system of use may involve the maintenance of several distinct covers (as certain farming systems combine cultivate land, woodlots, improved pasture, and settlements). Land use change is likely to cause land cover change, but land cover may change even if the land use remains unaltered” (Turner and Meyer 1994, 5). Meyer (1995) adds the important point that “changes in land cover by land use do not necessarily imply a degradation of the land” (Meyer 1995, 25 cited in Moser 1996, 247).

The importance and the necessity of distinguishing between land use and land cover is most evident in analyses of the environmental impacts of land cover changes. In the study of the interaction of grasslands with the physical processes of global change, for example, Graetz (1994) emphasizes the need “to retain the definition of grassland by ecological attributes (vegetation structure and composition) rather than by its principal use, livestock production. ….. it is not possible directly to relate land use as such to the major physical processes of global environmental change. Land use cannot be directly related to these forms of global change because it is a qualitative descriptor. Land use categories are abstract typologies that, although useful, cannot be meaningfully included in process models seeking to forecast the time and space patterns of global change. It is land cover, rather than land use, that has the mechanistic meaning in the processes of global environmental change” (Graetz 1994, 127).

However, the distinction between land use and land cover, although relatively easy to make at a conceptual level, is not so straightforward in practice as available data do not make this distinction clearly all the time, a fact that complicates the analysis of either one of them. At the global level, “key sources of global data do not distinguish clearly between cover and use” (Meyer and Turner 1994, 95). Skole (1994) provides more insights into these data problems. The links between land use and land cover are elaborated further in the next section.

1.3.3. Land Use Change and Land Cover Change

In the analysis of land use and land cover *change*, it is first necessary to conceptualize the meaning of *change* to detect it in real world situations. At a very elementary level, land use and land cover change means *(quantitative) changes in the areal extent (increases or decreases) of a given type of land use or land cover*, respectively. It is important to note that, even at this level, the detection and measurement of change depends on the spatial scale; the higher the spatial level of detail, the larger the changes in the areal extent of land use and land cover which can be detected and recorded.

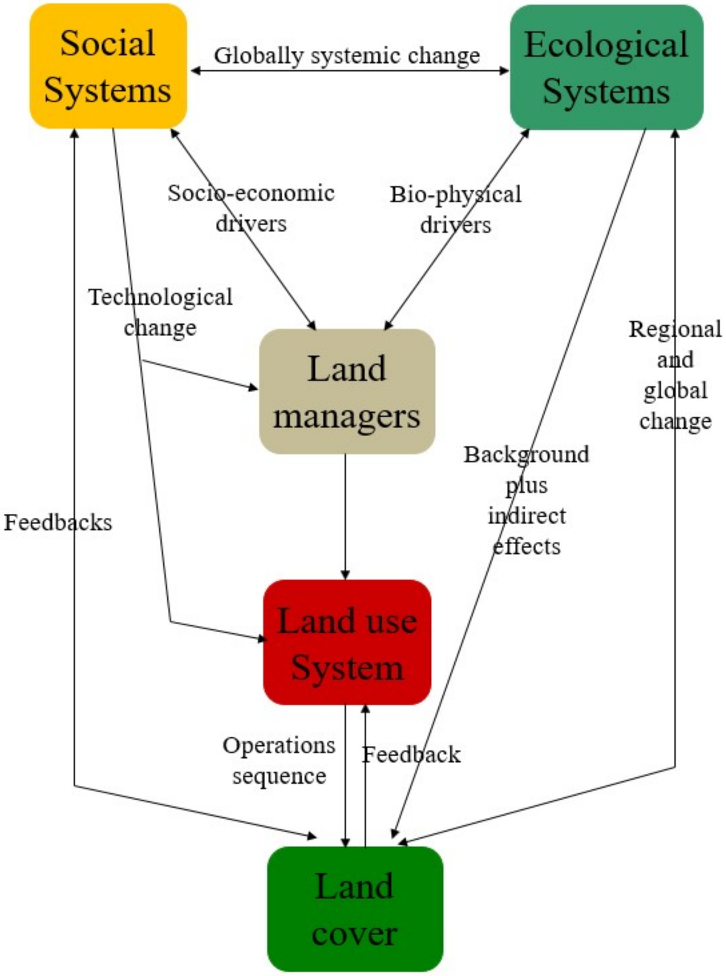
However, both in the case of land cover as well as of land use, the meaning and conceptualization of change is much broader. In the case of *land cover change*, the relevant literature distinguishes between two types of change: conversion and modification (Turner *et al.* 1995, 22; Skole 1994, 438). *Land cover conversion* involves a change from one cover type to another. *Land cover modification* involves alterations of structure or function without a wholesale change from one type to another; it could involve changes in productivity, biomass, or **phenology** (Skole 1994, 438). Land cover changes are the results of natural processes such as climatic variations, volcanic eruptions, changes in river channels or the sea level, etc. However, most of the land cover changes of the present and the recent past are due to human actions – i.e. to uses of land for production or settlement (Turner *et al.* 1995, 27). More specifically, Meyer and Turner (1996) suggest that “Land use (both deliberately and inadvertently) alters land cover in three ways: *converting* the land cover, or changing it to a qualitatively different state; *modifying* it, or quantitatively changing its condition without full conversion; and *maintaining* it in its condition against natural agents of change” (Meyer and Turner 1996, 238).

In a similar vein, *land use change* may involve either (a) *conversion* from one type of use to another – i.e. changes in the mix and pattern of land uses in an area or (b) *modification* of a certain type of land use. Modification of a particular land use may involve changes in the intensity of this use as well as alterations of its characteristic qualities/attributes – such as changes from low-income to high-income residential areas (the buildings remaining physically and quantitatively unaltered), changes of suburban forests from their natural state to recreation uses (the area of land staying unchanged), and so on. In the case of agricultural land use, Jones and Clark (1997) provide a qualitative typology of land use changes: **intensification**, **extensification**, **marginalization** and abandonment (Jones and Clark 1997, 26-27).

The reason why the linkage between land use and land cover change is emphasized is that the environmental impacts of land use change and their contribution to global change are mediated, to a considerable extent, by land cover changes. Thus, their analysis necessitates the examination of the ways in which land use relates to land cover change *at various levels of spatial and temporal detail.* The specification of the spatial and temporal levels of detail is of crucial importance for the analysis of both changes as: (a) it guides the selection of the types of land use and land cover that will be analyzed, (b) it determines the drivers and processes of change that can be detected and, thus, (c) it affects the identification *and* explanation of the linkages between land use and land cover within particular spatio-temporal frames. As regards the latter, the point is that *local* level land use changes may not produce significant *local* land cover change (and, consequently, significant environmental impacts). However, they may accumulate across space and/or over space and produce significant land cover changes at higher (e.g. regional or national) levels. This is the case, for example, of agricultural land conversion to urban uses that results from the decision of the individual land owners to convert their farmland to non-farm uses. Similarly, land use changes may be more qualitative rather than quantitative at lower levels of spatial and temporal detail but they show up as quantitative changes at higher levels and in the longer run. For example, gradual and incremental changes in the types of crops grown at the farm scale or in the quality of land management may result in the long run in abandoned agricultural land or seriously degraded farmland (in other words a change in category from productive to nonproductive land).

1.4. Land Use Change: Bio-Physical and Socio-Economic Drivers

The analysis of land use change revolves around two central and interrelated questions: "what drives/causes land use change" and "what are the (environmental and socio-economic) impacts of land use change". This section addresses the first of these questions. The precise meaning of the "drivers" or "determinants" or "driving forces" of land use change is not always clear, commonly accepted and understood by all those who engage in studies of land use change. Frequently, certain driving forces are emphasized over some others and there is confusion as to the **semantic** categories to which these causes of land use change belong. Two principal distinctions are made in the following. The first regards the origins of the drivers of land use-cover change. It is almost unanimously accepted that there are two main categories: bio-physical and socio-economic drivers. The *bio-physical drivers* include characteristics and processes of the natural environment such as: weather and climate variations, landform, topography, and geomorphic processes, volcanic eruptions, plant succession, soil types and processes, drainage patterns, availability of natural resources. The *socio-economic drivers* comprise demographic, social, economic, political and institutional factors and processes such as population and population change, industrial structure and change, technology and technological change, the family, the market, various public sector bodies and the related policies and rules, values, community organization and norms, property regime. The relationship between bio-physical and socio-economic drivers and other components of the land use-cover system are depicted in Figure 1.3a.



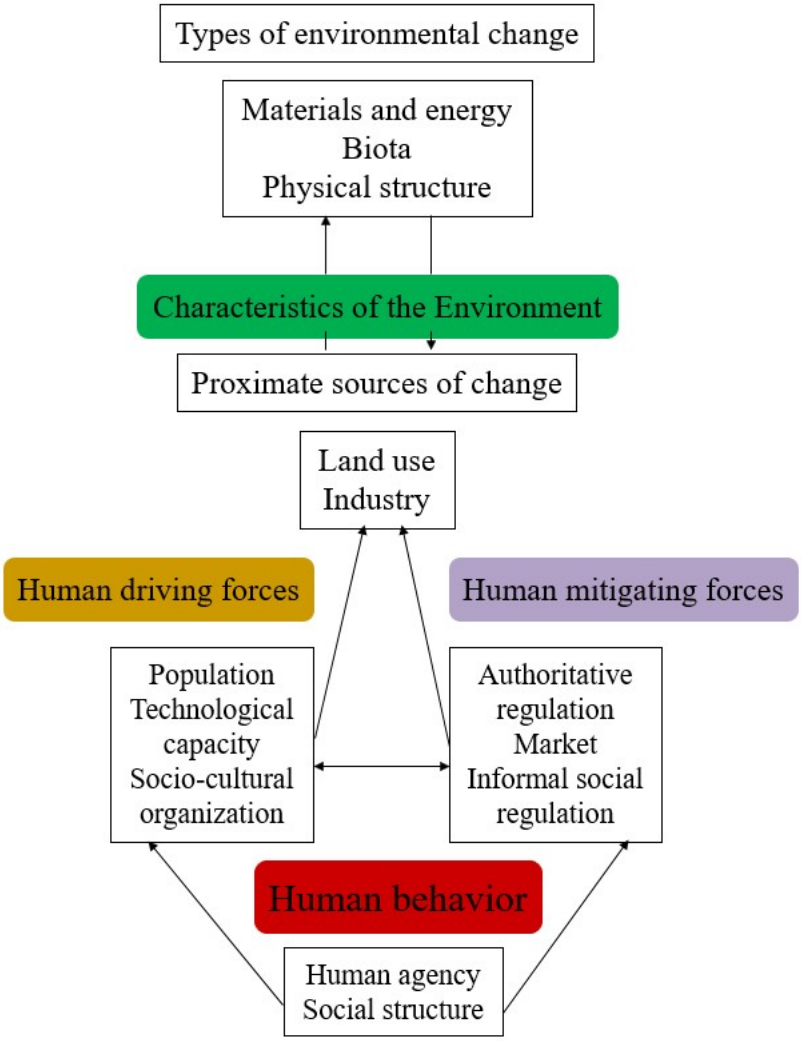
The relationship between bio-physical and socio-economic drivers and other components of the land use-cover system

Source: Adapted from Turner *et al*. (1995)

Figure 1.3a

It should be noted that the bio-physical drivers usually do not cause *land use change* directly. Mostly, they do cause *land-cover change* (or changes) which, in turn, may influence the land use decisions of land owners/managers (e.g. no farming on marginal lands). In addition, land use changes may result in land cover changes which, then, feedback on land use decisions causing perhaps new rounds of land use change (or changes).

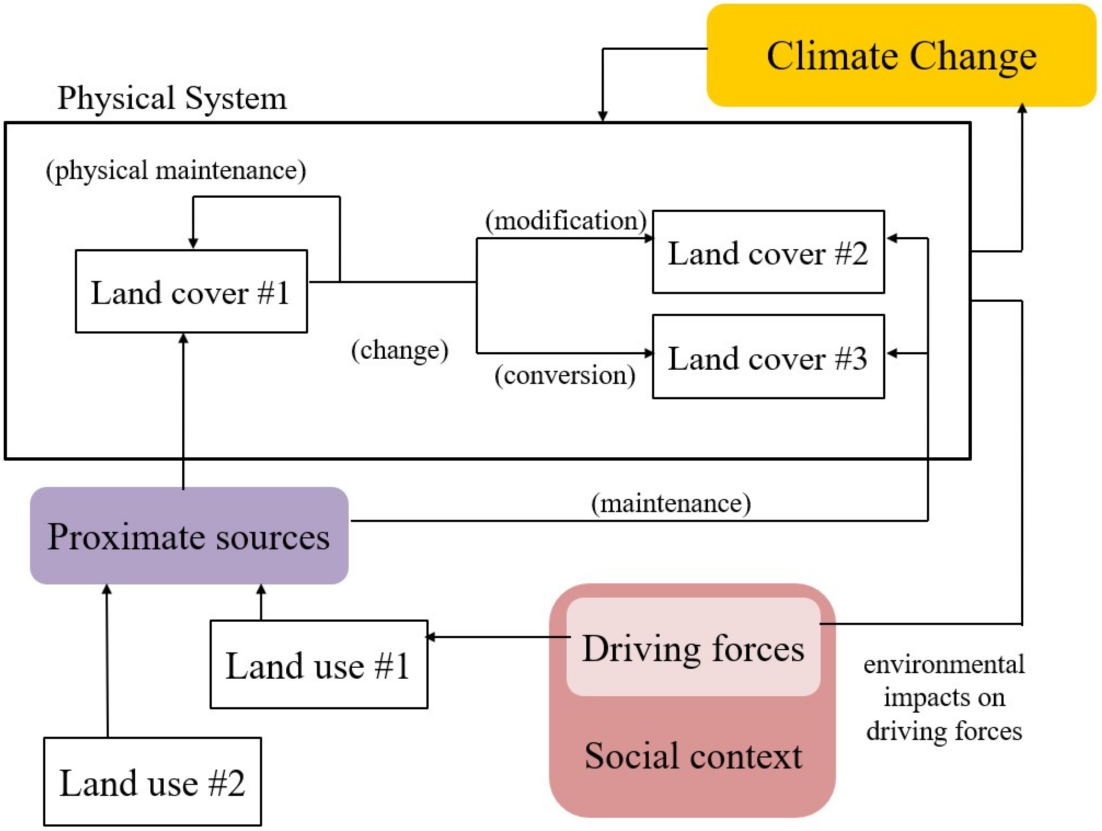
The second distinction is semantic and concerns a categorization of the various factors and processes that contribute, in one way or another, to land use change and, through certain human actions, cause land cover and environmental change. In this context, human driving forces, human mitigating forces and proximate driving forces are distinguished mainly (Turner *et al.* 1995, Moser 1996, Kates *et al.* 1990, Turner and Meyer 1994). *Human driving forces*, “or macroforces are those fundamental societal forces that in a causal sense link humans to nature and which bring about global environmental changes” (Moser 1996, 244). Examples of those forces include: population change, technological change, sociocultural/socioeconomic organization (economic institutions and the market, political economy, ecology, political institutions). *Human mitigating forces* “are those forces that impede, alter or counteract human driving forces” (Moser 1996, 244). Examples of these forces are local to international regulation, market adjustments, technological innovations, and informal social regulation through norms and values. *Proximate driving sources* “are the aggregate final activities that result from the interplay of human driving and mitigating forces to directly cause environmental transformations, either through the use of natural resources (e.g. as input to agriculture, mining activities, or as raw materials for industrial production), through the use of space, through the output of waste (solid waste, emissions, pollution, etc.) or though the output of products that in themselves affect the environment (e.g. cars, plastic bags)" (Moser 1996, 244-245). Many more examples of proximate sources of change can be added: biomass burning, fertilizer application, species transfer, plowing, irrigation, drainage, livestock pasturing, pasture improvement (Turner and Meyer 1994, 5), deforestation and site abandonment (Skole 1994, 438), breaking up of large tracts of grassland, expansion of cultures which promote erosion (e.g. maize, sugarbeet),farming of fields in the fall line (Lehmann and Reetz, 1994), urbanization, suburbanization, urban fringe development, fire. The relationships among those forces as well as among them and the other components of the land use-cover system are depicted in Figures 1.3b and 1.3c.



The human causes of global environmental change

Source: Adapted from Moser (1996)

Figure 1.3b



Linkages among human causes and land use and land cover

Source: Adapted from Moser 1996

Figure 1.3c

Land use and land cover are connected through the proximate causes of change which translate the human goals of land use into changed physical states of land cover. Land use change that drives land cover change is shaped by human driving forces that determine the direction and intensity of land use (Turner and Meyer 1994).

1.5. Land Use Change: Environmental and Socio-Economic Impacts

The second central question with which the analysis of land use change is concerned is: "the (environmental and socio-economic) impacts of land use change". In fact, it was the negative impacts that stimulated the scientific and policy interest on land use change. As Kates *et al.* (1990) put it, "The lands of the earth bear the most visible if not necessarily the most profound imprints of humankind's actions" (Kates *et al.* 1990, 6).

The impacts of land use change are broadly categorized into environmental and socio-economic, the former having received more attention and publicity than the latter. One of the reasons for this imbalance in attention may be that the latter are more subtle, longer-term and subject to the influence of many more complex, and less visible and verifiable, factors than the former. But, it should be noted that the environmental and the socio-economic impacts are closely interrelated; the former causing the latter which then feedback to the former again, potentially causing successive rounds of land use change. A widely publicized case of a chain of environmental and socio-economic impacts of land use change is that of shifting cultivators in Latin America and other parts of the world. The sequence of land use change starts with forest clearance; cultivation follows, then heavy grazing, and, ultimately, land abandonment and movement to another location (along newly built highways which serve oil drilling sites) where the sequence is repeated (Blaikie and Brookfield 1987).

The impacts of land use change are usually distinguished according to the spatial level on which they manifest themselves into global, regional and local impacts. Note that the terms global, regional and local do not have a precise physical meaning in studies of land use change especially as regards the regional and local levels. For example, a region may be a subdivision of the world (e.g. Latin America, China, the Sahel, large world **biomes**, etc.) or a subdivision of a large nation (e.g. a state or a group of states of the USA) or, even a subregional subdivision of a nation's region. From another viewpoint, for the purposes of the analysis of the impacts of land use change, a region may be defined on the basis of geographic and environmental characteristics like the Mediterranean region, the Baltic Region, etc. Similar comments apply to the delineation of local areas especially where the local is used as the opposite of the global.

As regards the *global environmental impacts* of land use and cover change, Meyer and Turner (1996) note that "Land use and land cover is a relatively new addition to the core concerns of global environmental change research. Its full incorporation was delayed by a narrow view of what could be considered global change, restricting it to those processes that occur in fluid global change systems: the atmosphere, the oceans, the climate. Human impacts in this realm have been referred to as *systemic* forms of global change (Turner *et al.* 1990); they are incontestably global in the sense that intervention at one point can affect the entire system, having direct physical repercussions on the other side of the globe. The classic examples are **stratospheric ozone depletion**, global climate change, through an intensified greenhouse effect, and **eustatic sea-level rise** as a consequence of climate change" (Meyer and Turner 1996, 237). These authors continue to point out that, even in the narrow, systemic meaning of global change, land use change impacts can be global in nature as: (1) many land uses (e.g. agriculture, grazing and forestry) release substantial amounts of trace gases that may produce global climate change and (2) a thorough understanding of the land-use/cover systems that are affected is required to assess the environmental and other impacts of many global phenomena like sea-level rise or stratospheric ozone depletion (Meyer and Turner 1996).

In addition, Meyer and Turner (1996) emphasize that land use-cover change impacts "are basic to another class of environmental changes that can be regarded as global in reach, the ones that Turner *et al.* (1990) call globally *cumulative.* Though not physically connected through a globally operating system, these changes can reach a global scale and status when their occurrence in many places adds up. Deforestation, wetland drainage, and grassland degradation have all amounted to a globally significant alteration of the land cover class involved" (Meyer and Turner 1996, 237-238). Large scale environmental phenomena like land degradation and **desertification**, **biodiversity** loss, habitat destruction and species transfer (Meyer and Turner 1996) fall in the same category as all of them are caused by land use changes. A comprehensive review of global environmental transformations associated with land use changes can be found in Kates *et al.* (1990).

At subglobal scales, what is broadly referred to as the *regional level*, the environmental impacts of land use change are equally significant and widely known. **Eutrophication** of water bodies, **acidification** of aquatic and terrestrial ecosystems, floods, **soil nitrate pollution**, land degradation and **desertification**, groundwater pollution, marine and coastal pollution and many more are environmental alterations that follow either directly or indirectly from land use changes (see, for example, Briassoulis 1994, Brouwer *et al.* 1991, Blaikie and Brookfield 1987, Jongman 1995, Laws 1983, Ortolano 1984). The sources of these regional impacts may not be located in the receptor region but they may be located in more than one (frequently distant) regions. The prominent example in this case is acidification that involves long-distance transport of acidifying gases and substances. In addition, several of the regional impacts of land use change take a long time to show up as it is the case of chemical soil pollution and the phenomenon of the so- called "chemical time bombs". These are defined as possible chains of events responding to slow environmental alterations, resulting in the delayed and sudden occurrence of harmful effects due to the mobilization of chemicals stored in soils and sediments (Hesterberg *et al.* 1992, Stigliani 1991).

Finally, land use change causes a multitude of environmental impacts at the *lower spatial levels* in urban, suburban, rural and open space areas which have been extensively documented. Especially important are the land use changes (land conversion) that occur in the periphery of large urban concentrations that are subject to urbanization and industrialization pressures and frequently result in losses of prime agricultural lands and tree cover. Their environmental impacts include changes in the hydrological balance of the area, increase in the risk of floods and landslides, air pollution, water pollution, etc. Other local impacts of land use change include soil erosion, sedimentation, soil and groundwater contamination and **salinization**, extinction of indigenous species, marine and aquatic pollution of local water bodies, coastal erosion and pollution. The importance of these impacts is not restricted to the local area of interest as they are frequently cumulative arising out of the decisions of many individual land and property owner to act in their narrow self-interest. In addition, land use changes in one area may have environmental repercussions in other distant areas. For example, urbanization or tourism development in an area increases the demand for water which, however, is provided by another area. Excess water abstraction reduces the water available for agriculture and plant growth in the latter area and may induce **saltwater intrusion** in coastal areas.

In addition to the environmental, the *socio-economic impacts* of land use change are equally significant and give rise to serious concerns at all spatial levels. *Global level socio-economic impacts* concern issues of *food security*, *water scarcity*, *population displacement* and, more generally, the issue of *human security and vulnerability* to natural and technological hazards. International and non-governmental organizations such as the FAO, the World Bank, the IHDP Programme, etc. undertake systematic assessments to support policy and decision making at all spatial levels on the above issues (Alexandratos 1988, Liverman 1989, Lonergan 1998).

The food security and the water scarcity issues may arise out of reductions in the area of agricultural land and decreases in available water supplies that result from soil erosion, land degradation, **desertification**, industrialization, urbanization, suburbanization, and above all, poor management of environmental resources. In all these instances, unsuitable uses of land play an important role. These issues concern the fundamental question of whether there is enough food to feed the growing population of the earth and enough water to cover present and future demands of an increasingly industrializing and urbanizing world. In parallel, they concern the question of whether the distribution of the food and water resources is even throughout the globe. Population displacement is another issue that is being investigated to identify the potential role played by environmental degradation to population movements away from localities experiencing environmental stress. Finally, human security and vulnerability is a collective term used to denote all those factors that may pose threats to human health, welfare and well-being in a given geographic area. A proposed measure is the “Index of Vulnerability” comprising 12 indicators – food import dependency ratio, water scarcity, energy imports as a percentage of consumption, access to safe water, expenditures on defense vs. health and education, indicator of human freedoms, urban population growth, child mortality, maternal mortality, income per capita, degree of democratization and fertility rates (Lonergan 1998, 27).

Regional level socio-economic impacts of land use change are more variegated reflecting the variety of regional settings where these changes occur. These, too, however, arise out of the same processes discussed above and evolve around such issues as availability of land for regional food production, changes (reduction) in land productivity and, consequently, (lower) profitability and changes in industrial structure, employment/ unemployment, poverty, population change and migration, and quality of life issues such as health and amenity.

Finally, *local level socio-economic impacts* of land use change comprise similar concerns but they are restricted to the particular localities where these changes occur. The issue of farmland conversion to urban and other uses (e.g. tourism) has received special publicity and concern has been expressed as, in addition to the environmental impacts mentioned before, it causes also serious socio-economic impacts (see, for example, International Regional Science Review 1982; Gray 1981). In the case of tourism development on previously agricultural land, a less visible but extremely important socio-economic impact is the increased dependency of the tourist region on not locally produced farm products and the increased pressures for agricultural output grown in and bought from other areas. Local level socio-economic, like the environmental impacts, may act cumulatively and cause larger than local impacts in the longer term.

A point that needs to be stressed is that usually all impacts of land use change are assumed to be negative. This is not always true for two reasons. First, whether an impact is positive or negative depends on the spatial and temporal scale concerned. Second, human mitigating forces mentioned above, such as environmental and social regulation and policies, land restoration projects and similar actions may impede the negative influences of human driving forces and, thus, mitigate if not eliminate, the unwanted consequences of land use change.

The larger question, however, that relates to the impacts of land use change is that of the *sustainability of development* at all spatial levels. Conceptualizing sustainability as the achievement of a balance between social, economic and environmental goals, the role of land use and its change is of central importance. The negative environmental and socio-economic impacts of land use change detract from the achievement of these go as they erode both the environmental and the socio-economic resource base of an area and, thus, reduce its ability to support equitably the needs of its population both in the short and in the longer term. In this perspective, land use planning and management become imperative. The broad goal of managing land use and its change is to develop the land resources in ways that capitalize on their local potential and suitability, avoid negative impacts and respond to present and future societal demand within the limits of the carrying capacity of the local environment (see, among others, FAO 1995).

1.6. Land Use and Land Cover Classification Systems

The analysis of land use change depends critically on the chosen system of land use and land cover classification. The magnitude and quality of land use change is expressed in terms of specific land use or land use/cover types. The assessment of the environmental and socio-economic impacts of land use change is possible only when the particular environmental and socio-economic features of the chosen land use/cover types are specified. If this requirement is not met, then, the analysis will be of limited value in guiding policy and decision making especially at lower scales. Hence, the need to discuss available land use and land cover classification systems and consider their suitability for the analysis of land use change at various spatial and temporal levels.

In developing any land classification system, a central dilemma concerns the choice between representing "what is" and "what should be". The "what is" encompasses the land available on earth and its characteristics as described by a given technology at a given point in time while the "what should be" relates to values placed on the land and its characteristics and the resulting choices made by people about uses for land (Wolman 1987, 655).

Before considering alternative land classification systems it is worth noting that all of them are distinguished in terms of the *spatial scale* of analysis for which they are developed and the *purpose* of their development. The spatial scale determines the level of environmental and socio-economic detail contained in the classification system while the purpose of the study determines the particular attributes of the land use types that will be considered. In addition, available *technology* for data collection is a significant determinant of their structure and content. The following presentation will attempt to focus on land use as opposed to land cover classification systems although the two are often interrelated (as land use and land cover are interrelated) and the existing systems do not always distinguish clearly between land use and land cover.

The development of land classification systems has a long history in various countries of the world. Soil classification systems were the first to be produced by both national (e.g. the U.S. Soil Conservation Service, Canada's Soils Directorate) and international (the FAO) organizations to serve the needs of producing soil maps and provide a basis for determining land capability and suitability for growing various types of crops (see, for example, Marsh 1991). The need for developing land use and land cover classification systems ensued first focusing, as it was natural, on agriculture and forestry – uses of land occupying large tracts of land and playing important environmental and economic roles. After the 1960s and 1970s, efforts to develop land use and cover classification systems for other types of land use proliferated, a response to growing urban and industrial pressures on land and the need to provide a basis for rational land use planning and management (see, for example, Kleckner 1981, Gray 1981, Pierce and Thie 1981). In the following, examples of land use and cover classification systems at various spatial scales and for various purposes are offered.

At the *world scale*, the first land use classification systems produced concerned the major land uses of the world. The FAO produces land use statistics, starting in the 1950s, using a 4-category classification of land use: arable land (or, cropland), grass land (or permanent pasture), forest land (or, forest and woodland), other land (which includes urban areas, unmanaged rangelands, land in polar regions, desert land, tundra, stony and rocky land in mountains and all other classified land) (Wolman 1987, 647; Beale 1997). Wolman (1987), however, cites another FAO publication describing world land use in terms of five categories: arable or cropped, meadow and permanent pasture, forest and woodland, unused but potentially productive, and built-over, wasteland and other. The relevant data are collected annually by means of questionnaires from national governments. Since the mid-1990s, the FAO is in the process of developing a more elaborate international framework for classification of land uses using a 3-level hierarchical system to develop classes of land use (see Appendix 1.A and FAO 1995).

At the subglobal level, mostly the *national level*, several land use classification systems are in use. In the U.S.A., the U. S. Geological Survey has developed the Land Use and Cover Classification System for use with remotely sensed data (Anderson *et al.* 1976). This system, like the FAO system, uses a 2-level hierarchy to define classes of land use and it is suitable up to the substate regional level (see Appendix 1.A). In Canada, the Lands Directorate of Environment Canada initiated the Canada Land Inventory in 1963 (Pierce and Thie 1981). An elaborate land use classification system has been set up which is being continuously improved to meet the variegated needs of users and uses. In Europe, several land use classification systems appeared especially after the 1980s. Two of them are mentioned here (the reader can find more information about other systems and related projects in Beale 1997). The CORINE system (Coordinated Information on the European Environment) was set up in 1985 in the European Community with the objective, among others, to improve data availability and compatibility across the European Community and within the member states. Its final product is a digital land cover data base made up of 44 classes with mapping units based on a tiered hierarchical classification scheme (NUTS) used in the European Community for statistical purposes. Another project, CLUSTERS (Classification for Land Use Statistics: Eurostat Remote Sensing Programme), is being developed in coordination with the EUROSTAT (the European Union Agency for statistical information). This system is also based on a hierarchical scheme of developing land use types that attempts to provide a standard system for studying land use applicable throughout the European territory whilst taking into account official classifications of land use at European level (see Appendix 1.A and Beale 1997).

Land use classification systems vary with the *purpose and context* of their use also. Classification systems for special types of land use usually employ more detailed and elaborate criteria that reflect the *particularities* of the land use type of concern as well as the intended use(s) of the classification system. In particular, emphasis is given on those characteristics of the land resources that determine the *suitability* of land for a given use or may *constrain* its development. Land use classification systems for *agriculture* are the most widely developed both by international (the FAO) and national organizations. The FAO has produced several documents describing procedures for land evaluation in agriculture in which criteria to classify agricultural land are described and detailed definitions of land use types and their subdivisions and other features are offered (FAO 1976, 1978, 1996; Alexandratos 1988). For example, in developing the Agro-Ecological Zoning (AEZ) methodology – a procedure for small scale land suitability assessment, *land* was described on the basis of the 15,000,000 Soil Map of the World and an inventory of climatic data. Land use requirements are *de facto* climate-related and soil-related crop requirements. *Land use alternatives* were restricted to those involving the world's major (annual) food and fibre crops, selected on the basis of the area occupied, the total production and the financial value they represent. Eleven major crops were selected: wheat, paddy rice, maize, pearl millet, sorghum, cotton, phaseolus bean, white potato, sweet potato and cassava (FAO 1996). Land use was classified into *Land Utilization Types* (LUT) defined as "a use of land defined in terms of a product, or products, the inputs and operations required to produce these products, and the socio-economic setting in which production is carried out" (FAO 1996, 72). Note that in a previous publication, FAO defined a *major kind of land use* as "a major subdivision of rural land, such as rainfed agriculture, irrigated agriculture, grassland, forestry or recreation" (FAO 1976). The AEZ typology presented above has been used in several studies of land use change and land use planning at various spatial levels (see, for example, Jansen and Schipper 1995, FAO/IIASA 1993, Fischer *et al.* 1996b).

Typologies for agricultural land use classification are developed also by competent national bodies such as the USDA, the USGS, the BLM in the USA, the Lands Directorate in Canada, various agencies in the European Union and its member states and other countries internationally. A very thorough analysis of past and contemporary efforts towards developing an agricultural typology is found in Kostrowicki (1991).

Land use-cover classification systems for *forest and woodland* are equally well developed despite the wide differences found among countries as regards applicable definitions and typologies (Moser 1996). FAO, the U.N. ECE, the World Resources Institute, the USGS, the USFS, the BLM, the Joint Research Centre (JRC) of the European Union at Ispra(Italy) and many other agencies worldwide provide systems of forest land classification that are instrumental in recording quantitative and qualitative changes in the status of forests in individual countries, large world regions and internationally. Classification systems for *parks and parkland* also exist given their important role in nature preservation and various types of recreation (Wolman 1987).

Finally, classification systems for the *built environment* (urban land use and transportation systems) are increasingly being developed the historical origin for their necessity being identified with McHarg's (1969) plea for designing the built environment within the limits set by nature. Given the variety of types of built-up land and the contexts within which it occurs, selected ways to classify urban land use are presented here based on Chapin and Kaiser (1979). These authors define classification as "a systematic means of grouping similar categories of land use in the pursuit of some predetermined goals" (Chapin and Kaiser 1979, 239). Many of the available systems have been influenced by the SIC (Standard Industrial Classification) system that is used for the classification of industrial activities (Chapin and Kaiser 1979, 240). This is a hierarchical system of classification, the lower level codes giving more detail on the characteristics of the industrial establishment(s) and products involved – and the associated space requirements for the present purposes. Appendix 1.A presents a selection of classification systems of urban land use categories.

Two things must be noted as regards the development of land use classification systems in general. Firstly, the context of development and use of these systems determines critically their structure and content. In several countries, particular land use types exist which are absent or negligible in other countries (e.g. informal settlements, desert). Secondly, the development of land classification systems is increasingly being influenced by the availability and use of satellite data and remote sensing techniques. These changes in technology facilitate the direct use of available data in conjunction with available techniques of analysis and models. Cowen and Jensen (1998) discuss the capability of remote sensing technology to measure key attributes of urban and suburban environments accurately at the requisite levels of spatial, temporal, and spectral resolution. They present a Table which depicts the relationships between selected urban/suburban attributes and the remote sensing resolutions required to provide such information (Cowen and Jensen 1998, 166).

To close this section, a brief discussion of the problems encountered in the development and use of land use/cover classification systems for the analysis of land use change is deemed necessary. Firstly, these systems have undergone several changes over time reflected in changes in definitions of the land use/cover types. These changes are due to changes in the qualitative characteristics of the uses of land itself (and the corresponding land cover), the needs of various types of users, the methods of analysis, and the technology used to collect and record the related data. Wolman (1987) notes that "the recent use of remote sensing techniques can introduce changes in classification as mapping units are defined by distinctive signatures of the many sensors used" (Wolman 1987, 647). Turner *et al.* (1995) observe that, originally, data collection was based on field surveys. After the 1960s, new survey techniques based on computer processing of aerial photographs and satellite images are being used. "These techniques directed classifications towards the *land cover* attributes captured in such imagery. Many existing land use classifications are based on the vegetational and artificial cover of the land surface: the World Land Use Classification, the Canada Land Inventory and Land Use Classification, the Second Land Use Survey of Britain Classification, the Canadian Land Use Classification, and the World Map of Present-Day Landscapes (Moscow State University-UNEP 1993, Rjabehakovnd.) to name a few" (Turner *et al.* 1995, 49).

The result of these changes is that "Not all classifications of land are semantically consistent and the typologies become even more complex as the scale is enlarged, covering smaller and smaller areas, and as the focus of interest shifts" (Wolman 1987, 647). A review of land use classification systems by Mucher *et al.* (1993) indicates that none of them is acceptable in a global change context (cited in Turner *et al.* 1995, 49). The drawbacks they note include: (a) lack of a sound definition of the units of analysis, ranging from field to farm to region (confused with mapping units); (b) overlapping of land use classes (because of the lack of clearly defined criteria; most hierarchical classifications are only comprehensive at the first level, and are far from comprehensive at lower levels); (c) near-total absence of quantitative class boundaries (critical or threshold values of the criteria), adding a significant subjective element to land-use assignments; (d) combination of land use with other dimensions, such as climate characteristics, that may influence land use but are not inherent features of it; (e) multiplicity of land use classification objectives, often closely tied to regional or disciplinary foci (Turner *et al.* 1995, 49-50). Turner *et al.* (1995, 50) observe that existing classifications do not use common classificatory principles and often conflate use and cover. Similar problems exist for classification systems of particular land use types (see, for example, Moser 1996). Appendix 1.B contains addresses of web sites of organizations which provide information on classification systems for land use and land use change.

Brief Historical Overview of Studies of Land Use Change

2.1. Introduction

The first thing people ever used to meet their needs was *land* – to move around, to rest, to settle, to feed themselves. Hence, the relationship of people with land has the same origin as their appearance on earth. But the widespread concern over this relationship expressed in diverse scientific quarters since ancient times focuses on its negative facets – either the adverse effects of human activities on land and environmental resources or the adversities humans experience due to constraints and hazards originating in land and the environment. As a full-blown historical review of this relationship is beyond the scope of this contribution, this chapter overviews briefly studies of land use change over time and across space with the purpose of providing a backdrop for the examination of the evolution of the theoretical and modeling approaches to land use change which is the core subject of this project. The changing modes of theorizing on and modeling land use change are paralleled to two broad streams of changes; first, in the conceptualization of land and land use which are affected by changes or differences in socio-cultural values, technology, economic organization, and magnitude of environmental problems associated with land use change, among others; and, second, changes in the modes of theorizing and modeling in the disciplines of the natural and the social sciences that engage in the study of land use change.

The present overview covers mainly studies of global, regional (in particular countries or in groups of countries) and local (in particular places within countries or in natural areas) land use change of the last 150 years of the second millennium. For the purposes of this presentation, three separate time divisions are introduced: (a) the "pre-industrial" period, (b) the first half of the 20th century, and (c) the second half of the 20th century. A perspective on the third millennium is based on current trends and expectations. Within each time division, the issues examined include: the purpose of a particular study, the spatial scale and the time frame of reference, the (implicit at least) **epistemological** basis and the contributing disciplines. The assumption is that the view of land and land use a study espouses is critically influenced by the latter two characteristics and, in its turn, influences the mode of theorizing and modeling land use change.

Before examining particular studies, the three generic approaches usually taken for the study of land use change which the "Implementation Strategy" of the Land Use and Land Cover Change project (LUCC 1999) names very lucidly "perspectives of understanding" should be mentioned. These are "the narrative, the agent-based, and the systems approach. The *narrative perspective* seeks depth of understanding through historical detail and interpretation. It tells the LUCC story, providing an empirical and interpretative baseline by which to assess the validity and accuracy of the other visions. It is especially beneficial in identifying stochastic and random events that significantly affect land-use/land-cover changes but might be missed in approaches employing less expansive time horizons or temporal sampling procedures. Both the agent-based and the systems approaches depend on explicit model development and empirical testing. The former (*agent-based perspective*) seeks to distill the general nature and rules of individual agents' behavior in their daily decision making. The forms of the distillation are many, ranging from the rational decision making of the average or typical actor in neo-classical economics to household, gender, class, and other such formations .... Central to this perspective, however, is the significance given to human agents in determining land-use decisions and the search for generalizations about this behavior. The *systems/structures perspective*, in contrast, finds understanding in the organization and institutions of society that establish the opportunities and constraints on decision making (Ostrom 1990). These structures operate interactively at different spatial and temporal scales, linking local conditions to global processes and vice versa (Morán, Ostrom and Randolph, 1998). The systems or structures may manifest themselves in unforeseen and unintended ways. Some institutions are direct drivers of change. Others, such as markets, are intricately linked to individual decisions – they affect these decisions and at the same time are the aggregate result of these decisions" (LUCC 1999, 14). In addition, LUCC (1999) stresses also that the study of land use change should strive to reconcile and integrate the three epistemological traditions: "(i) 'to observe and describe to understand' (i.e. *inductive approach*); (ii) 'to model to understand' (i.e. *deductive approach*); and (iii) 'to integrate to understand"'(i.e. *dialectic approach*)" (LUCC 1999, 14).

2.2. The Early Period – George Perkins Marsh and von Thunen

Among the most well known pioneers of the study of land use change are George Perkins Marsh in the U.S.A. and J.H. von Thunen in Germany. They approached the same issue from different perspectives and in different continents. The former, a (prescient) scholar and diplomat, examined in his seminal book *Man and Nature; or, the Earth as Modified by Human Action* (Marsh 1965; originally published in 1864) the extent and magnitude of impacts of human actions on the natural environment through the ages in various parts of the world. This study, while mainly descriptive, attempted to provide explanations of the environmental transformations observed and recorded as well as prescriptions of man's position *vis-a-vis* nature. The issue of land use is central (implicitly, at least) in Marsh's work as all human activity takes place and modifies space for particular uses. In the words of Kates *et al.* (1990) "The importance of *Man and Nature* lies less in the individual impacts that it catalogued ..... than in a grouping and wide-ranging synthesis that emphasized their interrelations and traced the innumerable distant effects of human action. The work was cited by many early conservationists... and influenced the views of nature-society relationships well beyond Marsh's native shores.....Marsh stressed the breadth and gravity of the unintentional human impacts, and thus the need to understand the complex interactions of natural processes prior to human intervention... Marsh also saw the transformation of the environment, if properly done, as almost entirely desirable....." (Kates *et al.* 1990, 3).

Somewhat earlier than G.P. Marsh, in 1826, from the other side of the Atlantic, a North German estate owner, J.H. von Thunen, "set for himself the problem of how to determine the most efficient spatial layout of the various crops and other land uses on his estate, and in the process developed a more general model or theory of how rural land uses should be arranged around a market town. The basic principle was that each piece of land should be devoted to the use in which it would yield the highest rent" (Hoover and Giarratani 1984, 142-143). Von Thunen viewed land as an economic resource whose main attribute worth considering was productivity and the landscape within which agricultural activity was taking place was flat and uniform in all directions. His purpose was **utilitarian** and the analysis of the "optimum" land use patterns static. The mechanism of land use change is implicit and can be derived from the assumptions of the theory; the only variable factor affecting location of a land use (and, presumably, its change) being the value of the associated product. Von Thunen's agricultural land use theory and model are discussed further in Chapter 3.

The two early studies just described represent the first diametrically opposed approaches to the study of land use change. In the decades that followed, a broad variety of studies covering the whole range between these two extremes appeared but Marsh's and von Thunen's legacy marked the two opposing currents along which theorizing on and modeling land use change developed in the 20th century. Marsh's comprehensive view of land, the natural environment and man's role in causing environmental change is in the core of a host of nature-society theories and integrated models proposed in the years that followed and that are much in vogue in the present. Von Thunen's economic, rational man producing economic goods for sale in a uniform, static and orderly landscape whose change is not a central issue founded the theories and models of mainstream urban and regional economics in the 20th century.

2.3. The First Half of the 20th Century

The first decades of the 20th century saw significant changes in the uses of land brought about by industrialization and urbanization in the western world not to mention by the two world wars and other major socio-economic events and technological progress. These changes were documented in studies of this period – most of which are not easily accessible, however – as well as in studies conducted in the second half of the century. They refer mostly to countries or geographic regions as well as to uses of land experiencing the most rapid and important changes such as urban areas in Europe and the USA, forests and agricultural areas in Europe, Russia, and the USA (e.g. the American Great Plains), coastal areas such as the Mediterranean basin and so on (see, for example, Braudel 1966, Kates *et al.* 1990, Bouwer *et al.* 1991). The most important trait of these studies is the establishment of the systematic and "scientific" analysis of land use change based on theories and models drawn from a variety of scientific fields – mainly, economics, sociology and geography. In fact, this trait is a reflection of a broader and more general development of this period: the emergence and development of dominant modes of theorizing and modeling on land and land use in the related fields of the social sciences: urban and regional economics, urban sociology, economic and social geography.

In the economics-oriented fields, central concepts and theories appeared in this period that relate directly or indirectly to the study of land use change. In 1933, Christaller (1966) formulated the Central Place Theory to offer a theoretical account of the size and distribution of retail establishments within an urban area employing two main concepts: the "range" of a good and the "threshold" for a good. In the 1940s, Losch (1954) used the conceptual framework of Central Place Theory to offer a more general account of the patterns of "central places" in a continuous space that accounted for other urban functions in addition to retailing. Extended to the level of an urban system, Central Place Theory accounts for the size and distribution of settlements within this system. The hexagonal hierarchical patterning of places is the distinguishing characteristic of both Christaller's and Losch's (and subsequent) versions of Central Place Theory. It should be noted, however, that these theorists dealt more with location in space rather than with land use *per se* and this is why the genre of location theory deriving from these founding fathers are not considered in the present contribution (see Chapter 3). Another concept drawing from concepts of social physics was that of human "interaction in space" (Stewart 1947, Zipf 1949) and the related notion of "accessibility" which was reflected mainly in the variability of transportation costs from some constant point in space (Haig 1927 cited in Korcelli 1982, p. 98-99). These latter concepts provided the foundations, in the latter half of the 20th century, for the development of the spatial interaction theoretical and modeling approaches which are discussed extensively in Chapters 3 and 4.

In the sociology-oriented fields, the development of the school of "human ecology" by sociologists of the Chicago School in the 1920s has had the greatest impact on the analysis of the land use structure and change of urban (and other) regions in this and subsequent periods (see, for example, Park *et al.* 1925, Chorley and Haggett 1967). The principal concepts of human ecology are drawn directly from the field of ecology and they are used to describe and explain the physical patterns observed in an urban region as well as the economic and social processes underlying them. Among them, the notions of "community", "**competition** ", "**invasion**", "**succession**", "conflict", "**climax equilibrium**" constitute central descriptive and explanatory conceptual devices (for definitions of some of these terms see, among others, Johnston *et al.* 1994). The concepts advanced to describe urban patterns, routinely mentioned in most texts of urban and regional studies and planning, are the "concentric zone" hypothesis (see, among others, Park *et al.* 1925, Romanos 1976), the "radial sector" theory (Hoyt 1939) and the "multiple nuclei" concept (McKenzie 1933, Harris and Ullman 1945). In the same vein, the notion of "sequent occupance" was proposed to describe the geography of an area as "a succession of stages of human occupance which establishes the genetics of each stage in terms of its predecessors" (Whittlesey 1929 cited in Johnston *et al.* 1994, 549). A well known application of this notion is Broek's study of the Santa Clara Valley, California (Broek 1932). The first human ecological studies that appeared in the first half of the 20th century marked the beginning of a long procession of similar studies undertaken in the following decades.

The concepts and theories discussed above share some common characteristics that bear importantly on the analysis of land use change. Firstly, most of them are **functionalist** approaches to the study of urban and regional structure and change – i.e. they reflect "an epistemological position in which teleological as distinct from causal explanatory forms are stressed" (Cooke 1983, 72). They look for "repeatable and predictable regularities in which form and function can be assumed to be related" (Bennett and Chorley cited in Johnston *et al.* 1994, 209). Second, some are predominantly descriptive (mostly the human ecology-based approaches) while some others are normative and prescriptive (Central Place Theory). Land, and space in general, does not have intrinsic properties. It is abstract and amorphous – an isotropic medium with uniform (though unspecified or highly abstract) qualities in all directions within which social and economic processes take place. Population and human activities and the uses of land associated with them are treated as though they do not extend over space but are points on a map. Even the city center is a point –simply, the center of a circle or a hexagon. The emphasis is on the *location* of human activities in space and on the *form* of the patterns produced – be they concentric rings or hexagonal market areas. Change in the uses of land – when it is a direct object of analysis in these frameworks – is a mechanistic and predictable response to changes in distance or transport cost, a natural consequence of the functionalism of these approaches.

2.4. The Other (Last) Half of the 20th Century

The scientific analysis and studies of land use change boomed after World War II along the lines of several of the approaches that had been formulated earlier. The numbers and diversity of extant studies make a complete and comprehensive overview impossible. Even a simple enumeration is difficult. The studies cover the whole range from the local (urban) to the global level. The approaches adopted stem from urban and regional economics, urban and rural sociology, geography and planning as well as from the natural sciences. In addition to the mono-disciplinary, a multitude of interdisciplinary approaches have appeared especially after the 1970s. Hence, this section attempts a selective overview of a vintage of the most important categories of studies the emphasis being on those where land use change is more or less the direct object of analysis.

The proliferation of studies and the particular directions pursued in the analysis of land use change are not unrelated to the broader theoretical and methodological changes in the disciplines that contributed to these studies as well as in the required supporting technology. The most important of them is perhaps the so-called "quantitative revolution" in geography but also in economics, sociology and planning in the 1950s and 1960s. Formal models and theories of land use and land use change were proposed in that period to be rejected – but not abandoned – later when their limitations became evident and their epistemological foundations were seriously questioned. The parallel progress in computer and data processing technology initially reinforced the quantitative orientation of the studies under consideration. Later on and at present, this technology appears to have an emancipating effect on the analysis of land use change in the sense that it facilitates the application of less quantitative (in the sense of the 50s and 60s), more qualitative and heuristic approaches that are not constrained by the frequently unrealistic assumptions of the earlier quantitative theoretical and modeling formulations.

Deeper changes in the epistemological perspectives of the scientific fields involved in the study of land use change at large have played and are playing also a catalytic role in directing the analysis towards particular paths and approaches as the current (beginning of the 21st century) diversity of land use change studies testifies. Finally, the recent policy interest in the (negative) implications of global environmental change – one component of which is land use change – may be exerting an influence on the orientation of the studies of land use change as practical approaches and decision support instruments are sought to guide policy making for sustainable land use.

The systematic and scientific analysis of land use change that had started in the first half continued in the second half of the 20$^{\text{th}}$ century in the same fields as before – urban and regional economics, regional science, sociology, geography and planning – in several of which the related theories and models were moving to or had reached mature stages. Again, land use and its change are not always the direct object of analysis in many fields reflecting the different focus of emphasis on particular aspects and dimensions of spatial change. However, the links to land use change are rather straightforward although not always obvious and explicitly elaborated. In addition, studies of land use change from particular fields of the natural and the applied sciences – forestry, agronomy, biology, ecology, remote sensing, environmental sciences – are not uncommon as well as studies attempting interdisciplinary approaches to the subject. Three main bundles of studies are presented below. The first originates in the economics-oriented fields such as urban and regional economics and the relevant subfields of regional science, geography and urban and regional planning. The second bundle draws from the sociology-oriented fields like urban and rural sociology and the relevant subfields of regional science, geography and urban and regional planning. A third bundle contains a multifarious collection of studies originating in the same fields as before but bearing the influence of the natural sciences and opting for integrated analysis of land use change.

The economics-oriented fields generated impressive numbers of theoretical, modeling and empirical studies of urban and regional spatial structure in the post war years. Broadly, they can be divided into those concerned with the urban and intra-urban spatial (economic) structure and those referring to larger than the regional scale areas. Most of the studies that explicitly account for land use change belong to the first group, the land-using activities more frequently analyzed being residential, commercial, transportation and, to a lesser extent, public and other services. A major stream of research is founded on neo-classical economics informed by spatial concepts; mainly the "friction of space" as measured by the distance among the location of activities. Alonso's (1964) urban land market theory and model (borrowing concepts from von Thunen's analysis) is considered the landmark study from which a series of urban economic models followed sharing a common characteristic: the description and explanation of urban spatial structure based on land rent and transportation costs and the assumption of utility maximizing individuals. For a selection of theories and models in this direction the reader is referred to Nijkamp (1986). In a related spirit, the 1960s saw applications of Central Place Theory to the location of retail centers, among others (Berry 1967). Another major stream of studies developed in the 1970s around the notions of spatial interaction and accessibility – already introduced in the 1940s and even earlier. It provided a theoretical framework as well as a "family of spatial interaction models" (Wilson 1974) to account for the location and allocation of activities in space taking into account the transportation network. Integrated land use-transportation models were built also to account for the simultaneity of changes in land use and accessibility (Putman 1983, Wegener 1986). Several variants of these models have appeared each attempting to relax the unrealistic and introduce more plausible assumptions regarding spatial economic behavior in space (for a review of such attempts, see, for example, Batten and Boyce 1986).

In a macro-economic perspective, regional equilibrium and disequilibrium theories and models, among others, developed in this period, too, to describe and explain processes of regional change (growth or decline) but their treatment of land uses is abstract and vague at best . The theoretical and analytical framework of general equilibrium and neo-classical welfare analysis has been employed to produce **Pareto optimal** solutions to social welfare maximization problems where land is one of the production factors together with labor and capital (see, for example, Cooke 1983, Andersson and Kuenne 1986, Clark and van Lirerop 1986, Miyao 1986, Takayama and Labys 1986, Fischer *et al.* 1996a). Finally, empirical analyses of land use changes in urban and rural areas were conducted responding, more or less, to pressing problems such as urban decline, rural-urban land conversion (especially on the fringe areas of metropolitan regions), urban sprawl, etc. (see, for example, McDonald 1984, Simon and Sudman 1982). These have a more practical orientation focusing on detailed typologies of land uses that capture the qualitative, and not only the quantitative, intricacies of land use change (see, for example, Bourne 1978).

The economics-oriented analyses of land use change share common traits the most important of which is the emphasis placed on the price mechanism (land and transportation costs) as the principal determinant of the location of human activities in space. They are **functionalist** , quantitative, sometimes highly mathematical, approaches relying on frequently very restrictive assumptions with respect to the nature of land, land use, land use change as well as the characteristics and preferences of the users of space. They attempt both to describe (directly or indirectly) land use patterns and their changes as well as to prescribe optimal land use configurations that satisfy set goals.

The sociology-oriented fields continued the tradition of human ecology developed in the first half of the 20th century producing quantitative, empirical studies of urban spatial and social structure especially in the 1960s and 1970s. Starting with the theory and technique of **social area analysis** and later moving to the more sophisticated inductive techniques of **factorial ecology** (Johnston *et al.* 1994, 558), studies of land use and its change focused on such variables as socio-economic, family, and ethnic status to provide explanations for observed differences in the location of particular activities – mainly, residential areas occupied by groups of varying socio-economic traits. The characteristic of human ecological studies of this period is best summarized in Johnston *et al.* (1994): "Later systematizers of sociological human ecology, such as Hawley (1950, 1986), have tended to play down the spatial focus of the Chicago School.....in favor of an emphasis on the demographic and institutional dimensions of society (Saunders 1981) although at the same time they have shown a strengthened interest in human interaction with the physical environment" (Johnston *et al.* 1994, 258). In fact,most sociological analyses see the urban spatial structure as an expression of the underlying social structure and the associated processes (see, for example, Suttles 1975, Korcelli 1982).

Within the broader realm of sociology-oriented studies of land use change, two particular approaches have developed: the behavioral and the institutional. The first attempts to describe and explain land use patterns as a function of factors influencing human behavior and decision making and focuses on human activity systems (see, for example, Chapin 1968, Chapin and Kaiser 1979, Korcelli 1982, Johnston 1982, Webber 1964a). A **idealistic** variation of this approach emphasizes the ways people perceive and experience the world around them and act correspondingly (Tuan 1975, 1976, Hugill 1975, Buttimer 1976 cited in Johnston 1982). The second (also called "radical" or "**structuralist**") places emphasis on the constraints imposed on human behavior by societal institutions in the effort to explain spatial patterns in urban and other areas. The central concept of this approach is "power", especially economic power, and a correlate concept is 'conflict', usually between unequals, or class conflict (Johnston 1982).

These latter approaches belong to a long repertoire of approaches developed in the 1970s and beyond when geography and planning showed an interest in and were heavily influenced by social theory. Developed frequently as attacks on the **empiricism** and **positivism** characterizing most post-war descriptions and explanations of spatial structure and change, alternative approaches appeared that offered explanations of social and spatial phenomena drawing from diverse philosophical and epistemological positions. **Historical materialism** provided a framework within which patterns of spatial and environmental change are explained as the result of the specific social relations of the capitalist or other **modes of production** (see, among many others, Harvey 1973, 1985; for an application to land use change, see, Hecht and Cockburn 1990). **Structuralist** approaches sought for the truth beneath the surface of the "facts" and the "taken-for-granted" categories by means of which social life was usually comprehended (Johnston *et al.* 1994, 599). **Realist** perspectives oriented themselves towards the identification of the causal mechanisms underlying specific (social and spatial) structures which occur under specific (contingent) conditions (see, for example, Sayer 1982, 1985b). Giddens' "structuration theory" sought to explore the time-space constitution of social life (see, for example, Giddens 1984). Symbolic interactionism emphasized the social construction of reality while **phenomenology** stressed the individuals' experiences of the world in a more or less similar fashion as **existentialism** which stressed the centrality of the human subject's existential being in the world (see, for example, Berger and Luckmann 1967, Relph 1976, Buttimer 1974). **Ethnomethodology** has taken an even more extreme stance emphasizing the unique and the idiographic and rejecting any attempt at generalizations (Jonhston *et al.* 1994, 175).

A striking characteristic of all these sociology-oriented approaches which deal, in one way or another, with space, spatial structure, spatial and social relations is that they treat space and the human subjects that exist within it and interact with it in an abstract fashion; i.e. they make no explicit reference to actual land use and its changes within the context of the causal social relations studied. Moreover, frequently they lack spatial and temporal explicitness and concreteness even when they refer to the urban, regional or international level and when they deal with real world applications. In addition, several of these approaches apply to particular socio-political and cultural settings and they cannot be transferred easily and without violating their very assumptions to other contexts. Overall, in their present form and orientation, they can inform the analysis of land use change very little in practical terms.

Besides economics-oriented and sociology-oriented, a host of other approaches to the study of land use and its change borrowing from ideas and concepts of the past developed in the second half of the 20th century. They combine elements of both the natural and the social sciences and they are based, broadly, on the notion of ecological equilibrium which attributes changes in a region to changes in the dynamic interaction of four sets of factors: population, resources, technology and institutions (see, for example, Coccossis 1991, Meyer and Turner 1996). Although not directly concerned with land use change, Ian McHarg's (1969) ecological method for land use and landscape planning is worth noting here. On the one hand, it bears the influence of past streams of thought on the man-environment relationship and, on the other, it has marked, in its turn, the way of thinking about the relationship between human activities and nature and of planning for their harmonious symbiosis. The ecological method he had advocated was an appeal to consider the life processes as constraints and opportunities for land use planning. His was a holistic approach as the following statement reveals: "The social value of a given environment is an amalgam of the place, the people, and their technology. People in a given place with opportunities afforded by the environment for practicing a means of production, will develop characteristic perceptions and institutions. These institutions will have perceptions and values that feed back to an understanding of the environment ... and that have a modification of technology" (McHarg 1979, 14).

Ecosystem-based theoretical approaches and integrated environment-economy-society models became widespread in the last half of the 20th century and especially after the 1970s. The broader climate of this period is marked by the growing appreciation of and concern about the environment in policy and academic circles as well as and among laypersons which created a demand for approaches and tools of analysis of the related problems. Land use and its changes came to be recognized as important elements of the broader nature-society system and non-trivial contributors to global environmental change whose study was a prerequisite for taking action (see, for example, Slocombe 1993, Lutz 1994, Fischer *et al.* 1996a, Manning 1988, 1991). What distinguishes these approaches from the previous two groups is the treatment of land and land use as having intrinsic and variable environmental (and not only economic and socio-cultural) properties, attributes and capabilities that influence and are influenced by human activities and actions. Hence, land use change is analyzed within a meaningful setting of nature-society interactions which appears to be more promising in handling policy and decision making issues in an integrated manner than the more uni-dimensional approaches discussed before which focus on only one dimension of the subject.

In addition to theoretical and methodological studies, a host of empirical studies have been and are undertaken at both the international and lower levels to identify and record changes in major uses of land, mostly when and where these changes have grave ecological (and economic) consequences as in agricultural, forest, and urban areas. Turner *et al.* (1990) and Meyer and Turner (1994) provide historical accounts of global studies and present the current trends in this perspective. Besides global level assessments of land use changes, land use change research in individual countries has provided stock taking of major land use changes on a variety of spatial scales as input to both research and policy activities (see, for example, Brouwer 1991, Jongman 1995, CLAUDE 1996). Technological progress in the domain of (spatial) data management and remote sensing has spurred major projects on observing and recording land use changes. Powerful earth observation systems covering the globe (e.g. those utilized in programs such as GCOS, GCTE, GOOS, GTOS, LANES, TREES to name but a few) together with advanced spatial data management systems (mainly, Geographical Information Systems) offer the possibility to monitor and map land cover (not land use necessarily) changes at very disaggregate levels of spatial and temporal resolution. In addition, they facilitate data storing and processing for use in various contexts such as in scientific research, policy making, and implementation of related programs (see, for example, Liverman *et al.* 1998). Technology is a significant – but not the sole and most important – contributor to the comprehensive and timely analysis of land use change and the fast dissemination of the information and knowledge produced. Despite the more impressive outputs it can produce, such as fancy and colorful satellite images and maps, it will never become a substitute for theoretically informed and methodologically sound analyses of land use change.

2.5. The New Millennium

Standing at the doorstep of the new millennium, it is natural to ask where the study of land use change is now and to where it is heading (or, to where it should head). This section takes a brief look at the current status of outlook, theorizing, modeling, tools, and initiatives on the subject based on the foregoing presentation.

In the last decade of the second millennium, the 1990s, the study of land use change could be no exception to the sweeping impact of the Brundtland report and the sustainable development movement. An almost universal concern with global environmental change had already gained ground also and had spurred a large number of research and policy initiatives around the globe especially after the Rio Summit of 1992. Examples include the research initiatives of IGBP, IHDP, the FAO, the European Environment Agency (EEA) as well as the UN Conventions on Climate Change (UNCCC), Desertification (UNCCD), and so on. Land use change was soon recognized as a significant component of the global environmental system as "the lands of the earth bear the most visible, if not necessarily the most profound, imprints of humankind's actions" (Kates *et al.* 1990, 6) and specific research initiatives, such as LUCC, were formed. At the same time, the scientific fields contributing to the analysis of land use change had matured more or less in terms of theories, models and tools (technology). Interdisciplinary research was undertaken both within broad scientific realms (e.g. the environmental sciences) as well as between scientific realms on the society-environment interface as it was beyond question that the answers to almost all environmental and social problems could not be provided within the narrow confines of any discipline.

As a result of these developments, among many others, the outlook on the subject has broadened and the approaches advanced are more holistic than they were in the past. Despite the persistence and inertia of strong disciplinary boundaries, new forms of scientific cooperation are promoted under the call for "transdisciplinarity". A return to the view of land as a multi-faceted resource and of land use as the wise manipulation and stewardship of this resource is encouragingly visible, echoing the legacy of the past, although it cannot be claimed that it is the dominant view yet.

In fact, it may be difficult to speak of a dominant view and approach on the subject as, at the time of this writing, at least the economics-oriented and the natural-sciences-oriented fields as well as the interdisciplinary research orientation are raising strong voices and claims with respect to theories and models. Only the sociology-oriented fields are still lagging behind despite the strides they are making recently on the subject of land use change. The result of this imbalance is that, from the epistemological point of view, most approaches to the analysis of land use change move, more or less, along empiricist and positivist lines (cf. remote-sensing and GIS applications, integrated models, the neo-classical economic welfare maximization approach). The critique and alternative views to this **epistemology** which developed in particular disciplines of the social sciences have not found their way yet into the practical analysis of land use change where they may have potentially a beneficial impact in contributing to the development of more socially-informed and responsive theoretical schemata.

Studies of land use change cover the whole spectrum from the global to the local. But, in most cases, studies at particular spatial levels are usually conducted in isolation from one another and, frequently, they fall within the purview of particular disciplines (e.g. urban economics, geography, environmental sciences, forestry, etc.). This kind of scientific segregation inhibits the exchange of concepts, theories, tools, and results among spatial levels. Global level land use change studies have received greater publicity compared to the other levels given the stronger interest, in general, in global environmental change and the requirements of global policies such as UNCCC and UNCCD. It is recognized, however, that many of the global impacts of land use change result mostly from the many, incremental local level decisions and actions of the actual users of land. Hence, the heightened recent interest on *integration* – among spatial scales, of local with regional and global level analyses, of urban with rural analyses. Integrated analysis is a relatively under-researched area in most disciplines given, among others, the problems with integrating/synthesizing theoretical and methodological frames of analysis from different disciplines as well as the more mundane but hoary “data problem”. Judging from the LUCC Implementation Strategy (LUCC 1999), however, it seems that future studies of land use change will be increasingly characterized by integrated, interdisciplinary approaches to address the issues associated with the management of land use change. This task is expected to be facilitated greatly by further advances in the systems of data collection, compilation and management assuming that the currently high costs and long times associated with the provision of the required data will be reduced to reasonable levels.

The following chapters present in greater detail available theoretical frameworks (Chapter 3) and modeling approaches (Chapter 4) developed for the analysis of land use change. The last chapter (Chapter 5) discusses the links between theories and models over time and identifies future research needs.

Theories of Land Use Change

3.1. Introduction

This chapter presents a representative collection of theories of land use change. It is, thus, necessary to clarify: (a) the meaning or definition of "theory" as it will be used in the present context, (b) the theories of land use change that will be included (and, equivalently, those that will be excluded) and (c) the need to consider and take into account theories of land use change in the overall project of studying this subject.

The Greek word "theory" means, literally, "looking at something", "observing something". Consequently, it denotes "knowledge" – the result of observation. Theory is considered "a set of connected statements used in the process of explanation" (Johnston *et al.* 1994, 622). Chapin and Kaiser (1979) define theory as "a system of thought which, through logical constructs, supplies an explanation of a process, behavior, or other phenomenon of interest as it exists in reality" (Chapin and Kaiser 1979, 27).

Because theory denotes knowledge, the nature and status of theories differ among different **epistemologies** – discourses on how knowledge is acquired, transmitted, altered and integrated into conceptual systems (Johnston *et al.* 1994, 168). For example, "within **positivism** , a theory comprises a set of hypotheses and constraining conditions which, if validated empirically, assume the status of laws, so that theory structures understanding of the relevant portion of the empirical world through its system of interrelated laws.... Whereas within positivism, a theory is assumed to be universal in its application, within **idealism** , on the other hand, there are no universals – only the individual theories resident in each individual's mind – which are used to guide action...... In **realism** , a theory is a means of conceptualizing reality, and thus provides a mental framework for its apprehension: the test of a theory is not its validation against empirical evidence but, rather, its coherence and, especially, its practical adequacy...Realists argue that because societies are open systems in which the same conditions are rarely reproduced, theories cannot, as positivists contend, predict the future; they can only illuminate the past and the present, and provide guidance to an appreciation of the future" (Johnston *et al.* 1994, 622-623).

The differences among the theories of land use change which will be presented in the following sections can be attributed, to a considerable degree, to the different **epistemologies** adhered to by those who have proposed them (and by those who use them). But what is a theory of land use change? Simply stated, it is a set of propositions used to understand the "what" of land use change and the "why" of this change. In other words, a theory of land use change describes the structure of the changes in the uses of land from one type to another – and explains why these changes occur, what causes these changes, what are the mechanisms of change. The "what" and the "why" of land use change are closely related although extant theories rarely address both; they refer either to the "what" or to the "why". As regards the latter, it is important to cite Sack (1990): "describing 'what'.... can be accomplished up to a point without considering social and individual motivations. These motivations, however, must be included in the 'why' of human behavior, and knowing the 'why' is essential if we expect to change 'what' we do..... Much of the 'why' in human-nature relations can be understood only through the social side of the equation – that is, through understanding the nature of individuals and societies that create the 'what"' (Sack 1990, 659).

Getting to the second issue, which theories of land use change are included in this chapter, it is noted that the majority of theories of land use change have to be sought in the more general theoretical frameworks of disciplines studying economic, environmental and spatial change (or, transformation). Andersson and Kuenne (1986) state that (static) spatial analysis is concerned with four reasonably distinct bodies of spatial phenomena: (a) locations, (b) interaction flows, (c) changes in availability of factors of productions and (d) spatial structures. The latter are defined as "including areal or curvilinear patterns of economic activities such as land use patterns, urban structure, transportation networks, and market or supply areas" (Andersson and Kuenne 1986, 201). Hence, for the present purposes, a broad distinction is drawn between those theoretical schemata which treat land, land use and, more importantly, land use change *explicitly* and those where reference to land use change is more or less indirect and implied by the broader discussion. In other words, an attempt is made to cover those theories where land is defined, at a minimum, as "a delineable area of the earth's terrestrial surface" (see Chapter 1) as opposed to those theories in which land is either reduced to a point in space or it is totally absent.

Based on the above criterion, the genre of location theory analyses (Central Place theoretical studies included) are considered to a limited extent in this contribution. These theories are not considered theories of land use change *per se* as their emphasis is on particular, *individual* activities (usually treated as points) locating in space and not on an area of land used by various activities (see a related comment by Beckmann and Thisse 1986, 22; also, for a concise description of the "point" nature of spatial equilibrium analysis, see Takayama and Labys 1986, 171). The point is that an individual activity, say a manufacturing firm, may locate within an area whose land use may not be necessarily "industrial". Of course, the opposite is also true. Similarly, the analysis of "market areas" in location theoretic studies does not imply analysis of a particular, concrete land use or its change as the physical area designated as the market for a good or service may comprise of several types of land use (e.g. residential, commercial, open space), in general. The only exception to the location theoretic studies which are considered in the present contribution are residential location theories and models as the aggregate outcome of individual choices considered by the related theories are residential land use patterns (or, segments of the housing market).

A broader set of theories which deal with the dynamics of urban and regional spatial structure are given consideration in this contribution. These theories treat land and land use as points in space mostly (but not always) but their significance lies in that they analyze the broader *spatial* processes that ultimately result in land use change. The majority of these theories are agent-based; in other words, they deduce changes in spatial structure starting from the behavior of the individual household or firm. One of the reasons these theories may prove important in the future for the analysis of land use change is that they can support the building of spatially-explicit models which focus on the level of the individual decision making unit (farm, firm, household). Lastly, a set of theories that will be noted in passing but do not refer directly to the issue of land use change are those in which land use is not included at all within their stated objects of concern and analysis. These are termed frequently "aspatial" theories. They refer mostly to economic, social and other determinants of land use change and they are concerned with broader socio-economic changes that may, however, impinge on and cause land use change in one way or another. These theories include economic base theory, input-output analysis, economic development and growth theories, international trade theories, social theory, etc.

Finally, the role of theories of land use change in the study of the subject needs to be stressed. Common to all analytical tasks is the need to have a vehicle to structure the conception and explanation of reality – i.e. a theory. The analysis of land use change is no exception. Idealist and theories adopting similar epistemologies aside, theories of land use change guide thinking about land use change, indicate conceptual and operational expressions of change, its determinants and the relations between them, and suggest explanatory schemata for making sense of available empirical evidence; i.e. they support model building. Moreover, to reiterate Sack (1990) mentioned above: "knowing the 'why' is essential if we expect to change 'what' we do"; in other words, theory is a guide to policy on land use change – a strong and critical demand of the contemporary times. Inappropriate and inadequate theories of land use change may misguide policy and produce more ills than those policies are assumed to cure.

Although the use of theory in model building seems indispensable, of the several theories of land use change proposed, a relatively small number has been used to support and guide operational model building. Some theories and models have been conceived simultaneously; hence, the use of the terms "theory" and "model" either interchangeably or to denote a set of conceptual and operational statements about reality (e.g. the urban land market theory and model). In this case, the term "model" may denote mostly a formal theoretical model and not necessarily a symbolic (or, operational or empirical) model (Lonergan and Prudham 1994). But the majority of theories are still without modeling (not necessarily mathematical) counterparts and the reverse is also true. Several models are devoid of theoretical foundations. There are many explanations for this gap in the relationship between theories and models only two of which are mentioned here. One reason is the differing **epistemological** positions adopted by theory and model builders; usually models move in the **positivist** tradition while theories cover a much broader spectrum of **epistemologies** . A strong reflection of these differences is the way land is usually being conceptualized in theory and in models. A related reason is that reality is highly complex; land use change comes about under the influence of many macro and micro factors, acting and interacting within varying time frames and geographical space. Land use change problems are essentially **metaproblems** . Therefore, the reduction and simplification of this real world diversity to serve the purposes of model building is either extremely difficult, or results in a very crude representation of reality. The contrary may happen also; models have a very complicated structure that is impossible to handle within the bounds of reasonable time and other resources to provide answers to practical problems.

The sections that follow provide a broad overview of the variety of theories pertaining to the subject of land use change and present certain of them in some detail. The last section evaluates briefly the theories of land use change covered and attempts to address the question of whether a general theory of land use change is possible and meaningful or whether a synthesis of theoretical schemata is the most fruitful way of providing support to model building and policy making.

3.2. Theories of Land Use Change – Classification

The theoretical literature on land use change contains a considerable variety of theories where land use is treated explicitly and is the direct object of theoretical inquiry. Six interrelated sources of variation, in a roughly decreasing order of importance, can be discerned:

- the purpose of the theoretical project
- the approach to **theorization**
- the spatial scale and level of spatial aggregation adopted
- the types of land use considered as principal objects of analysis
- the types of land use change determinants taken into account, and
- the treatment of the temporal dimension (which in the case of analysis of change, in general, is inherent in any project).

Hence, there exist:

a. descriptive, explanatory, and normative theories
b. individualist/ **behaviorist** theories and institutional/ **structuralist** theories (see, Cooke 1983, 12)
c. theories of urban, regional and of global land use change
d. theories of particular types of land use – mainly residential, industrial, agricultural and forest land
e. theories prioritizing the economic or the social or the environmental determinants of land use change or particular combinations of them, and
f. static, quasi-static, and dynamic theories of land use change (however counterintuitive static theories of change may sound).

It is, thus, evident that, for the purposes of systematic exposition of extant theories, it is necessary to adopt a classification scheme as a presentation and discussion vehicle of these theories.

A general-purpose, unambiguous classification scheme of theories that can reflect meaningfully the six sources of variation mentioned above does not seem to exist for various reasons. The same subject is studied by many disciplines (that may traditionally have particular outlooks, spatial and temporal foci, interests in certain uses of land); theories filter from one discipline to the other – for example, from economics to geography (Cooke 1983, 83); disciplinary boundaries are blurred especially in modern times when there is also a tendency towards interdisciplinary research. Hence, a decision was made to adopt a classification scheme based on an aggregate criterion, the **theorization tradition** to which a theory belongs. This is taken to denote the particular way of thinking about and conceptualizing reality – land use and its change in the present case – that is mostly a function of particular disciplinary cultures and, consequently, of epistemological orientations, value systems, choice of space and time frameworks and of objects of analysis.

Based on the theorization tradition criterion, a three-fold typology is used to classify extant theories of land use change into three main categories:

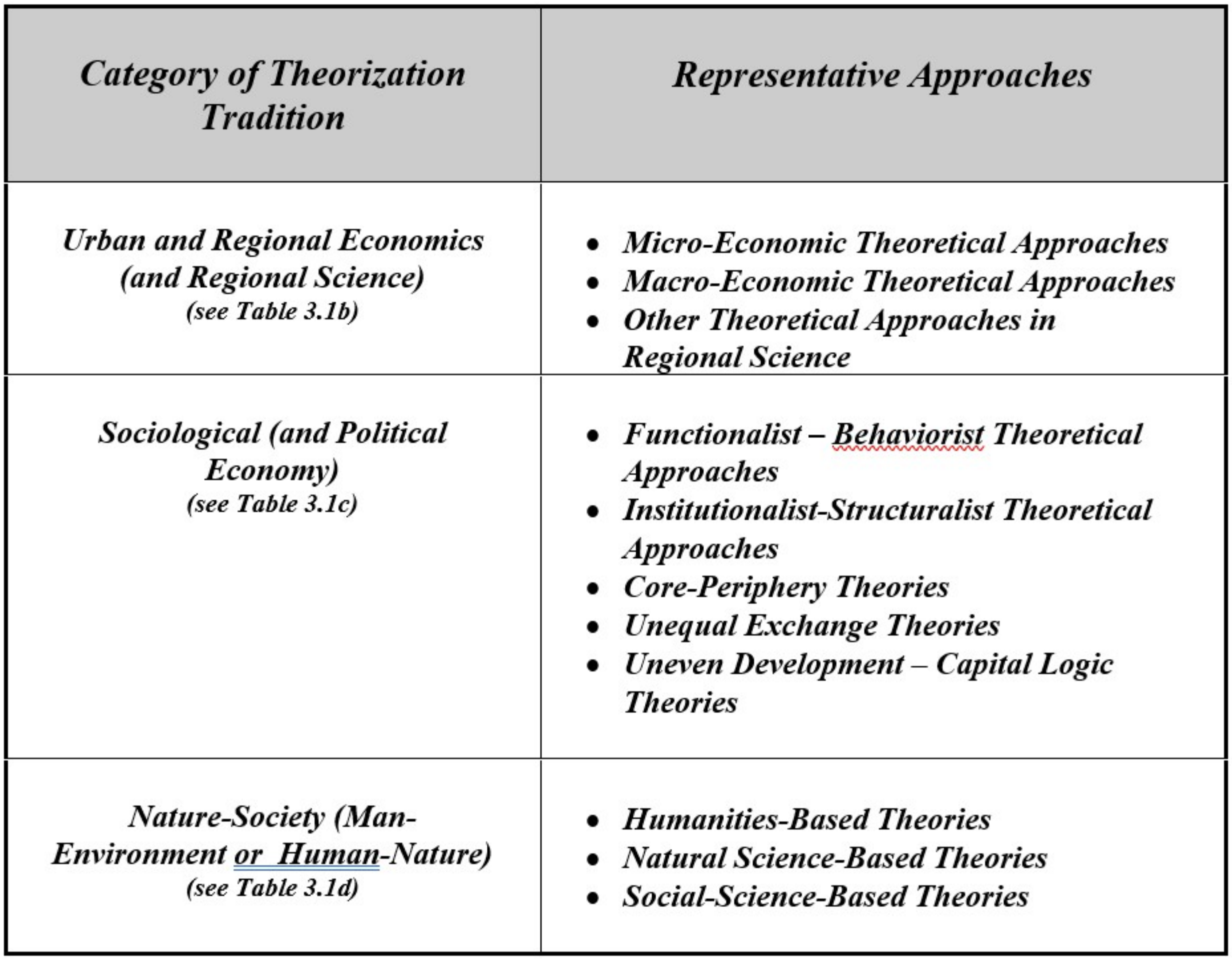
a. the urban and regional economics theorization tradition

b. the sociological (and political economy) theorization tradition, and

c. the nature-society (or, human-nature) theorization tradition.

Within each of these three main categories, theories can be further classified according to other, more focused and particular criteria as it is indicated in the following discussion. Table 3.1a is an attempt to draw together and present selected theories that belong to each of the three categories.

TABLE 3.1a A Classification of Theories of Land Use Change



Category of Theorization Tradition	***Representative Approaches***
Urban and Regional Economics (and Regional Science) ***(see Table 3.1b)***	• ***Micro-Economic Theoretical Approaches*** • ***Macro-Economic Theoretical Approaches*** • ***Other Theoretical Approaches in Regional Science***
Sociological (and Political Economy) ***(see Table 3.1c)***	• ***Functionalist – Behaviorist Theoretical Approaches*** • ***Institutionalist-Structuralist Theoretical Approaches*** • ***Core-Periphery Theories*** • ***Unequal Exchange Theories*** • ***Uneven Development – Capital Logic Theories***
Nature-Society (Man-Environment or Human-Nature) ***(see Table 3.1d)***	• ***Humanities-Based Theories*** • ***Natural Science-Based Theories*** • ***Social-Science-Based Theories***

Tables 3.1b, 3.1c, and 3.1d present theories within each category, according to criteria particular to the each category.

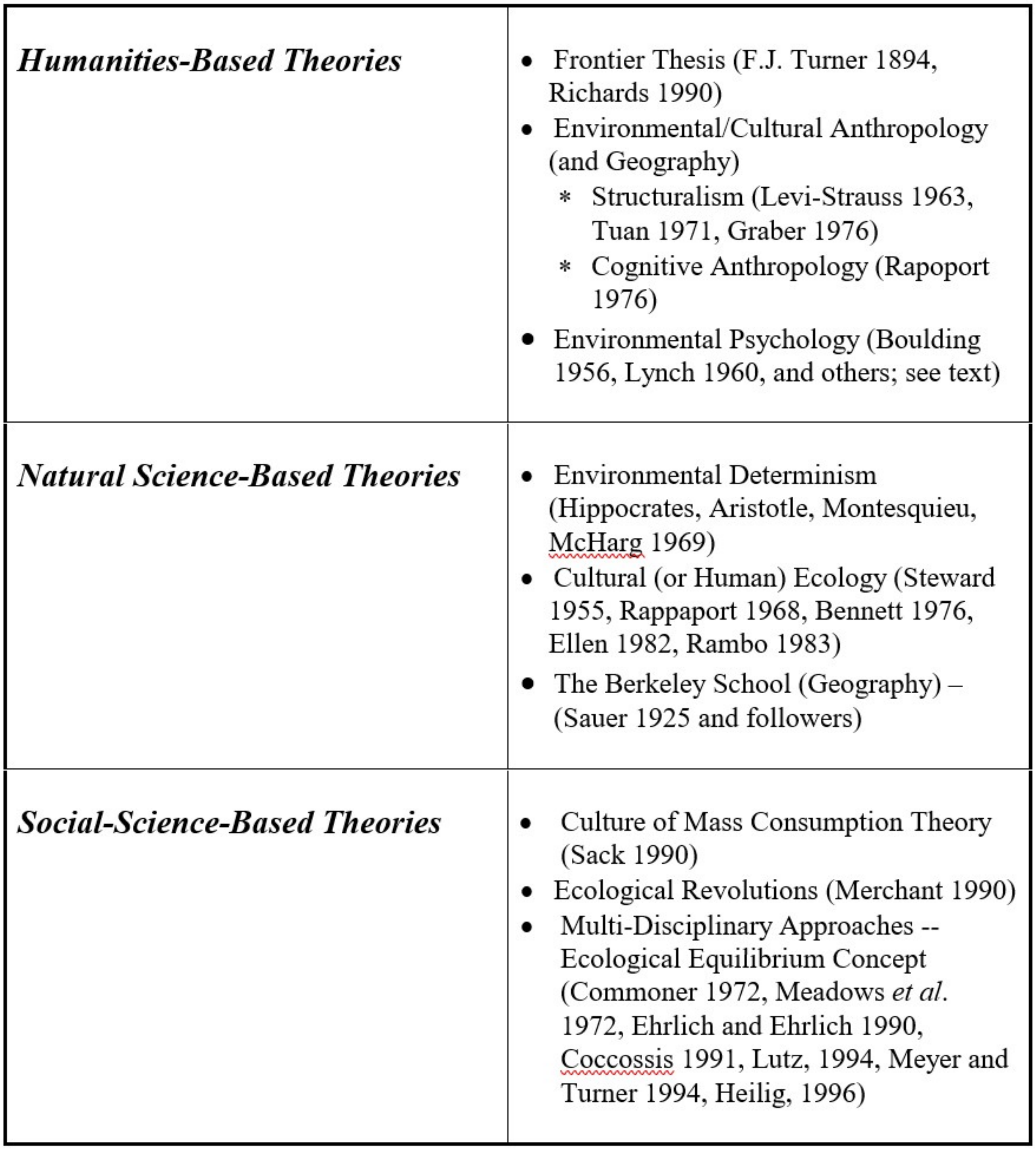
TABLE 3.1b Urban and Regional Economics Theoretical Approaches to Land Use Change

<table>
<tr><th colspan="2"><i>Micro-Economic Theoretical Approaches</i></th></tr>
<tr><td colspan="2">• Agricultural Land Rent Theory (von Thunen 1966; original in 1826)
• Urban Land Market Theory (Alonso 1964)
• Agent-based theories of urban and regional spatial structure (Henderson and Mitra 1996, Krugman 1995, Anas <i>et al</i>. 1998, Fujita <i>et al</i>. 1999, Page 1999</td></tr>
<tr><th colspan="2"><i>Macro-Economic Theoretical Approaches</i></th></tr>
<tr><td><i>Spatial Economic Equilibrium Theory</i></td><td>• A. Weber (1929)
• Losch (1954)
(See, also, Isard <i>et al</i>. 1969, Takayama and Labys 1986, Andersson and Kuenne 1986, Ginsburgh and Keyzer 1997)</td></tr>
<tr><td><i>Regional Disequilibrium Theories</i></td><td>• Cumulative Causation Theory (Myrdal 1957)
• Growth Pole Theory (Perroux 1955, Boudeville 1966)</td></tr>
<tr><td><i>Keynesian Regional Development Theory</i></td><td>• Harrod-Domar Models
• Export-Base Model
• Factor-Export Models
• Neoclassical Multiregional Growth Models
(see, Cooke 1983, Hoover and Giarratani 1984, 1999, Andersson and Kuenne 1986, Bennett and Hordijk 1986)</td></tr>
<tr><th colspan="2"><i>Other Theoretical Approaches in Regional Science</i></th></tr>
<tr><td colspan="2">• Social Physics (Reilly 1931, Stewart 1950, Wilson and Bennett 1986, Isard 1999)
• Urban (Mathematical) and Regional Ecology (Wilson 1981; Dendrinos and Mullaly 1985, Nijkamp and Reggiani 1998)</td></tr>
</table>

TABLE 3.1c Sociological Theoretical Approaches to Land Use Change

Functionalist – Behaviorist Theoretical Approaches	**Human Ecological Theories** • Concentric Zone Theory (Burgess 1925) • Radial Sector Theory (Hoyt 1939) • Multiple Nuclei Theory (McKenzie 1933, Harris and Ullman 1945) • Sequent Occupance Concept (Whittlesey 1929) **Planning theories** • D. Foley's Theory of Metropolitan Spatial Structure (Foley 1964) • The Urban Place and Non-Place Urban Realm Theory (Webber 1964) • Activity Systems Theory (Chapin 1965)
Institutionalist-Structuralist Theoretical Approaches	• Urban Social Movements (Castells 1977) • Urban Land Nexus Theory (Scott 1980) • Crisis Theory of Late Capitalism (Harvey 1973, 1975a, 1975b, 1982)
Core-Periphery Theories	• Modernization Theories (Lewis 1955) • Stages Theory of Economic Growth (Rostow 1960) • Core-Periphery Model (Friedmann 1966) • Internal Colonialism (Hechter 1975) • World System Theory (Wallerstein 1974, 1979)
Unequal Exchange and Dependency Theories	• Unequal Exchange (Emmanuel 1972) • Unequal Development (Amin 1976, 1978) • Dependency Theory (Frank 1969, 1979, Dos Santos 1970, Cardoso 1973)
Uneven Development -- Capital Logic Theories	• Unequal Regional Exchange (Lipietz 1977, 1980) • The Theory of the Spatial Divisions of Labor (Massey 1984) • Uneven Development (Smith 1990)

TABLE 3.1d Nature-Society Theories of Land Use Change



Humanities-Based Theories	• Frontier Thesis (F.J. Turner 1894, Richards 1990)
	• Environmental/Cultural Anthropology (and Geography)
	    * Structuralism (Levi-Strauss 1963, Tuan 1971, Graber 1976)
	    * Cognitive Anthropology (Rapoport 1976)
	• Environmental Psychology (Boulding 1956, Lynch 1960, and others; see text)

Natural Science-Based Theories	• Environmental Determinism (Hippocrates, Aristotle, Montesquieu, McHarg 1969) • Cultural (or Human) Ecology (Steward 1955, Rappaport 1968, Bennett 1976, Ellen 1982, Rambo 1983) • The Berkeley School (Geography) – (Sauer 1925 and followers)
Social-Science-Based Theories	• Culture of Mass Consumption Theory (Sack 1990) • Ecological Revolutions (Merchant 1990) • Multi-Disciplinary Approaches -- Ecological Equilibrium Concept (Commoner 1972, Meadows *et al.* 1972, Ehrlich and Ehrlich 1990, Coccossis 1991, Lutz, 1994, Meyer and Turner 1994, Heilig, 1996)

As these Tables show and the ensuing discussion will reveal, it is difficult, if not impossible, to provide a neat categorization of theories as more than one criteria can be used to classify them. For example, a classification by theme or subject of analysis (e.g. development) will include economics-based theories as well as sociology and political economy-based theories. The same is true if theories are classified by their **epistemological** foundations or the basic concepts around which they are organized (e.g. core-periphery). Hence, some theoretical concepts will be discussed in more than one groups or categories within groups. The next sections are devoted to a brief discussion of the theories within each tradition. For each theory, the following main issues are examined: purpose (descriptive, predictive, explanatory, prescriptive), mode of theorizing (assumptions, type of land use and their determinants considered, especially the proposed mechanism of land use change), spatial scale of reference, and temporal dimension (duration, dynamics).

3.3. The Urban and Regional Economics Theorization Tradition

The urban and regional economics **theorization tradition** adopts the way of thinking in economics in general. Reality is represented using concepts and procedures of an economic nature – among them, prices of the factors of production, of products and of services, transport (or, transfer) cost, marginal cost, economies of scale, externalities, and, above all, **utility** . All behavioral assumptions made refer to the model of the rational, economic, utility maximizing man despite efforts to replace it with less inflexible and more realistic constructs (such as Simon's "satisficer" – Simon 1956, 1982). Real world phenomena are analyzed either from a micro-economic or from a macro-economic perspective. Hence, theories of land use change belonging to this tradition are broadly grouped into micro-economic theory-based and macro-economic theory-based. Micro-economic approaches start from individual consumer behavior and then aggregate over the behavior of all consumers to yield *land use patterns* produced when utility is being maximized for all consumers (usually, maximization of profits or minimization of cost or distance). In contrast, macro-economic approaches deal with aggregate behavior and indicate how aggregate patterns may be produced. A third group of theories is included which contains that belong generally to the field of Regional Science and utilize concepts from both economics and sociology. Their inclusion in the urban and regional economics theorization tradition is justified by their emphasis on economic factors and processes of spatial change. Table 3.1b presents in greater detail the microeconomic, the macroeconomic, and the regional science theoretical approaches discussed below.

3.3.1. *Micro-Economic Theoretical Approaches*

Three main micro-economic theory-based theoretical schemata for the analysis of land use patterns and their changes are discussed below: J. F. von Thunen's agricultural land rent theory, W. Alonso's urban land market theory, and agent-based theories of urban and regional spatial structure. It should be noted that all three are considered theories as well as models because their developers proposed a theoretical structure which they translated then into a mathematical, form; i.e. a symbolic model (not necessarily operational, however).

3.3.1A Agricultural Land Rent Theory

The analysis of land use patterns and their changes in the micro-economic theorization tradition (but also in the macro-economic) has been influenced in fundamental ways by the agricultural land rent theory developed in 1826 by the North German estate owner, J. H. von Thunen (1966). The purpose of von Thunen's exercise was to prescribe the optimum (most economical) distribution of rural land uses around a market town (Hoover and Giarratani 1984, 1999). The basic concept he used was that of the *land rent* which is defined as the "price for the use of a piece of land" (Hoover and Giarratani 1984, 132) or, equivalently, "the price of the services yielded by land during a specific time period" (Romanos 1976, 32).

At the regional level of analysis, to which von Thunen's formulation refers mostly, the land use types considered are various types of agricultural land primarily and, secondarily, forest land. The analysis concerns land which is devoted to growing different types of crops (and forestry). Land was assumed to be a uniform, isotropic (of equal fertility) flat plain with movement possible in all directions around a market town located at the center of the region of interest. Land rent varies only with distance from the center. Each crop has an associated rent gradient (or, rent curve) that extends in all directions from the center in Figure 3.2a (Hoover and Giarratani, 1999) as well as the same delivered price and unit transport cost irrespective of location or rent.

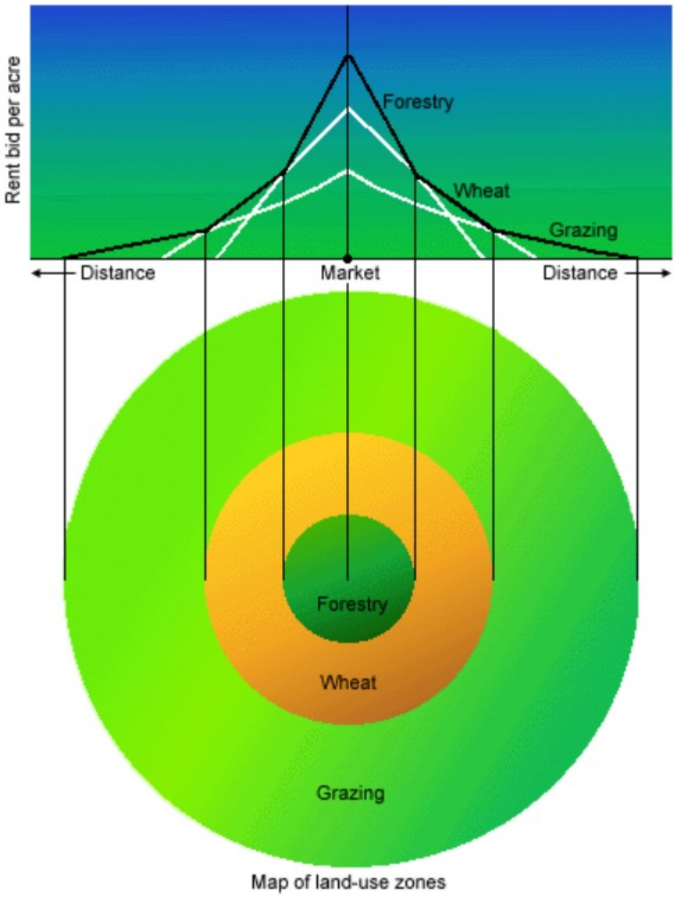


FIGURE 6-4: Hypothetical Rent Gradients and Land-Use Zones

Figure 3.2a

von Thunen's land rent curves and the resulting land use pattern
(same as FIGURE 6.4 in Hoover and Giarratani 1999)

Moreover, the intensity of land use for each crop and the yield per acre are fixed regardless of the relative prices of land (rents), the other inputs, and the output. Perfectly competitive markets are assumed. The rule of determining the location of a particular activity (land use) with respect to the market center is that each activity (land use) occupies the zone in which the user can pay the highest rent than any one of the other users. And the rent the user of a particular land use can afford to pay depends on the value of the products produced on a parcel of land. Hence, in the jargon of land economics, the user of an activity (land use) associated with high value products can *bid* higher land rents and, thus, *outbids* other users that cannot pay the same rent. In von Thunen's formulation, the activity (land use) with the largest amount of output per acre (highest value of output) has the steepest rent gradient and, hence, locates closest to the market center. The other activities (land uses) follow in decreasing order of the slope of their rent gradients. The resulting land use pattern is a set of concentric rings around the market center with each ring devoted to growing a particular crop (Figure 3.2a). The envelope of the individual crop rent gradients (formed by their uppermost parts) is the *bid rent curve* (for the study region) (Figure 3.2a). A last remark on this formulation: the optimum solution to the land use pattern produced following the above procedure is independent of "whether: (1) one individual owns and farms all the land, seeking maximum returns; (2) one individual owns all the land but rents it out to tenant farmers, charging the highest rents he or she can get; or (3) there are many independent land owners and farmers, each seeking his or her own advantage" (Hoover and Giarratani 1984, 143). A mathematical exposition of von Thunen's theory can be found in Hoover and Giarratani (1984, 1999). An exposition of von Thunen's theory with several extensions can be found in De la Barra (1989).

The von Thunen formulation makes no explicit reference to mechanisms of land use change because it is a static theory where the optimum land use pattern is assumed to be produced instantaneously. However, it is not difficult to see an implicit mechanism even under all the restrictive assumptions of the theory. If the relative prices of the crops change exogenously, this will change the relative ability of farmers (the users of land) to bid for particular locations making, thus, possible a change in location (the land use pattern preserving its circular form). The very restrictive and unrealistic assumptions of the original formulation of the agricultural land rent theory were relaxed by von Thunen himself and by researchers who used it in subsequent applications (see, for example, Alonso 1964, Romanos 1976, Wheeler and Muller 1981, Hoover and Giarratani 1984, 1999, Stahl 1986). These applications covered a wide range of spatial scales from the global (Peet 1969 cited in Johnston *et al.* 1994, 673) to the individual village and farm holding (Blaikie 1971 and Chisholm 1979 cited in Johnston *et al.* 1994, 673) as well as other land uses such as residential and commercial. More importantly, perhaps, this theory provided the foundations for Alonso's (1964) urban land market theory (discussed below). In general, there is no doubt that von Thunen's theory is the predecessor of both **location theory** and the analysis of urban and regional spatial structure.

3.3.1B Urban Land Market Theory

In the years that followed von Thunen's seminal approach to a theory of land use, several attempts were made at analyzing various components of the urban and regional system (see, for example, Romanos 1976). However, it was only after almost 140 years that W. Alonso would present his celebrated *urban land market theory* that applied and refined von Thunen's original ideas (Alonso 1964). This theory aims to describe and explain the residential location behavior of individual households and the resulting spatial structure of an urban area. The focus is on residential location; the behavior of firms is treated more briefly and abstractly. The central concept of this theory is the *bid-rent function* for each household and/or firm. The bid rent of a household is defined as the "maximum rent that can be paid for a unit of land (e.g. per acre) some distance from the city center if the household is to maintain a given level of **utility** " (Hoover and Giarratani 1984, 153) (Figure 3.2b – Figure 6.8 in Hoover and Giarratani 1999). The bid rent curve R of the actual land rents in the city reflects the outcome of a bidding process by which land is allocated to competing uses (residential demanded by households and commercial/ industrial demanded by firms).

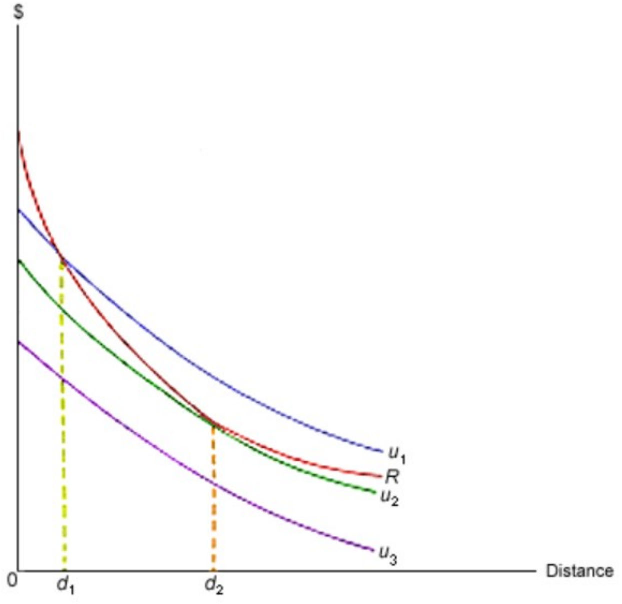


FIGURE 6-8: Bid Rent Curves and Residential Location

Figure 3.2b
Alonso's bid rent of a household and the bid rent curve R of the actual land rents in the city pattern same as FIGURE 6.8 in Hoover and Giarratani 1999)

As in von Thunen's theory, a monocentric, flat, continuous and uniform urban area is assumed. The city center is the central business district (CBD) where households work and shop. A household's **utility** (or satisfaction) is assumed to depend on: housing (of a given lot size), distance from the city center (reflected in the transportation cost) and all other goods (Chapin and Kaiser 1979, Romanos 1976). The household allocates its fixed budget among these three components with the aim to maximize its utility. Its preferences determine the trade-offs it is willing to make among the above three items. The price of housing and of other goods is independent of the quantities purchased. The price of housing and of commuting depend on distance from the city center. There is a *distance decay* relationship between land rent and distance from the CBD. The further a household lives from the city center, the more it will have to spend on commuting and the less it will be able to spend on housing. Based on these assumptions, the bid-rent curves are downward sloping (rent decreases with distance from the city center to offset transport costs) and single-valued; i.e. for a given distance from the CBD only one rent bid is associated with a given level of utility. The steepness of the slope of the bid rent curve depends on transport costs and the household's (or the firm's) demand for space. Steeper curves are associated with higher transport costs and/or less demand for space (hence, higher value attached to accessibility). Flatter curves are associated with lower transfer costs and/or higher demand for space (and, hence, preference for more outlying locations). Finally, lower bid-rent curves are associated with greater utility as, assuming fixed budgets, at any given distance from the CBD, if a lower rent bid is accepted, more goods can be consumed (Hoover and Giarratani 1984, 154).

Alonso's theory distinguishes two stages in the residential location process. In the first stage, the theory derives individual equilibria for households (and firms) on the basis of their bid-rent functions (one for each level of utility/satisfaction). Households, possessing perfect knowledge of the actual land rent structure in the city (curve R in Figure 3.2b) and of the transport costs, choose a location that maximizes their utility subject to their budget constraint; this is the point where the lowest bid-rent curve touches the actual rent curve (Figure 3.2b). At a second stage, the equilibrium for the entire urban market is derived through a market clearing mechanism that starts from the CBD and involves potential users bidding for land and landlords selling or renting the land to the highest bidder. The most central locations go to the highest bidders (steepest bid-rent functions). Remaining available land goes to the next bidder and the process continues until the last user is located at the edge of the city. The price of land at the edge of the city is adjusted to agree with the actual price there (basically, the value of agricultural land close to the edge of the city). However, as Romanos (1976, 71) notes, because Alonso does not assume a perfectly competitive market and bid-rents are not unique but members of families of bid-rent curves, the theory cannot provide an equilibrium market solution as it was the case with von Thunen's theory. In order to derive equilibrium land use patterns, additional assumptions must be made about the level of utility of the bidders or the number and types of bidders (Strazheim 1986). In the simplest case, equilibrium in the land market results if all bidders have identical incomes and preferences; hence, a common set of bid rent curves and land rents within the city coincide with this set (Strazheim 1986). The discussion of Alonso's urban land market theory (and its extensions) resumes in Chapter 4 in the presentation of the formal (mathematical) model of the urban land market.

Alonso' urban land rent theory provides a static description and explanation of urban (mainly residential) land use. In the present context, its significance lies in its explicit treatment of the actual amount of housing consumed; hence, it is a theory of (residential) land use. The bidding process is a realistic account of the way land is allocated to various competing users and it has been used in the theoretical and modeling exercises that ensued Alonso' original contribution (see, for example, Romanos 1976, Brueckner 1986, Strazheim 1986). However, the *mechanism of land use change* is implicit; it has to be elicited from the factors which the model assumes to determine the steepness and the height of the bid-rent curves. These depend on preferences for various locations within the city (measured as distances from the city center) and income. Hence, when preferences and income change, the land use system will move to another equilibrium position. Other potentially important influences on the bid-rent curves such as socio-cultural and political forces are not accounted for directly by the theory.

While Alonso's theory has been used extensively in analyses of urban spatial structure as well as in impact analysis of urban policies (see, for example, Bockstael and Irwin 1999), it suffers from several restrictive assumptions which limit its usefulness in approximating observed land use patterns as well as in analyzing land use change. The two most important perhaps are the assumption of a single, exogenously-given center (the monocentric city assumption) and the importance assigned to accessibility to this single center in explaining urban spatial structure. The theory does not consider a number of interrelated factors which, on the one hand, capture the particular forms that characterize modern urban agglomerations and, on the other, account for the dynamics of urban land use change. The most important of them include: the existence of more than one centers in metropolitan areas, externalities (e.g. traffic congestion, air pollution), increasing returns to scale, imperfect markets, the durability and inflexibility of the housing stock, technological change (see, among others, Romanos 1976, Quigley 1985, Arnott 1986, Krugman 1995, Bockstael and Irwin 1999).

The monocentric city assumption has several implications for the land use patterns derived from this theory. First, as the size of an urban area increases, employment can by no means be concentrated in the CBD. Real world evidence reveals the continuous decentralization of employment centers in large metropolitan areas and the development of polycentric cities coupled with a declining or minimal growth of the CBD. At the same time, the role of land developers in determining the location and timing of ex-urban development is critical in the evolution of urban spatial structure. Hence, the urban land market theory assigns to the CBD greater importance than it actually deserves. Secondly, the analysis of land uses in the rest of the urban area is not adequate as other nonresidential uses are present (Romanos 1976). The heterogeneity of the natural environment in which the city is embedded is also ignored as a factor which may distort the analytical tractability of the bid-rent functions. Thirdly, the monocentric city assumption is associated with another assumption; that of constant returns to scale in the production of goods and services in the CBD. However, increasing demand for these goods and services, implies increased demand for transportation to the CBD, hence, increasing diseconomies associated with congestion, pollution, etc. that lead to decreasing returns of central city production. Therefore, the assumption of constant returns is at variance with the importance attributed to the city center.

Several attempts have been made to modify the original theory to account for the presence of more than one centers, more than one places of employment, and the existence of externalities, among others, whose discussion is beyond the intent of this contribution (see, for example, Solow 1973, Romanos 1976, Shieh 1987). These modifications, however, have aimed mostly at providing improved operational versions of the theory – i.e. of the urban land market model – while leaving its basic tenets intact. Therefore, the basic limitations of the theory, the absence of a dynamic explanatory schema of land use change, still remain. A brief discussion of more recent theoretical attempts at analyzing the evolution of urban spatial structure is undertaken in the next section.

3.3.1C Agent-Based Theories of Urban and Regional Spatial Structure

A broader set of theoretical schemata have been proposed for the description and explanation of the evolution of urban spatial structure which focus on the agents operating in urban contexts and *the interactions* among them which influence the resulting spatial patterns. This group of “agent-based” theories does not always treat explicitly land use as in Alonso’s theory (i.e. as amount of space consumed by an agent) and their emphasis is mostly on agents’ characteristics as well as on the processes through which and the conditions under which agents interact in space. In other words, they are *indirect* theories of land use change for the present purposes. The following is a schematic presentation of certain of their particular features and the gist of their approach to the analysis of the evolution of urban spatial structure which render them more realistic frameworks for the study of land use change. The reader may find more detailed accounts and reviews of these theories in, among others, Krugman (1995), Henderson and Mitra(1996), Anas *et al.* (1998), Fujita *et al.* (1999).

The agent-based theoretical approaches differ from the micro-economic approach of the urban land rent theory in that they stress particular features of these agents which relate to their linkages and interactions in space; broadly speaking, they take into account the *market structure* of the urban setting. Several of the ideas contained in these approaches can be found in earlier theories of urban and regional spatial structure and development (e.g. Christaller 1966, Pred 1966, Myrdal 1957, Henderson 1974) as well as in broader theories stressing the role of human agency in general in the evolution of spatial form (for a collection of references see, Pred 1985). However, it seems that the synthesis of these ideas into more rigorous theoretical schemata as well as their use in building models of change began in the early 1980s. Agents are assumed to operate in the context of markets mostly. Imperfect competition is allowed in several approaches (see Krugman 1995). To explain the clustering or the dispersion of certain uses in space which is observed in the real world, the concepts of external economies, externalities, backward and forward linkages between activities, and durability of urban development are employed in the broader schema of centripetal and centrifugal forces impinging on agents' behavior.

Centripetal forces account for the cohesion and clustering of certain activities in space (Hoover and Giarratani 1984, 1999; Krugman 1995). These forces derive from the existence of economies of scale (increasing returns to scale) and agglomeration economies in certain locations. Activities linked by means of *forward* (being suppliers of goods and services to other activities) and *backward* (being buyers of goods and services) *linkages* are held together in a given location. Forward and backward linkages among activities are called also *vertical linkages* (Hoover and Giarratani 1984, 1999). A circular relationship develops also between the location of the market and the location of an activity; i.e. activities concentrate where the market is large and the market is large because it contains a large number of activities (see Krugman 1995).

At the same time, however, *centrifugal forces* work against the clustering of activities in space and cause their dispersion. These concern the *horizontal relationships* among activities (Hoover and Giarratani 1984, 1999) and involve the competition among activities for markets and/or inputs as well as the cost of transport to the sources of inputs or to the markets. Increased competition for certain locations (having locational advantages for certain activities or containing scarce resources) drives land rents up. Some activities are driven away to sites where land rents are lower. Some others may remain in the same location, however, because of the presence of other advantages it offers which render it profitable for its user. Other centrifugal forces are associated with various kinds of diseconomies or negative externalities caused by either the clustering of activities or owing to the particular nature of certain activities which reduce the potential benefits to be reaped from being at a specific location.

Several other factors enter the decision making calculus of individual agents which may function either as centripetal or centrifugal forces that impact on their utility function and, thus, affect their locational choices. These include speculation, in particular land speculation, the durability of the physical infrastructure associated with particular activities, the cost of land conversion to other uses (the land use inertia), other local conditions, and "historical chance" (Arthur 1989). The spatial result of the interaction of centrifugal and centripetal forces on individual but interdependent agents is the generation of monocentric, polycentric, dispersed, linear, etc. urban land use patterns. In other words, the resulting spatial structure is characterized by multiple instead of a single equilibrium pattern.

The main point put forward by agent-based theories is that the decisions and actions of agents are influenced by past locational decisions and they influence future location decisions. Thus, the resulting spatial patterns (the spatial distribution of agents and of the associated activities) are *endogenously determined*. Variations and changes in the factors underlying these patterns mentioned before give rise to land use change; or, in broader terms, they explain the evolution of the spatial system over time. Agent-based theories have been used in building corresponding models of locational behavior but several of the interactions these theories postulate have not received empirical testing yet. Finally, most theories focus on equilibrium patterns while real world experience shows that most of the time the process of land use change is out of equilibrium (Bockstael and Irwin 1999). Nevertheless, these theories represent a considerable improvement over the monocentric model of the 1960s and exhibit a flexibility which permits the consideration of many more factors – even idiosyncratic – which account for land use change as well as for the impacts of this change.

3.3.2. *Macro-Economic Theoretical Approaches*

Compared to the micro-economic theory-based approaches to the analysis of land use change which start from the behavior of the individual consumer (or, producer) and then aggregate over the population of consumers to derive the resulting land use pattern, macro-economic approaches operate at an aggregate level employing aggregate concepts, measures and forms of behavior. For the present purposes, two macro-approaches are distinguished: the spatial and the aspatial macro-economic theories. The first group refers to the body of theories known as "spatial economic equilibrium theory" (Takayama and Labys 1986, Fischer *et al.* 1996, Ginsburgh and Keyser 1997) while the second comprises a variety of mostly aspatial theories.

3.3.2A Spatial Equilibrium Theory

Spatial (economic) equilibrium theory is essentially the application of utility maximization theory of **welfare economics** to a spatially dissaggregated economy. Building on the original contributions of Alfred Weber (1929) and August Losch (1954), the field of spatial equilibrium analysis developed fully after the 1950s with the parallel development of mathematical programming that provided the tools (techniques) to express symbolically the theoretical propositions (Takayama and Labys 1986). A finite number of demand and supply regions are represented by points in space which are interconnected by various modes of transporting goods with the transport cost structure specified in some way (Takayama and Labys 1986). In broad terms, the theory seeks to determine the equilibrium prices of goods and services as well as the wage levels which satisfy an efficient distribution of demand (consumption), supply (production) and flows of goods and factors of production (labor and capital) among those points. This distribution is derived by maximizing the welfare (or, **utility** , or well-being) of the population located on the points (i.e. living in the demand regions) or the profits of the firms located on the supply points. Consumer welfare is measured variously as income, consumption of goods, etc. The conditions under which this equilibrium is achieved in the spatial system are derived by elaborating the mathematical relationships which express the welfare maximization problem. Assumptions commonly made in applying spatial equilibrium theory concern the distribution of population, resources, accessibility, and preferences. The common assumption is that these are uniform. In addition, a market economy is assumed where perfect competition holds, perfect technical knowledge is available, and no barriers to market entry exist. Assumptions are made also about the relationships among regions as well as about their self-sufficiency in terms of raw materials. Among the various feasible solutions of the welfare maximization problem, the theory considers as optimum those satisfying the **Pareto-efficiency criterion**. Several versions of spatial equilibrium theory have appeared which attempt to relax one or more of the restrictive assumptions such as the perfect market assumption (an important prerequisite to applying the theory to non-capitalist spatial contexts, at least). The theory does not specify the appropriate spatial level of analysis although it is more commonly used at higher spatial levels (regional, interregional, national and international). Spatial economic equilibrium theory provides the theoretical underpinning of the body of spatial equilibrium as well as of regional (spatial) dynamic models (Takayama and Labys 1986, Andersson and Kuenne 1986, Isard *et al.* 1969, Ginsburgh and Keyzer 1997, van den Bergh *et al.* 1996). In addition, it is employed in the context of integrated land use modeling to be discussed in the next chapter.

Evidently, spatial (economic) equilibrium theory cannot be considered a direct theory of land use as land and land use are treated at a very high level of abstraction reduced to points and spatial configurations follow geometric shapes (lines, curves, discs) (Andersson and Kuenne 1986). The same level and degree of abstraction characterizes also the representation of several other components of the spatial system. In their static versions they do not address explicitly the issue of change as they concern equilibrium demand and supply configurations and they are used either in a descriptive or in a normative fashion usually under restrictive assumptions. In their dynamic versions, change is brought about by changes in demand, product prices, transport costs, technological change, etc. Essentially, spatial equilibrium theory is heavily mathematically oriented deriving spatial relationships deductively from a set of initial assumptions and axiomatic propositions most of which concern the *mathematical* prerequisites necessary to solve the welfare maximization problem. In other words, it is a **functionalist** theory which treats spatial relationships and patterns by means of an "aspatially constricted theoretical framework, general equilibrium theory" (Cooke 1983, 116). Its relevance to the analysis of land use change, if one accepts its **epistemological** orientation as well as its behavioral and other assumptions, lies in its providing the broader context of changes in the economic determinants of land use change; namely, changes in the location of production and consumption, the associated changes in demand, supply, product prices and wage levels, and changes in trade among regions (or, flows in general).

A variety of other macro-economic theoretical approaches dealing with regional and supra-regional growth and development are mentioned briefly here as their object of analysis is the development of activities in space and they touch on issues of land use and its change although in an abstract and rather indirect fashion. Regional disequilibrium theories and Keynesian type regional development theories are discussed briefly below.

3.3.2B Regional Disequilibrium Theories

Representative among the *regional disequilibrium theories* are Myrdal's well known "cumulative causation theory" (Myrdal 1957) and Perroux's "growth pole theory" (Perroux 1955, Boudeville 1966). The "cumulative causation theory" recognizes the unequal endowment of regions in terms of human and natural resources and skills and posits that development starts from regions with higher endowments. Industrialization of one region implies transfer of capital from the agricultural to the industrializing region and, hence, increasing inter-regional wealth disparities. The process becomes cumulative as the developed regions dominate the underdeveloped draining them of products and factors of production (the "backwash" effect in Myrdal's terminology). There is the opposite tendency, however, of growth diffusing from the developed to the underdeveloped regions in the form of, e.g. increased agricultural demand, causing the industrialization of the latter (the "spread effect"). Overall, however, superior regions continue to grow and dominate all other. Despite the abstract treatment of land and land use (as well as of time), this theory implies a mechanism of land use change within and between origin and destination regions – from developed agricultural to abandoned agricultural or to industrialized agricultural, from non-industrial to industrialized regions, etc. However, because regional imbalances may take an indeterminate number of forms and the origin of the regional development process is not explained – development is assumed to start spontaneously from some region with an original advantage (Cooke 1983, 121), the cumulative causation theory neither postulates orderly land use patterns nor can offer rigorous explanatory assistance in concrete cases of land use change.

The "growth pole theory", originally conceived by Perroux (1955) and later expanded by Boudeville (1966), moves along somewhat similar lines in that growth is assumed to originate in some region where a **propulsive industry** is located and then spreads to the surrounding regions. However, it is possible that contiguous regions are deprived of their factors of production and markets because of the growth of the growth pole. This theory describes processes of growth which have land use implications in both the growth pole and its contiguous regions but these implications are not spelled out explicitly by the theory. Moreover, the mechanisms that account for the growth of the pole are not specified, a fact that detracts from the explanatory power of the theory itself and its relevance to analyzing the determinants of land use change in this context.

3.3.2C Keynesian Development Theory

Another group of regional development theories is based on the Keynesian macro-economic theoretical framework such as the Harrod-Domar models, the export-base model, the factor-export models, neoclassical multiregional growth analysis (Cooke 1983, Hoover and Giarratani 1984, 1999, Andersson and Kuenne 1986, Bennett and Hordijk 1986). Their most important characteristic for our purposes is that they are "purely aspatial" theories; they do not even abstract from space, they ignore it. Because of this lack of spatial specificity they cannot be used to analyze directly land use change in specific regions and locations. Another feature of these theories is that they are demand oriented and ignore the supply side of the regions of interest – land suitability for various uses being a limiting factor on regional development (especially sustainable regional development); or, negative externalities being generated when land is put to uses for which it is not suitable. The mechanism of change (implicit in their static versions or explicit in their dynamic versions) is, naturally, **exogenous** changes in the demand for regional goods and services which may, subsequently, lead to social, physical and other changes. Keynesian-type macro-economic growth theories have found formal expressions in corresponding mathematical models of aggregate economies – those mentioned above as well as various versions of **Input-Output models** . If one accepts their assumptions and **epistemological** position, these theories can provide directions for the changes of the macro-economic determinants of land use change – incomes, investments, consumption, imports and exports. In fact, these theories underlie contemporary global models of land use change (at the aggregate world level mostly) which will be examined in the next chapter.

3.3.3. Other Theoretical Approaches in Regional Science

The broader field of Regional Science, although dominated by economics-based theoretical approaches to spatial change, contains a rich variety of several other approaches which attempt to describe the structure and evolution of spatial systems and, consequently, underlie the particular analysis of land use change. Of the extensive and variegated literature on the subject, two theoretical streams are briefly mentioned below: (a) Social Physics and (b) Urban and Regional Mathematical Ecology.

Social Physics is a term used to denote an approach to the study of social phenomena by drawing analogies from Physics. It is mostly concerned with the notion of “interaction” among individuals and groups and aims to explain human interaction on the basis of laws governing the motion of particles in physics. Its first codification is attributed to Carey (1858) while Ravenstein (1885) applied the idea to the study of migration. This theoretical stream has provided the basis for the gravity model which is presented in detail in Chapter 4. In this context, the magnitude of the interaction between two interacting activities located at a distance d from one another in space is proportional to the “mass” of these activities and inversely proportional to the distance between them. The “masses” of the activities are approximated variously depending on the activity considered. Most common measures include population residing at the two points in the case of residential activities (or population income) and floorspace or sales in the case of shopping activities. Measures of distance vary from physical distance or time to aggregate, composite measures taking into account various aspects of the “friction of space” which usually reduce the magnitude of interaction. More details are given in chapter 4 in the context of the gravity (or, more generally, spatial interaction) models.

The theoretical framework of Social Physics has been applied to the study of urban and regional phenomena which involve interactions such as trade and migration. It has framed also the study of urban and regional spatial structure; namely, the study of the location of residential and commercial areas which are linked through the transportation network. In this framework, change occurs when either the “masses” change or when the “friction of space” separating them changes (due, e.g., to improvements in the transportation network). One of the main objections to the use of Social Physics for the analysis of urban spatial structure and change is grounded on the lack of an economic rationale for the interactions analyzed. Niedercorn and Bechdolt (1969) derived the operational expression of the theory – the gravity model – starting from micro-economic principles of **utility** maximization. The theoretical issue that remained, however, was the application of a macrolevel theory to the explanation of individual level phenomena (Hanes and Fotheringham 1984). Wilson (1967) introduced concepts from statistical mechanics as well as the concept of entropy to derive the gravity model starting at the macro rather than at the micro level. However, this approach also ran into the problem of using concepts fromphysics to analyze social phenomena.

Entropy is another concept borrowed from Physics, in particular from Thermodynamics, which has been used to analyze urban spatial structure and change (see Wilson 1970, 1974; Wilson and Bennett 1986). Entropy measures the amount of uncertainty in a system of interest. A macrostate of this system relates to a number of possible microstates which arise out of the interactions of the individuals in this system. Entropy measures express the relationship between the macrostate and the microstates that correspond to it. A value of zero indicates a completely certain system – there is only one microstate of the system which coincides with the macrostate. When all microstates are equally possible, entropy obtains its maximum value – there is complete uncertainty in the system. In the analysis of the distribution of population and uses of land in an urban system, the entropy-maximizing principle is employed. In other words, the most possible macrostate of the system is found subject to certain constraints. This approach has been used to approximate the distribution of actual land use patterns or the most likely distribution of these patterns which results from changes in the characteristics of the system (e.g. changes in the transportation network, changes in the location of people or of employment). Despite criticisms of the Social Physics approach to the study of social phenomena, mainly its lack of a rigorous grounding on economic or sociological theories, it has found several applications in the analysis of spatial structure and change as the associated gravity and entropy models have been verified in several empirical situations.

In the 1980s, other concepts from physics were employed to the analysis of urban spatial structure and growth; namely, the concept of *fractal growth* and *fractal structures* (see, for example,Tobler 1979, Batty *et al.* 1989, Fotheringham *et al.* 1989, Frankhauser 1991, White and Engelen 1993). The process of urban growth and the resulting patterns are paralleled to the growth of organisms (e.g. corals) or particles (e.g. water drops, zinc oxide particles) which leads to particular fractal patterns. The notion of *diffusion-limited aggregation* is applied to the case of urban settlements to simulate their growth. Diffusion-limited aggregation (DLA) “refers to a process whereby a structure grows through the accretion or aggregation of units which diffuse over space until they reach a point on the periphery of the structure where they ‘stick’.” (Fotheringham *et al.* 1989, 56). Various behavioral assumptions are used to “guide” the DLA process which is used as a means of uncovering the order which underlies the apparent chaotic structure of modern urban settlements. Various elements such as the contiguous nature of development, the tentacular nature of urban growth, and the presence of density gradients have been explored on the basis of this approach. The broader theoretical framework of fractal analysis is the basis for the development of cellular automata models to be discussed in chapter 4. The use of the concepts of fractal growth and structure to the analysis of urban growth, like the previous concepts from physics, lacks a rationale based on economic and sociological theories. The models developed on the basis of these concepts may replicate observed patterns and growth processes but they do not get at the causes, they do not answer the "why" of these processes and patterns. They are **functionalist** approaches whose explanatory power is poor compared to other theories firmly grounded on economic and/or sociological principles. For other recent proposals to use concepts from Physics and Chemistry for the study of urban and regional phenomena see, for example Isard (1999).

Urban and Regional Mathematical Ecology is another theoretical stream concerned with the study of patterns and processes of urban and regional growth. It borrows ideas and concepts from Ecology as well as from the sociological theories of the Chicago School of Human Ecology (see next section 3.4.) and applies theories from Mathematics (see, for example, Wilson 1981, Dendrinos and Mullaly 1985, Nijkamp and Reggiani 1998). Cities and population residing in cities are paralleled to animal species in nature whose interactions are governed by symbiotic, predatory, competitive and other types of ecological relationships. These parallels are transferred to land uses which are seen as appearing in certain places and growing while other land uses in other locations shrink in size or disappear. Ecological relations are analyzed both within and between cities with the ultimate aim to obtain the spatial and growth patterns which result from these relations. In the intra-urban case, both the open and the closed city cases are analyzed where a dynamic version of the standard urban land rent model is derived which allows for various types of behavior besides equilibrium (Dendrinos and Mullaly 1985).

The emphasis of this theoretical stream is on the macroscopic features of urban and regional phenomena and it claims that these can be analyzed by focusing on the most important qualitative features of urban evolution observed at particular time periods. Urban and Regional Mathematical Ecology attempts to analyze the dynamic behavior of urban and regional systems such as the existence of urban cycles, the sudden growth or disappearance of settlements (discontinuities), suburbanization, slum formation, gentrification, etc. It addresses the issue of dynamic, non-linear interdependencies, stability, smooth and abrupt evolutionary change, and multiple equilibria of spatial phenomena and it aims at providing an appropriate basis for modeling these phenomena. Towards this purpose, it combines elements of mathematical population ecology and the mathematical theory of bifurcation to create a framework for the analysis of urban evolution which comes close to the general theory of evolution.

The presentation of the many applications of Urban and Regional Mathematical Ecology to the analysis of urban and regional evolution as well as to the models that have developed on their basis are beyond the intent of this contribution. The reader is referred to the references provided for further study. The basic point with respect to this theoretical stream is that it focuses on aggregate form, behavior, and processes and does not deal with land use explicitly. In addition, it can be subjected to the same evaluation as the Social Physics theoretical stream; namely, it is a functionalist and **positivist** type of theory which lacks economic or social theory foundations despite the fact that it can *describe* satisfactorily observed urban and regional phenomena.

3.4. The Sociological (and Political Economy) Theorization Tradition

The sociological **theorization tradition** draws from the way of thinking in Sociology and in the broader realm of the Social Sciences (Anthropology, Psychology, Political Science and related disciplines) which, compared to Economics, is more diverse and variable. In general, theorization in this tradition emphasizes the importance of human agency, social relationships, social networks, and socio-cultural change in bringing about spatial, political, economic, and other changes. The term "social" is used here in a broad sense which encompasses all manifestations of society – **modes of production**, institutions, politics, culture, life styles, etc. Hence, a broad variety of factors are introduced in the analysis of spatial structure and its change whose relative importance depends on the particular discipline of the Social Sciences from which they derive. Similarly, the behavioral assumptions made and the view of reality adopted depend on the "mother" discipline as well as the theory's epistemological position. As it was the case with the urban and regional Economics theorization tradition discussed before, some theories in the sociological tradition treat space, in general, and land use, in particular, explicitly as areas on earth's surface with particular properties (with various degrees of abstraction, of course) which have to do with its use and change as well as with the determinants and implications of this change. In contrast, other theories are "aspatial" in the sense that although they deal with spatial relations as they change under the influence of social changes, they treat space and land use abstractly (in the background) necessitating a "translation" of their findings to concrete contexts and uses of land.

Given the breadth and diversity of these theories, their categorization is neither easy nor straightforward. An attempt is made here to group together theories that share a common set of concepts about spatial structure and its change. Five groups are presented in the following: **functionalist/behaviorist** theories, **structuralist** /institutionalist theories, core-periphery theories, unequal exchange theories and uneven development-capital logic theories. Needless to say that, because this classification is not unambiguous, theories in one group can be classified under another group (as it is the case with the first two classes that may contain/include theories from the other three). Table 3.1c presents in greater detail particular theories included within each one of these five groups.

3.4.1. *Functionalist – Behaviorist Theories*

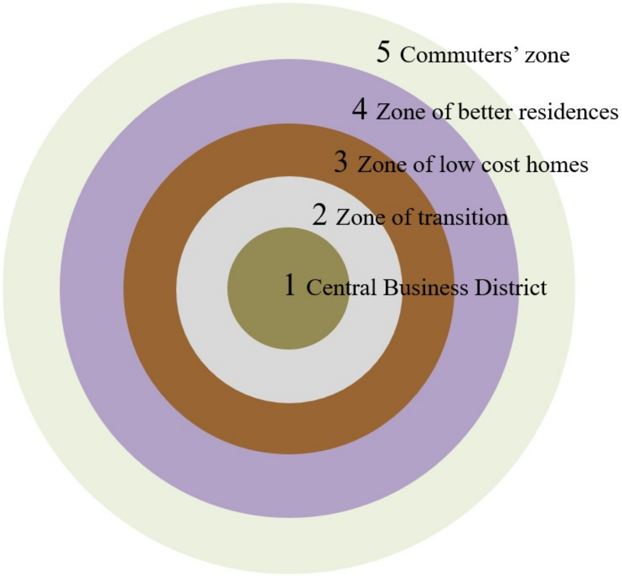
Two classes of theories are discussed as most representative of the **functionalist/behaviorist** theoretical approaches to the study of land use change: the well known "family" of human ecological theories and another class of theories of (urban) spatial structure originating in the field of planning.

3.4.1A Human Ecological Theories

Human ecology is a term coined to denote a sociological approach which borrows concepts and ideas from the field of Ecology and applies them to the analysis of the relationships of humans with their physical and social environment mostly in urban areas. It was developed in the 1920s by sociologists of the Chicago School – Robert Park, Ernest Burgess, Roderick McKenzie and others. Later, it was systematized by other scholars – Amos Hawley, James Quinn, Brian Berry, J. Kasarda, among others (Johnston *et al.* 1994, Romanos 1976). Human ecology advances the "idea that cities are the outward manifestation of processes of spatial competition and adaptation by social groups which correspond to the ecological struggle for environmental adaptation found in nature" (Cooke 1983, 133). Basic ecological concepts used to describe social groupings and processes include "community", "**invasion** ", "**succession**", "**adaptation**", "**dominance**", "disturbance", "competition", "climax equilibrium" (Johnston *et al.* 1994, Romanos 1976, Chapin and Kaiser 1979).

In its earliest versions, human ecology viewed the urban development process as producing and maintaining an equilibrium system and assisting the urban system to return to a stable order following any disturbance. The state of equilibrium and order resulted from a struggle for survival of different communities where the most powerful occupied the best locations in the city while the rest occupied the remaining space. The structural form of the city expressed the dominance of the fulfillment of the needs of industry and business which was then followed by the fulfillment of the residential needs of the population. The urban system was viewed to develop through processes of **invasion** and **succession** ; new interests *invade* certain parts of the city *succeeding* the former occupants who, in their turn, move to (invade) other parts, and so on. This process gives rise to particular land use patterns – the concentric ring (or, zone), the radial sector and the multiple nuclei patterns.

The *concentric zone theory* was proposed by Burgess (1925) to describe city patterns resulting from the ecological processes presented above. A monocentric city consists of five concentric rings containing particular urban functions; the center (the "loop") is occupied by commercial, administrative, financial, and recreational facilities. It is surrounded by a "zone of transition" which is occupied by poor and old residential property and run-down areas that have been invaded by business and light manufacturing as the CBD expands. The third zone contains the homes of the working class while the fourth is a high class residential area (white collar and middle-class families). The fifth zone is devoted to suburban and satellite development (Figure 3.2c).



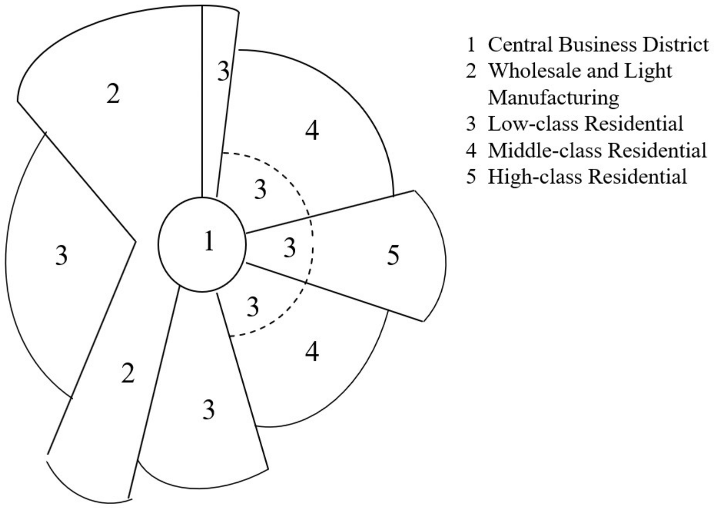
The Concentric Zone Theory of Urban Spatial Structure

Source: Adapted from Chapin and Kaiser (1979)

Figure 3.2c

As the city grows, each zone extends to the next, outer zone in the process of "invasion-succession"; this is the proposed mechanism of change of the concentric zone theory which, however, does not explain the "why" of city growth. It is evident that this conception of the urban land use structure and its change bears close similarities to those suggested by von Thunen and Alonso on the basis of other (although not dissimilar) arguments.

The *radial sector theory* was proposed by Hoyt (1939) who argued that similar types of (residential) land uses occupy wedge-shaped sectors extending from the city center along transportation routes (Figure 3.2d).



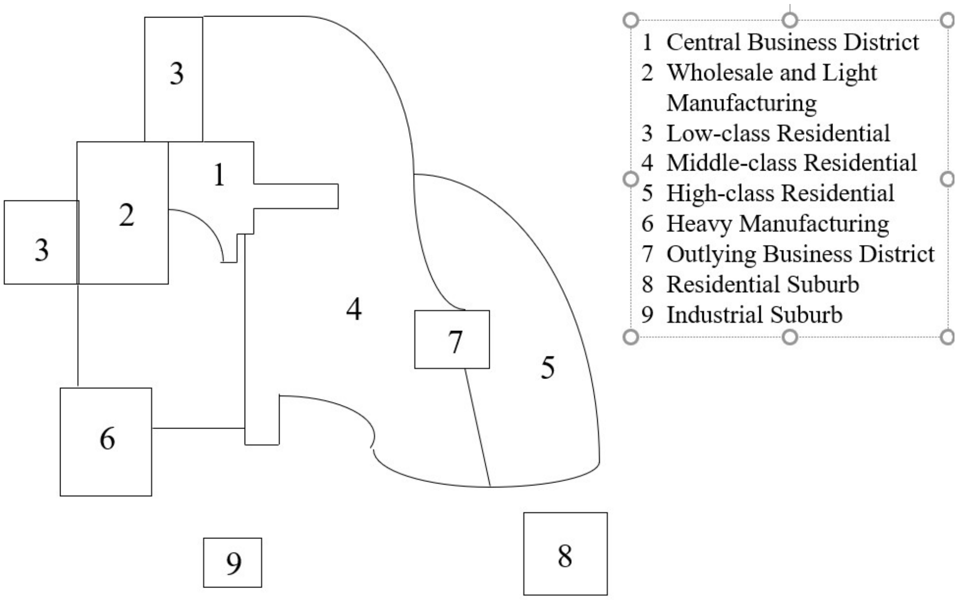
The sector theory of urban spatial structure

Source: Adapted from Chapin and Kaiser (1979)

Figure 3.2d

High-rent residential areas occupy certain sectors and rents decrease in all directions away from those areas. Adjoining residential areas are occupied by intermediate income classes while low-rent areas occupy other sectors extending similarly from the city center to the periphery (Chapin and Kaiser 1979, Romanos 1976). In this theory, the needs of high income groups dictate the patterns of urban expansion and residential relocation. The mechanism of change, thus, rests with the changing wealth and (spatial preferences) of those groups and, thus, cripples the theory of accommodating other forces of change – e.g. the influx of a large number of workers drawn by new manufacturing who create a demand for low and medium income housing (Romanos 1976). Hoyt's radial sector concept bears similarities to Burgess's concentric zone concept (Romanos 1976) and it has been criticized for its many defects (Lloyd Rodwin 1950 cited in Romanos 1976, 153-154).

Finally, the *multiple nuclei theory* of urban land use structure was suggested originally by McKenzie (1933) and it was expanded later by Harris and Ullman (1945) in an effort to overcome some of the restrictive assumptions of the previous two theoretical schemes (especially, the monocentric city assumption). Drawing on the observation that urban land uses are organized frequently around particular nuclei (pre-existing agglomerations or new centers of activity) rather than around a single center, they proposed a city structure that is schematically represented in Figure 3.2e.



The Multiple Nuclei Concept of urban spatial structure

Source: Adapted from Chapin and Kaiser (1979)

Figure 3.2e

The number and functions of the nuclei differ from city to city. The mechanism of change of this structure – the emergence of new nuclei – is attributed to: (a) the need for specialized facilities by certain activities, (b) agglomeration economies, (c) agglomeration diseconomies, and (d) the effect of the city rent rate structure on attracting or repelling certain activities (Romanos 1976, Chapin and Kaiser 1979). High income groups occupy the most desirable locations while low income residents are clustered in noxious environments. The multiple nuclei theory asserts that, as industrial societies become more complex and wide-ranging in their organizational scale, the social composition of city districts changes as a function of this increasing (social) differentiation. The changes residential areas undergo – differentiation and segregation – are caused by the changing economic status, extent of acculturation to urban ways of living, and ethnic status of individuals and households.

All three theories presented above are static descriptive devices of urban land use structure with an apparent focus on residential land uses. Although not stated directly, the underlying land allocation mechanism is similar to the urban land theory's bidding process where the determining factor is the ability of a user to pay for the price of a particular site in the city. None of these theories, however, *explain* the "why" of the processes of change in the land use patterns – the factors that account for the growth and decline of economic activities, the dominance of certain activities, the changes in preferences and other constraints (e.g. institutional) on land development and use. Human ecological studies that developed after the 1950s "have tended to play down the spatial focus of the Chicago School .... in favor of an emphasis on the demographic and institutional dimensions of society (Saunders 1981) although, at the same time, they have shown a strengthened interest in human interaction with the physical environment. Sociological human ecology has also moved away from those aspects of the Chicago School – embodied more in its ethnographic research monographs than in its theoretical pronouncements" (Johnston *et al.* 1994, 258).

Closely corresponding to the human ecological notion of succession, but not restricted to urban areas, the concept of "sequent occupance" was advanced by Whittlesey (1929) to describe the changes in the geography (landscape) of an area over long periods of time as "a succession of stages of human occupance which establishes the genetics of each stage in terms of its predecessors" (Whittlesey 1929 cited in Johnston *et al.* 1994, p. 549). It is worth noting Whittlesey's qualifications of the concept. "While 'human occupance of area, like other biotic phenomena, carries within itself the seed of its own transformation' ... such uninterrupted or 'normal' progression were 'rare, perhaps only ideal, because extraneous forces are likely to interfere with the normal course, altering either its direction or rate, or both' and 'breaking or knotting the thread of sequent occupance"' (Johnston *et al.* 1994, 549). A well known application of this notion is Broek's study of the Santa Clara Valley, California (Broek 1932). Korcelli (1982) cites applications of the notion by Hoover and Vernon (1959), Duncan, Sabagh and van Arsdol (1962) and Birch (1971) (Korcelli 1982, 96-97).

Before moving to the next class of theories in the functionalist/behaviorist group, a clarification and word of caution is in order. The term "human ecology" is being used in another sense in addition to the sociological covered in the preceding presentation. As Johnston *et al.* (1994) note "it is nonetheless frequently used in contemporary nature-society geographies ... that continue Barrows' focus on human adjustment to the natural environment, emphasizing the interactive and adaptive character of the human-nature interaction and its mediation by social institutions" (Johnston *et al.* 1994, 258). This different theoretical version of human ecology will be discussed in the context of the nature-society theories discussed below.

3.4.1B Planning Theories

Another class of theories of urban and regional spatial structure originated in planning circles. Cooke (1983) calls them "The Berkeley School" (not to be confused with the Berkeley School of nature-society theories associated with Carl Sauer to be discussed in the next section) and comprises contributions to theorizing about urban structure by Melvin Webber, Donald Foley and Stuart Chapin (see, Webber 1964). Common to theories in this class is the belief that spatial structure is a reflection of social structure and that new social norms give rise to changing spatial forms. Foley's urban structure theorizing builds on Talcott Parsons' hierarchical framework on which social life is structured and which consists of four systems: the social, the cultural, the personality and the physical system (Foley 1964, Cooke 1983). The four systems are related through particular relationships that lead to ordered social relations with norms playing a central role in this process. What is striking, especially for our purposes, is that, in Foley's schema, "the physical system is analytically unimportant except in so far as it imposes functional prerequisites upon the other three systems. The functional prerequisite it imposes on the social system is one of *adaptation* of social organization such that system maintenance is ensured .... Foley conceptualizes a relationship between cultural values and the spatial form of the city which is more reflexive than that of Parsons. ... Cultural norms may be understood as receiving partial expression in the built environment, but they are themselves modified by the cognitive feedback offered to the cultural system by the resulting physical system. In this way, abstract but fundamental social values receive spatial expression and the link between the sociological and the geographical spheres is forged..... *Physical lag* occurs when the built environment fails to respond to social system needs" (Cooke 1983, 88-90).

Webber's theorizing moves along similar lines emphasizing human interaction as the basis of urban communities. In his famous contribution "The urban place and the non-place urban realm" (Webber 1964b), he distinguishes between human interaction within the confines of a metropolitan area (a "place community") and human interaction that extends over scattered places on the face of the earth (a "non-place community"; their set constituting “urban realms”). Improved transportation and communication systems extend the interactions among individuals, firms, organizations and institutions to a global level making thus inadequate their analysis within an urban region (Chapin and Kaiser 1979). These dynamic interactions are traced through linkages centered upon interests rather than upon contiguity; hence, his conceptualization of “community without propinquity”. The spread of communications technology “frees spatial structuring from the locational constraints exerted by localized linkage patterns and heralds the emergence of a formless spatial development in ‘nonplace urban realms”’ (Cooke 1983, 91).

Similarly, Chapin’s theorizing on residential activity systems (Chapin 1965, 1968) is premised on the idea that the needs of human interaction is the key to the spatial organization of cities and adopts the sequence: basic values – activities spatial patterning. In his view, the personality system (see, Foley’s schema above) is instrumental in explaining residential mobility and competition in the housing market. Rational households “struggling to measure up to internalized norms of appropriate behavior locate in the optimal spatial location. Hence, social structure reveals itself in spatial structure as the outcome of a game in which those who adhere most closely to the rules win the best prizes” (Cooke 1983, 91).

All three theorists of the “Berkeley School” presented above follow a functionalist-structuralist approach to the explanation of urban (or, more narrowly, residential) spatial structure and its change. The theories address the dynamics of the urban system in terms of changing social needs, norms, technology. No particular spatial patterns are proposed as it was the case with the human ecology theorists as they place emphasis more on the determinants of urban land use rather than on particular spatial patterns; space, land and land use are treated in rather abstract terms (as in the concept of “nonplace urban realms”) compared to the earlier formulations reviewed thus far.

3.4.2. *Structuralist - Institutionalist Theories*

Structuralist -institutionalist approaches emerged from a general disappointment with and as a reaction to the idealism of the functionalist-behaviorist approaches to the description and explanation of urban and regional spatial structure, a selection of which was presented before (others will be discussed in the next section). The main point of criticism they advance against the **functionalist** approaches is that they ignore the social and institutional constraints on individual behavior. They propose alternative conceptualizations of urban and regional spatial structure and of the determinants and processes of its change most of which are premised on the belief that the main determinant of locational behavior is power. Hence, analysis of spatial patterns has to be based in the relevant political economy (Johnston 1982, 83). Conflict between unequals, which has a class basis mostly, is an instrumental concept in these approaches many of which have taken anti-capitalist, Marxist ideological stances. Diverse theories exist which can be divided broadly into those concerned with the urban, metropolitan level and those referring to larger scales. This section discusses briefly the former group; the latter is covered in the next sections.

The common theme of most structuralist-institutionalist theories is urban development in late capitalist societies. Hence, their relevance is confined to those societies and cannot be transferred easily to the analysis of spatial development either in past periods or in contemporary societies that do not conform to this type of political economic system. In this particular context in which they operate, the analysis focuses on the (capitalist) **mode of production** and the ways in which it structures space and spatial relations. The latter reflect the tensions and conflicts between capital (associated with the production space) and labor (associated with the consumption space). The state plays a critical role in mediating these conflicts with the purpose of supporting those relations which contribute to the capital accumulation process. Various state functions (planning, provision of services, etc.) contribute to shaping space towards this end.

Structuralist -institutionalist theories differ between them with respect to the conceptualization of space, spatial relations, the locus and nature of conflict, and the choice of mechanisms by which the system of power relations works and shapes space. Castells’s Structuralist -Marxist theoretical contribution (Castells 1977, 1978) focuses on collective consumption and the power of the state, as the main supplier of collective consumption services, to control urban structure in ways beneficial to the interests of the owners of capital. Castells relies on Althusser’s **structuralist** theory of social formations (Althusser and Balibar 1970) which distinguishes three main levels in the organization of society: the economy, the state, and ideology. The economy is dominated by the capitalist **mode of production** whose main elements are the *relations of production* – owners of capital vs. laborers and the *forces of production* – technology, the structure of the division of labor, machines, structures, etc. Castells assumes that there is a relative autonomy between the three levels and identifies the main processes through which their interrelationships influence the development of the urban spatial structure; how the dominant mode of production shapes space. The spatial expression of the economy includes: (a) the *production space* – industry and offices, (b) the *consumption space* – with elements of the reproduction of the labor power: housing and welfare services, and (c) the *exchange space* – transportation and communication networks. The *administration space* – local government and urban planning – relates to the economic space but also to the exchange space. The organization of production is conducted mostly, although not exclusively, at the regional scale while the reproduction of the labor power is an urban level activity. Hence, a link is postulated among all three – the sphere of reproduction, the urban level and consumption. Collective consumption structures urban space. The state supplies collective consumption services through its planning apparatuses and, in this way, controls the process by urban spatial structure is formed.

The concept of *urban social movements* is central in Castells' explanatory schema, the theory of reproduction. Urban struggles develop as dominated groups (the labor class) in urban areas come into conflict with state policies which aim to maintain those social relations that further the interests of the capitalist, ruling class. This is very broadly the mechanism by which Castells attempts (though not successfully as his critics contend) to explain the development process and spatial change in urban areas (for a collection and synthesis of the critiques, see Cooke 1983; also Mingione 1981).

In another perspective, Scott (1980) focuses his analysis on the *urban land nexus* which denotes the differential locational advantages offered by the intersection of variable land rent with the spatial requirements of households and firms. The urban development process is conceived again as resulting from the conflicts between capital (over the distribution of profits) and labor (distribution of wages). The state legitimizes capitalist social relations and assists capital accumulation through welfare and other subventions. Urban development is seen as "a function of changing capital to labor ratios among firms as they engage in technical switching to maximize profits. Increased capital intensity associated with investment in technology is accompanied by increased decentralization of location from the urban core. . . .these changes in the production space stimulate responses in the reproduction space as households seek suburban locations closer to employment centers . . . The state is heavily involved in unraveling the spatial knots to which this process gives rise, especially in the spheres of reproduction and circulation, to overcome market failures in the provision of housing and transportation facilities. . . Urban planning performs its main functions by solving land use dilemmas . . . .. and smoothing the dynamics of land development" (Cooke 1983, 145). Scott attempts to integrate planning and urban theory, to analyze the peculiarities of the land market and its role in focusing urban development unevenly, and to introduce the notion of *civil society* to explain the development process.

David Harvey's voluminous and influential contribution to the analysis of the urban development process in capitalist societies is impossible to summarize in a few lines. The reader is referred to his writings as well as to the analysis of his works by other scholars (see, for example, Harvey 1973, 1975a, 1975b, 1982a, 1982b, Cooke 1983). It is also difficult to categorize his theorizing in just one category – such as the institutionalist as it is done here – as it is broad and relates to several other theoretical currents within the sociological/political economy tradition; in particular, the uneven development-capital logic group of theories discussed below. Harvey adopts a Marxist theoretical and analytical framework to analyze spatial forms and processes as the result of socio-political inequalities inherent in capitalist societies. He theorizes on the *recurrent crises in capitalist societies* which result from the inherent contradiction between class struggle and capital's drive towards accumulation. He explains urban development in late capitalism in terms of the generation of massive economic surpluses, underconsumption, and the state's direct and indirect involvement in the process of modifying the built environment, among others, to support the interests of the capital. Conflicts and struggles between labor and capital are manifested in the ways the built environment is produced, manipulated, and used. Harvey has proposed a three-circuit schema to represent the connection between finance capital and the built environment. Over-accumulation of capital in the primary circuit of production causes capital to switch to a secondary circuit – investments in the built environment. Furthermore, capital may switch to a third circuit – investments in various welfare services (Harvey 1975b, 1982b). To overcome economic crises, capital seeks a *spatial fix* (Harvey 1982b) – spatial arrangements that help solve the crises. This is how investment in one place and disinvestment in another over time is explained as well as the ensuing spatial transformations. Harvey's analysis, although focusing on late capitalist societies and the urban environment is broad enough to frame the qualified analysis of the land development (and, consequently, the issue of land use) in other contexts.

Structuralist -institutionalist theories in the vein of those presented above provide potentially valuable insights and analyses of the political and institutional determinants of land use and its change in urban areas of developed, capitalist countries. **Functionalist** undertones are apparent in several of them. Land and land use are treated in rather abstract manner as the main emphasis of these theories is not on land itself as on the forces that impinge on the uses of land. Hence, these theories do not explain always the critical connections between the political and institutional factors and the resulting land use patterns except for broad accounts of such phenomena as urbanization, suburbanization, decentralization of production and other forms of development. This caveat may be attributed, in part at least, to the relative neglect of the role of human agency and their excessive focus on aggregate forms of social organization. A theoretically interesting and operationally useful task is their "translation" into more spatially-explicit and place-specific contexts. This will necessitate a broadening of the explanatory schemata advanced by including additional factors as well as by developing more explicit linkages between the development process at various spatial levels.

3.4.3. *Core-Periphery Theories*

Core-periphery theories represent another group of theoretical approaches which refer mostly to higher than the urban (up to the global) levels. Their purpose is to describe and explain the spatial organization of human activities premised on the idea of unequal distribution of power in socio-economic and political affairs. In this way, they can be considered to provide general level theorization schemata about the uses of land and changes of land use resulting from the relations of dependence which develop between the core (a developed – but not necessarily spatially defined – region) and the periphery (underdeveloped regions). Its distinctive difference from similar theoretical approaches (dependency theory, unequal exchange theory) is perhaps that it subscribes to the goal of spatial equilibrium and ignores the uneven development of the division of labor in capitalist societies (Johnston *et al.* 1994, 95).

There are several variants of the basic core-periphery theoretical formulation. Its origins can be placed in earlier modernization theories (Lewis 1955 cited in Cooke 1983, 151) as well as in Rostow's (1960) *stages theory of economic growth.* More generally, it can be embedded within a broad **diffusion theoretic** framework as the central idea is that development spreads out (diffuses) from a core region which contains the most modern economic sectors towards the periphery – regions which are at the first or pre-industrial stage of development (Cooke 1983, 151). Actually, Friedmann (1966) – with whom the core-periphery model is more closely associated – defined the core-periphery relations as the second of a four-stage sequence of the development of the space economy. These stages are: (a) pre-industrial society with localized economies; (b) core-periphery; (c) dispersion of economic activity and (d) spatial integration (Johnston *et al.* 1994, 95). A more radical variant of the core-periphery idea, the *internal colonialism* concept, has been formulated by Hechter (1975 cited in Cooke 1983, 151) who rejects the assumption of spatial equilibrium of the original idea. Hechter posits, instead, that industrialization spreads in a spatially uneven way. Groups in the core region reinforce their advantageous position and the periphery is forced into specialist, complementary functions. Continued monopolization of peripheral trade, credit and employment patterns by core institutions prevents equalization of wealth between core and periphery (Hechter 1975 cited in Cooke 1983, 152).

A more general, global version of the core-periphery dualism is the *world- system theory* (Wallerstein 1974, 1979), a theorization of how core, industrialized regions relate to the underdeveloped periphery on a world scale. Colonial expansion undertaken by a capitalist, industrialized core region results in a structuring of the relations of the world regions with one another according to the international division of labor. The international division of labor reflects the functionality of different areas for particular types of production. Between core and periphery, Wallerstein introduced the concept of the *semi-periphery*, "countries that have regressed from core status through undergoing a process of deindustrialization and those heading for core status as they experience rapid industrial development" (Cooke 1983, 153).

Evidently, this group of theories deals, in general, with broader development issues of which land development (and the implied land use change) is but one. Land and land use is treated in some of them in some way (e.g. when agricultural production and systems are analyzed) although the level of detail is necessarily coarse, a consequence of the coarse level of analysis. Most of the theories are dynamic as they indicate stages of economic development although in a prescriptive/normative sense mostly. However, they can be used to frame questions and answers about the determinants of land use change at higher spatial scales as well as to be combined with analyses of land use change at these scales.

3.4.4. *Unequal Exchange and Dependency Theories*

Sharing more or less the basic core-periphery dichotomy with the previous group, a number of related development theories are discussed in this section. *Unequal exchange theories* build their explanatory schemata around the mechanism of *exchange* to account for the nature of socio-economic and other relationships developing among regions. Dependency theorists emphasize the power of external forces in imposing a situation of *dependence* on underdeveloped countries.

Unequal exchange theories (Emmanuel 1972, Amin 1976, 1978 cited in Cooke 1983, 154) draw from propositions of the labor theory of value (and the broader trade theory) which state that, because of differential costs of reproduction of the labor power between countries, the commodities exchanged are not equivalent in terms of "socially-necessary" labor time (technology, labor productivity and transport costs assumed constant). Usually, in developed, industrial countries real wages are higher than in the less developed countries with inferior productive facilities and large, unorganized labor reserves. The differential exchange of purchased (through commodity trade) labor power produces an exploitative relationship which is to the advantage of the high wage regions and to the detriment of low wage areas (Cooke 1983, 155). "Unequal exchange may help to maintain a permanent inability to gain from trade by the systematic extraction of value from underdeveloped economies and by the development of a permanent development gap. This may not only result in the increased penetration of imports into developed economies, but may also undermine traditional modes of production and intensify technological dependence in the underdeveloped economies" (Johnston *et al.* 1994, 637).

The broader idea of unequal exchange is common to the uneven development theories which are discussed below. In addition, it is observed that the notion of differences between countries in terms of "socially-necessary" labor time embodied in commodities resembles the notion of differences between countries in the "resources import content" of economic sectors and embodied in related products which is accounted for by the "environmental space" and the "ecological footprint" concepts (Hille 1997, Wackernagel 1993). Land is one of the principal resources which is "imported" by industrialized countries in the form of products produced beyond their national boundaries. More specifically, if a country or region consumes more than its own resources can produce – beyond its carrying capacity – it appropriates resources from other regions; this is the notion of the "**appropriated carrying capacity**" (Rees 1996). Drawing a parallel to the unequal exchange theories, commodities exchanged are not equivalent in terms of "resources import content" or of "appropriated carrying capacity". The differential exchange of purchased (through commodity trade) land and **carrying capacity** produces an exploitative relationship where land use and its change in underdeveloped countries is controlled by the demands of the developed countries.

Dependency theories (Frank 1967, 1972, 1979, Dos Santos 1970), although different in several respects from unequal exchange and core-periphery theories, stress the *conditioning situation of dependence* of underdeveloped on developed economies which is produced from the imposition of particular forms of development and technology by international enterprises in advanced industrial societies on peripheral countries. Hence, the latter are conceived as being locked in a permanently asymmetric economic relationship with the former which prevents them from breaking out from their underdeveloped status. An alternative, less deterministic, version of the dependency thesis – the *associated-dependent development* (Cardoso 1973) – holds that there are changing forms of dependency as factors internal to the economies of the dependent areas (e.g. the prevailing class structure and the role of the state) are as important as those external to them.

Both the unequal exchange and the dependency theories do not refer directly to land use issues but to critical determinants of land use and its change focusing specifically on the international level. As it was the case with the core-periphery theories, they do not make explicit the links between the relationships on which they focus and the resulting land use patterns and changes although these can be derived from the context of the broader analysis of the issues of inequalities and relations of dependence and exploitation. Nevertheless, the relatively high level of spatial abstraction of these theories makes them suitable, if one accepts their ideological and **epistemological** positions, as broad guiding frameworks for elaborating the particular influences of changing social, economic and technological relations between developed and underdeveloped countries on the land use patterns of both.

3.4.5. *Uneven Development – Capital Logic Theories*

A last group of theories which overlaps considerably with all those discussed previously (with the exception of the functionalist-behaviorist theories) revolve around the general theme of *uneven development*. Uneven development is defined as "a systematic process of economic and social development that is uneven in space and time, and endemic to capitalism. ... (It) is a basic geographical hallmark of the capitalist mode of production.... combining the opposed but connected processes of development and underdevelopment" (Johnston *et al.* 1994, 648-649). Uneven development is closely related to the logic of *capital accumulation* (hence, the label "capital logic" used by Cooke 1983) and, thus, takes place at all geographical scales. Hence, the employment of the concept in various theories which focus on particular spatial scales. The unequal exchange and dependency theories presented above may be considered as global scale applications of the concept of uneven development. Two theories from the uneven development-capital logic group are presented briefly below followed by an outline of the main elements of the broader theory of uneven development.

At the sub-global level, an influential theory is Lipietz's *theory of unequal regional exchange* (Lipietz 1977, 1980) which examines the ways in which different **modes of production** connect across inter-regional space. Underdeveloped regions are characterized by pre-capitalist (e.g. peasant and petty-commodity) modes of production while developed regions are dominated by the capitalist mode of production. Development follows a phased course. First, control of petty commodity production passes to financial institutions as credit is extended to enable producers purchase the means of more intensive production. Then, the processing of agricultural output passes into the control of centralizing capitalist industries. The emergent spatial division of labor, based on unequal exchange between regions with different levels of technical development provides the setting for unequal exchange in terms of differences in wage levels. Underpayment and the subsequent squeeze upon living standards stimulates rural depopulation and migration to urban-industrial agglomerations. The theory describes the spatial implications (concentration and decentralization) of the course determined by the logic of capital accumulation in both the dominant and the dominated regions (Cooke 1983).

A less deterministic and restrictive, flexible theorization of uneven development which focuses on the sub-regional, local level (in industrial, capitalist societies) is offered by Massey's (1984) *theory of the spatial divisions of labor* (see, also, Massey 1978, 1979, 1980 cited in Cooke 1983, 162). This theory is distinctive in that it seeks to relate the operation of the processes of capital accumulation to the areal differentiation of the space economy recognizing that the character of each region and locality modifies these processes in particular places and times. Hence, there are no pre-determined patterns of relations and spatial outcomes (as the previous groups of theories more or less asserted they do). No spatial equilibrium or disequilibrium towards which the economic system is necessarily tending is being postulated (Cooke 1983, 163) as the theory stresses the variability of spatial outcomes sector-by-sector. Massey develops the concept of "layers of development" as a way of characterizing the changing spatial structure of the economy. "The structure of local economies can be seen as a product of the combination of 'layers', of the successive imposition over the years of new rounds of investment, new forms of activity" (Massey 1984, 120). Each time, "the existing character of the area interacts with the new 'layer' in a process of 'mutual determination"' (Johnston *et al.* 1994, 326).

The more general theoretical shell which encompasses those theories which, in one way or another, aim at analyzing and explaining facets of the uneven nature of socio-economic and spatial development is provided by the *theory of uneven development*. The subject of the theory is the geography of capitalism and it has a dual purpose; first, to determine the characteristics of this specific geography, and, second, to show how "the geographical configuration of the landscape contributes to the survival of capitalism." (Smith 1990, xi). The idea of uneven development has a heritage in Marxist theory but in its contemporary, 20th century, form it is addressed at the geography of capital accumulation. In order to explain the resulting geographical patterns it attempts to integrate space and social process at various levels something which capital achieves in practice on a daily basis. In the words of Smith (1990, xiv): “In its constant drive to accumulate larger and larger quantities of social wealth under its control, capital transforms the shape of the entire world. No God-given stone is left unturned, no original relation with nature unaltered, no living thing unaffected. To this extent, the problems of nature, of space, and of uneven development are tied together by capital itself. Uneven development is the concrete process and pattern of the production of nature under capitalism”. The exposition of the theory of uneven development which follows is based on Smith (1990).

Under capitalism, specific social relations develop involving two classes: the class who possess the means of production for the whole society and do no labor (the capitalists) and the class who possess only their own labor which they must sell to survive (the laborers). The capitalist **mode of production** implies the generation of surplus product which takes the form of *surplus value*. The capitalists, under competitive conditions resulting from the private ownership of the means of production, are totally dependent on reinvesting this surplus value in order to create more. Thus, *capital accumulation* becomes the necessary condition for the reproduction of material life, the necessary condition for the survival of capitalism. Two contradictory tendencies emanate from the capitalist mode of production: a tendency towards *differentiation* and another tendency towards *equalization* of the levels and conditions of production. Differentiation results from increased production which necessitates increased division of labor. Because, historically, the division of labor has been based upon the differentiation of natural conditions, the spatial or territorial division of labor is not a separate process. However, with the general increase in the productive forces (technology) under capitalism, the territorial division of labor is freed from its roots in nature. Natural differences are leveled off, hence the tendency towards equalization.

But social differentiation results not only from the division of labor but also from the division of capital into: (a) *departments* (means of production, consumer commodities, and collective items); (b) *sectors* of the economy, and (c) *individual* units of property. The integration of the division of labor with the division of capital defines four identifiable scales at which the process of social differentiation takes place:

1. “the *general* societal division of labor and capital into different departments,
2. the division of labor and capital in *particular* different sectors,
3. the division of social capital between different *individual capitals*, and
4. the *detail* division of labor within the workplace.” (Smith 1990, 108)

At the scale of the *general* division of labor, the separation between town (place of production) and country (place of reproduction) has been historically the spatial expression of the social division of labor which, however, causes further division of labor and, ultimately, leads to the disappearance of their original difference. At the level of the *individual capitals*, the differentiation process is expressed as concentration and centralization of capital in some places at the expense of others. Finally, at the level of the *particular* divisions of labor – the divisions of the economy into sectors – the differentiation of geographical space “occurs in a cyclical manner according to the equalization of the profit rate within a given sector and the resulting movement of capital between sectors ... This movement ... takes on a spatial dimension due to its timing; insofar as those sectors attracting quantities of capital are relatively young in the economy, their rapid expansion generally coincides with some kind of geographical expansion or relocation in order to supply the space for burgeoning productive facilities. And the corollary also holds. Insofar as sectors systematically losing large quantities of capital are old and established ... and insofar as they therefore tend to have been clustered relatively closely in the landscape, then whole areas will tend to experience a systematic and uncompensated devalorization of fixed capital located there.” (Smith 1990, 113).

Parallel to the tendency towards differentiation, a tendency towards equalization in the conditions of production develops whose origins coincide with those of differentiation. The accumulation of capital progresses by leveling of pre-capitalist **modes of production** to the plain of capital. The same is true for the quality of nature which is leveled downward at the hands of capital. Similarly, “new techniques adopted by one capital must be equaled or bettered by other capitals in the same sector if they are to survive in the marketplace...... With the development of the means of communication and transportation, the barriers to the geographical generalization of new technologies are diminished. To the extent that this generalization is achieved, the tendency toward the equalization of conditions and levels of production is realized" (Smith 1990, 115).

Capital accumulation leads to the geographical expansion of the capitalist society and necessitates the continuous investment of capital in the built environment for production. The built environment, in all its material manifestations, is the geographically immobilized form of fixed capital which is so central to the progress of accumulation. Two processes operate here: social and spatial *concentration* and *centralization* of capital. Capital is concentrated in existing units to facilitate the expansion of the scale of production and it leads to the centralization of capital. Although there is no one-to-one correspondence between social and spatial centralization, the former necessitates the latter which eventually expresses itself in the geographical differentiation associated with the concentration of capital in certain centers of production. Spatial centralization concerns productive capital mostly; the spatial clustering of capitals in established places of production. This process brings about also the spatial centralization of labor as this reduces considerably the cost of the reproduction of labor. Capital accumulation, hence, leads to the accumulation of labor in certain places of production.

The model of investment in the built environment described by Harvey has been already mentioned before. It is a cyclical process involving three circuits – a primary, a secondary and a tertiary – a distinction which Harvey dropped later to emphasize the unity of the process. But the central logic remains the same. Overaccumulation is a condition and a result of capitalist crisis. "Overaccumulation results in a massive devaluation of capital, and because of its long turnover period, fixed capital is particularly vulnerable.... This devaluation represents an absolute destruction of value. As Harvey emphasizes devaluation is place-specific" (Smith 1990, 126). The devaluation of fixed capital is place-specific at the level of whole sectors of the economy also. Where these sectors are spatially centralized, sectoral crises are translated into geographical crises affecting entire regions. The critical question is whether "the capitalist mode of production can resolve or displace its inherent contradictions through some sort of spatial solution, a 'spatial fix"' (Smith 1990, 130).

Harvey has shown the impossibility of a spatial equilibrium under the capitalist **mode of production** (Smith 1990, 132). Uneven development – a dynamic process operating at different spatial scales – characterizes instead the landscape of capitalism. Smith (1990) argues that "an understanding of scale gives us a final, crucial window on the uneven development of capital because it is impossible to comprehend the real meaning of 'dispersal', 'decentralization', 'spatial restructuring' and so forth, without a clear understanding of geographical scale ... There is little doubt about the impossibility of a spatial fix for the internal contradictions of capital, but in the doomed attempt to realize this spatial fix, capital achieves a degree of spatial fixity organized into identifiably separate scales of social activity" (Smith 1990, 134-135). He discerns three primary scales: the urban scale, the scale of the nation-state, and the global scale. However fixed these scales are made to serve the purposes of capital accumulation, they are subject to change. It is "through the continual determination and internal differentiation of spatial scale that the uneven development of capitalism is organized" (Smith 1990, 136).

At the urban scale, the pattern of urban development is the fullest spatial expression of the centralization of capital. In the capitalist city, "urban space is divided between spaces of production and spaces of reproduction leading to the local concentration of specific activities and land uses – industry, transport, residential, recreation, retail, commercial, financial, and so forth." (Smith 1990, 137). The geographical differentiation of urban space is mediated by the *ground rent* – the price of an individual absolute space of private property. "The ground rent system levels urban space to the dimension of exchange value, but does so as a means of then coordinating and integrating the use of individual spaces within urban space as a whole. The equalization of urban space in the ground-rent structure becomes the means to its differentiation. Competing uses are geographically sorted in the first place through the ground-rent system" (Smith 1990, 138). However, because land becomes an object of speculative exchange and development, the integrative role of the ground rent is disrupted.

At the global scale, the necessity of capital accumulation leads to the equalization of the relations of production. Geographical differentiation results from the differential determination of the value of labor power and the associated geographical pattern of wages. Capital expands to pre-capitalist societies in search of surplus value and converts these places into spaces of production and accumulation. But, at the same time, under the threat of overaccumulation, capital converts them also to markets for its goods, places of consumption. In this process, however, these places are developed and wages are raised to facilitate consumption; hence, the contradiction between the means of accumulation and the conditions necessary for it to proceed.

At the scale of the nation-state, the organization of capital takes a fixed form, the subdivision of the globe into more than 160 countries – absolute spaces – within which capital is defended against other capitals if it is to produce surplus value. At this scale, regional development and differentiation are important as they are the geographical expression of the division of labor. The tendency towards spatial centralization causes the regional concentration of capital. A territorial division of labor emerges as different sectors of the national and the international economy are concentrated and centralized in certain regions which function like their international counterparts of developed and underdeveloped countries providing geographically fixed sources of wage labor. Regions are more sensitive to the crises of capital as particular sectors are geographically localized and the mobility of capital is not constrained by national boundaries. The movement of capital in and out of the regions is more rapid; hence, the effects of accumulation and devaluation of fixed capital are more intense expressed as regional growth or decline.

In sum, in its drive to equalize the conditions of development, capital produces different spatial scales through a continual differentiation and redifferentiation of relative space. These scales are neither fixed nor impervious. What *is* fixed is the necessity of discrete scales and their internal differentiation. Smith (1990) proposes that capital moves in a *see-saw* fashion producing patterns of uneven development. Capital moves to areas where the rate of profit is high and develops them while the others, where the rate of profit is lower, remain underdeveloped. But in the process of development, the rate of profit decreases taking away the very reason for development. At the international and the national scale, development brings about a drop in unemployment, an increase in wage rate, the development of labor union, all of which pull the profit rate downwards. At the urban scale, the development of underdeveloped areas leads to increases in the ground rent and, thus, removes the impetus for further development. At the other end, in the case of underdevelopment, the lack of capital or its oversupply keeps unemployment high as well as wages and workers organization into unions low. Over time, these conditions render the area profitable and its development starts.

Smith describes the "see-saw" movement of capital as follows. "Capital attempts to see-saw from a developed to an underdeveloped area, then at a later point back to the first area which is now underdeveloped, and so forth. To the extent that capital cannot find a spatial fix in the production of an immobile environment for production, it resorts to complete mobility as a spatial fix ... Capital seeks not an equilibrium built into the landscape but one that is viable precisely in its ability to jump landscapes in a systematic way." (Smith 1990, 149). But this see-saw movement is not equally visible or operational on all three spatial scales identified before. Its most clear expression is found at the urban scale where capital is readily mobile. The creation of the suburbs, a result of the geographical decentralization of capital, led to the underdevelopment of the inner city. Devaluation ensued and the ground rent dropped there. A point was reached when the rent "gap" – between actual capitalized ground rent and potential (given a 'higher' use) ground rent – became sufficiently large to induce the process of redevelopment and gentrification of the inner city. This is the contemporary experience of many North American and, to a lesser extent, European cities.

The see-sawing of capital is less visible at the scale of the nation-state as, despite the restructuring of geographical regions, it is not clear whether this is a see-saw movement of capital. The question arises whether this is a matter of empirical verification and/or whether other factors operating at the level of nation-states do not support this type of movement. Finally, at the global scale, the see-saw movement of capita is hardly evident as capitalist wealth and development is concentrated in a few well-off nations, capitalist poverty is also segregated, and the mobility of capital and labor is restricted by national boundaries and the opposite conditions of development and underdevelopment. Thus, the see-saw theory of uneven development has limits being most relevant to the urban scale.

Theories adopting the uneven development theorization optic rely on more or less abstract conceptualizations of land and land use as their emphasis is more on the analysis of critical determinants of the spatial transformations than on the resulting spatial patterns. The latter point is made forcefully by Massey's theorizing that there are no pre-determined patterns but that these have to be uncovered in concrete spatial and historical contexts. Each theory makes valuable contributions to the understanding of the broader socio-economic, institutional and political determinants of spatial transformations but it seems that there is no theory that makes explicit the linkages between the changes in the determinants and associated land use changes. Massey's provocative and influential theory is restricted to the (changing) location of industry (at the sub-regional level). For this and the broader theoretical framework of uneven development to be usefully and meaningfully applied to the analysis of land use change, further research is required to provide for their adaptation to the variety of land use types and the socio-economic contexts where they occur.

3.5. The Nature-Society Theorization Tradition

The nature-society theorization tradition is the broader and more diverse of all three categories of theories considered in this project as it embeds the analysis of land use change within the broader discourse on global environmental change. This discourse is informed by a variety of theoretical approaches which are called, in addition to "nature-society", "human-nature" and "man-environment" theories. The principal, deeper question they address is "how man relates to nature" which translates into the more common and popular question of "man's role in causing environmental change" or "the human causes of global environmental change". Their common characteristic is that they deal with the totality of the interactions between nature (or, environment), economy, society (including politics and institutions), and culture (henceforth called the "**total system**" for brevity) although each from a different (usually disciplinary) perspective. Hence, the behavioral and other assumptions they make may differ from one theoretical scheme to another but all of them attempt to address the relationships among all four components of the total system. Because the environment is explicitly considered in this tradition, the theories included are more relevant to the analysis of land use and land use change as they treat those concepts less abstractly than the two previous **theorization traditions**. This does not mean that all theories in this group treat land use change explicitly and concretely; on the contrary, there are several theoretical approaches that are vague in spatial terms even more so than some aspatial theories belonging to the two previous traditions. It is speculated, however, that the connections to issues of land and land use may be more easily made in the case of the nature-society theories than it was the case with the economic and sociological theoretical approaches.

Categorization of the theories belonging to this theorization tradition is neither easy nor straightforward. The scheme adopted here borrows from Sack's tri-partite division of the social theoretical *realms of explanation*: the realms of meaning, nature, and social relations (Sack 1990, 659, 661). The first realm corresponds to the academic terrain of humanities, the second to the academic terrain of the natural sciences, and the third to the academic terrain of the social sciences. Hence, the broad grouping of the nature-society theories into: humanities-based theories, natural sciences-based theories and social-sciences-based theories. Within each grouping, a variety of theories originating in particular fields (or, disciplines) of each academic terrain are presented although not all of them are discussed at length. This classification is not unambiguous because several theories attempt to incorporate all three of Sack's realms "but even these draw their primary rationale and model of human behavior from one realm, tending to make the others derivative" (Sack 1990, 661). This is why theories in one group can be classified under another group especially theories which are interdisciplinary in their conception. Table 3.1d presents in greater detail particular theories included within each one of these three groups.

Before presenting these theories, it is worth remembering that the concern with the total system dates back to Malthus's concern with the relationship between land availability (in quality and quantity) and population growth in late 18th century (Malthus 1970; original in 1798). In 1864, George Perkins Marsh, a prescient man, followed with his seminal "Man and Nature" essay where he described concisely and comprehensively how people use and modify land to serve various purposes altering, thus, the environment (Marsh 1967). The impact of these analyses is evident in the theories that developed in this tradition and fostered lively debates in the 1960s and 1970s when the environmental crisis ascended to the scientific and the political arena.

3.5.1. *Humanities-Based Theories*

Contributions to the analysis of how people relate to nature and the environment originate mainly in the disciplines of history, anthropology and psychology within the broader academic terrain of the Humanities Studies. The terms "environmental history", "environmental (and/or cultural) anthropology", and "environmental psychology" usually denote the particular subdisciplines specializing in the above theme. The following discussion is a selective presentation of characteristic approaches from the broad collection of contributions in each of the three sub-disciplines.

Environmental history is concerned with recording, presenting, and analyzing the socio-economic, political, institutional, and cultural forces that have shaped and transformed particular environments spanning all spatial scales from the local to the global (see, for example, the contributions in Turner *et al.* 1990). A theory advanced to provide a broad explanatory framework for the historical changes in the uses of land under the influence of the above-mentioned forces is the *frontier thesis* (Richards 1990) which is applicable to all scales but it seems more suitable to the larger regional and global scales.

The *frontier* is defined as "a zone of varying width that refers either to the political division between two countries or to the division between the settled and the unsettled parts of a country" (Johnston *et al.* 1994, 208). Richards (1990) describes the frontier as "that period of time and area in which a peripheral region is created or extended" (Richards 1990, 165) and notes that "partly stimulated by external forces, partly generated by internal energies, one society after another has undergone frontier expansion" (Richards 1990, 166). The *frontier thesis* was advanced originally by F.J. Turner (Turner 1894 cited in Johnston *et al.* 1994, 208) to explain American development since the beginnings of the European settlement of the United States. He described frontier expansion as "a series of 'settlement waves' which corresponded to identifiable 'evolutionary stages"' (Johnston *et al.* 1994, 208). The geographer Ratzel has described this thesis as an organic theory as it combines concepts of biology and geography treating the "struggle for space" as a requirement of the "social organism" (Johnston *et al.* 1994, 208). According to Meinig, Turner's thesis contained four embryonic concepts: areal differentiation, connectivity, cultural succession, and spatial interaction (Meinig 1960 cited in Johnston *et al.* 1994, 208). The thesis received heavy criticism but "few modern studies of the frontier can ignore Turner's seminal contribution" (Johnston *et al.* 1994, 209).

Richards (1990) states that "frontier expansion generally followed irregular, rather than smooth, patterns of spatial diffusion. In each frontier episode, frontierspeople followed river valleys, grassland corridors, or other natural corridors to reach desirable lands, which they exploited first" (Richards 1990, 166). The process involves an initial penetration to an unsettled area followed by the creation of secondary and tertiary frontier zones. Land conversion and resource use is more intense in these later zones. Important physical and economic impacts ensue expanding settlement frontiers, such as more traffic and more operations on land from earth-moving and tilling to intensive cultivation and big irrigation, transportation and other projects. The *land use intensity* is measured on the basis of the scale, frequency and duration of these impacts. But Richards (1990) contends that the true measure of use intensity in frontiers land is not physical impact or economic product but "the extent to which land is controlled and managed" (Richards 1990, 166).

Spatial scale is important in delineating the opening and closing of frontiers as well as in specifying the particular social forces which lie behind frontier expansion and the associated consumption of natural resources and uses of the land. Richards (1990) indicates an important "complex set of interlinked causes: state power and organizational momentum, expanding economic demand expressed through increasingly integrated world markets, and population growth… technological advance facilitates but does not drive transformations in the land" (Richards 1990, 166). He adds an important note also: "to identify the dominant force for a particular episode or case study is often difficult. To assign primacy on a global scale is extremely speculative" (Richards 1990, 166).

Lastly, Richards (1990) emphasizes the power of an imposed cultural artifact – "territoriality" – which in its various expressions has contributed and is contributing to the struggle to dominate the land. According to Sack (1986), "territoriality is intimately related to how people use the land, how they organize themselves in space, and how they give meaning to place" (Sack 1986, 2 cited in Richards 1990, 175). Richards (1990) adds: "Sack points out that modern societies have employed territoriality to further centralization, hierarchy, and bureaucracy; to mold human activities and to reify dominant power. Perhaps most significant for our purposes, territoriality can be used to empty space, to demarcate an area that is unused and capable of being filled. In other words, the use to which land is devoted can be altered and rearranged. The new world order made frequent use of the idea of a 'socially emptiable place' (Sack 1986, 33). Whatever the numbers of human and animal inhabitants, or the vegetation, soils, and natural features, the new rulers could define an area as devoid of socially valuable use. This cleared space was then available for a new, more productive use" (Richards 1990, 175). In this context, the definition of landed property and terms of ownership by the state has been instrumental in the changes of the uses of land as the demand for its various services changed (Richards 1990).

In the field of environmental/cultural anthropology, theoretical contributions to the study of man-nature and/or nature-society relationship abound and only a few are mentioned as indicative of the direction of analysis pursued. Their emphasis is mostly on how the human mind receives, structures, and interprets the real world and, consequently, acts according to these mental schemata. Levi-Strauss's theory of "**structuralism**" is "a complex set of ideas of how the mind creates a world of nature and of social relations" (Sack 1990, 663). Levi-Strauss contends that people form mental categories of extreme oppositions and apply them through unconscious mental processes in their attempt to construe reality and relate to the world. Levi-Strauss uses the device of myths (in preliterate societies mostly) to demonstrate his theory (Sack 1990).

In the same vein, the more contemporary contributions of geographers such as Tuan and Graber (Tuan 1971, Graber 1976 cited in Sack 1990, 663) employ the "interpretation of the world through opposing mental categories" thesis to analyze the modern conception of wilderness. In their view, "in order to reduce oppositions, we create intermediate categories and places such as suburbia, city parks, and zoos" (Sack 1990, 663). Finally, contributions in the area of cognitive anthropology are important to the study of the relationship between people and the environment. Cognition is considered as an important "mediating mechanism between the individual and the environment, but the psychological view tends to stress *knowledge* of the environment while the anthropological view takes the position that cognitive processes are concerned with making the world *meaningful* and that there are different ways in which meaning can be given to the world....... A basic premise of cognitive anthropology is that different cultures classify the world differently by the use of different taxonomies and this may be linked to the relative importance attached to the elements, .. Ordering schemas are used to shape the built environment (e.g. ideal cities, ideal landscapes, cosmological schemas) and ordering systems are in turn imposed on environments as experienced" (Rapoport 1976, 221). The emphasis of these approaches is on symbols, cultural schemata, preferences, and culturally-determined cognitive processes all of which affect the ways with which people represent, communicate with, and use space, the environment, and, consequently, land.

Finally, environmental psychology offers alternative theoretical frameworks to analyze people's relationship to the environment and their subsequent mode of use of the environment. These, too, center on environmental cognition but they stress the ways by which psychological drives shape people's perceptions, spatial images, mental maps, and knowledge of the environment and how these, in their turn, impact on people's behavior and use of the environment. Seminal contributions include Boulding's (1956) *The Image: Knowledge in Life and Society* and Kevin Lynch's (1960) *The Image of the City*. Other important contributors include D. Lowenthal, D. Stea, R. Downs, R. Golledge, G. Moore, E.T. Hall, T.F. Saarinen, P. Gould, R. White to mention but a few.

The selective presentation of humanities-based theories reveals a wealth of theoretical approaches and outlooks which deal with the nature-society relationship at various spatial levels from the global to the very local and the personal level. The related applications cover past and present time periods and employ methods (e.g. ethnographic analysis and related qualitative techniques) which uncover the dynamics and mechanisms of change of the relationship studied. They concern mostly the deeper social and personal determinants of land use change although in most of them the direct connection to land use and its change is not always made. They adopt non-positivist**epistemological positions** in general which emphasize the culture-specific and variable nature of the nature-society relationship in contrast to most theories in the two previous **theorization tradition** which rely on a standard and rigid model of man which applies across all spatio-temporal settings. Depending on the level of analysis, they can be used to inform the analysis of land use change and offer alternative explanatory frameworks in addition to those deriving from the economics and sociological theorization traditions.

3.5.2. *Natural Sciences-Based Theories*

The relationships between the four components of the **total system** have been examined also from the perspective of the natural sciences and more specifically, within biology and ecology. Important contributions come also from geography, a discipline with a traditional focus on holistic approaches to the interactions of people with their bio-physical environment. The common feature of the theories of this group is that they treat the environment, land and land use concretely and comprehensively – as material entities with characteristic properties and particular ways of relating to one another and to the socio-economic forces that impinge on them. The list of theories is long and the following discussion will focus only on a small selection of them.

Within the field of the biological sciences, theories originating in neurophysiology and sociobiology take an extreme position that reduces human behavior to biological, chemical and physical processes. Borrowing ideas from the natural sciences, they claim that mental and social processes are affected by chemical states, biological instincts, or drives. They go as far as to assert that "social organizations, social hierarchies, territorial behavior and the like can be structured by our biological instincts and drives that evolved within the 'pristine environments' of our ancestors" (Sack 1990, 664). Similar theoretical claims have been advanced by other disciplines of the natural sciences (the earth sciences) which state that the climate and the entire biosphere are the driving mechanisms that affect human behavior (**physiographic determinism**). The most comprehensive theory has been the "classical doctrine of elements and humours". This related the elements of air, water, earth and fire with the humors of phlegm, bile, black bile and blood to link natural forces that originated in the stars and planets at one end with the mental and social behavior at the other (Sack 1990, 664).

The most widely publicized and well known of those theories, however, is *environmental determinism* – "the doctrine that human activities are controlled by the environment" (Johnston *et al.* 1994, 162). "(Environmental determinism) explains cultural development and, indirectly, environmental transformation, in terms of the physical geography of a place or a region" (Turner 1990, 657). Its roots go back to ancient Greek scientists such as Hippocrates and philosophers like Aristotle (Kanellopoulos 1985). The former linked the characteristics of people in certain places to the influence of environmental factors while the latter believed that the world's climatic zones (frigid, temperate and torrid) determined global habitability. Environmental determinism was publicized during the Enlightenment period owing to Montesquieu's *The Spirit of the Laws* and it flourished in the pre-Darwinian period as well as after it when human culture was construed through categories of the natural law (Johnston *et al.* 1994, 162). Although it has been largely abandoned after the mid-20th century, elements of this theory can be found in several nature-society theories which give primacy to environmental variables in explaining human development (Turner 1990). Ian McHarg's celebrated *Design with Nature* and the ecological method to land use and landscape planning he advocated is an example of environmental determinism's influence in more recent times (McHarg 1969). Several other studies of environmental and land use changes reflect or adopt outright an environmental deterministic stance considering that land use patterns are determined solely – at least on large, regional scales – by natural factors (climate, geology and soils) primarily (see, for example, Yassoglou 1987).

More balanced theoretical frameworks for the study of nature-society relationship are offered by ecologically sensitive approaches known as "*human ecology*" or "*cultural ecology*". The first of these terms should not be confused with the Chicago School of human ecology which concerns sociological approaches to the study of urban and regional spatial structure and its change (discussed in section 3.4.1A of this chapter). To avoid confusion, the rest of this discussion will use the term "cultural-human ecology" to refer to the ecologically-oriented approaches. These approaches draw upon ecology and systems theories to provide comprehensive descriptions of the complex interactions between people and their bio-physical environment (Sack 1990, Butzer 1990); or, to study "the adaptive processes by which human societies and cultures adjust through subsistence patterns to the specific parameters of their local habitat" (Johnston *et al.* 1994, 111). As Sack (1990) observes "the primary, though by no means only, device that ecologists employ to connect human and natural systems is, to put it positively, to focus on characteristics that both systems possess, or to put it slightly negatively, to reduce human actions to physical ones" (Sack 1990, 665). Butzer (1990) notes that cultural-human ecology has attracted contributions from sociologists, anthropologists and geographers that make it an interdisciplinary field of study of the nature-society relationship. Important in most studies is the concept of 'adaptation' – "an on-going process of adjustment as people cope with internal and external impulses, in the short or long term. The basic function of adaptation is to maintain a balance between population, resources and productivity" (Butzer 1990, 696).

Julian Steward is considered the pioneer of the cultural-human ecological approach with his "Theory of Cultural Change" (Stewart 1955 cited in Merchant 1990, 674). His studies examined the ways by which relatively isolated traditional societies adapted to such environmental factors as topography, climate and physical resources. However, they are of limited value in the broader context of the study of land use change as the physical and human systems of these societies were characterized by relatively long-term stability (Merchant 1990).

Rappaport (1968) drawing upon structural-**functionalist** and ecological concepts proposed "an ecosystem approach that related culture to abiotic and biotic components of the environment as a spatially bounded unit" (Merchant 1990, 674). Ellen (1982) proposed a materialist-ecological approach to overcome the limitations of past cultural ecological approaches. In his scheme, flows of energy draw together natural and human processes and link organisms within an ecosystem according to the **laws of thermodynamics** and flows of materials through biogeochemical cycles. Technological progress, on the one hand, increases the potential impacts of humans on the environment but, on the other, allows population and social formations to reproduce themselves. Ecological reproduction results from species and population reproduction whereas economic reproduction creates value in order to reproduce social and economic formations (Merchant 1990, 674).

Rambo (1983 cited in Merchant 1990, 674-675) uses general **systems theory** to propose a unified model of human ecology as the interaction of a social and an environmental system which mutually exchange energy, materials and information. Each system is open to external influences through diffusion, migration and colonization. Bennett (1976 cited in Merchant 1990, 675) attempting to improve on Rambo's model offers an energy-output model in which historical changes in the nature-society relationships are the result of decisions to increase energy and goods (Merchant 1990, 675).

Merchant (1990) summarizes the inherent limitations of the above cultural-ecological theories to provide an integrative theory of environmental transformation as follows: "First, these approaches do not adequately specify the processes of social change that lead to environmental impacts, and do not account for the power relations that both maintain class structures and lead to social struggles to break them. Second, ...they do not account for the inequalities created by class relations, inequalities that do not give all people within a system similar choices, including environmental ones. Third, (they) assume the unity and structure of systems, perhaps not recognizing that, like the platonic form, a system is nothing more than a conceptual framework with which we interpret the world. Fourth, the use of structuralism-functionalism . . . .leads to approaches that are a-historical and do not account for the fact that environmental transformations are the product of decisions made in specific social systems and locational settings" (Merchant 1990, 675-676).

Although difficult to classify unambiguously in one of the three main groups of nature-society theories, the theories of *Berkeley School* appear most appropriate to be discussed here. This collective term refers to "the group of geographers influenced by Carl Sauer during his long years in the Department of Geography at the University of California, Berkeley" (Johnston *et al.* 1994, 33). Although no particular common theoretical or methodological doctrine united these scholars, they "shared Sauer's interests in landscape creation as a representation of culture and followed his emphasis on studies of the evolution of the cultural landscape" (Johnston *et al.* 1994, 33). Sauer's approach – described in his classic essay "The morphology of landscape" (Sauer 1996; first appeared in 1925) – "involved appreciation of the 'natural environment', reconstruction of past landscapes, and processes of change through the spread (diffusion) of human agency" (Johnston *et al.* 1994, 33).

The selection of natural sciences-based theories briefly presented above adopt definitions of land and land use which address their material and intrinsic characteristics and attributes and they get into the physical processes which account for the observed transformations. However, although these theories address the important linkages between the use of land to serve human needs and purposes and the environment, they tend to place excessive emphasis on the environmental factors ignoring or assigning a secondary role to a host of other factors which condition the use of land such as institutional, political, and economic factors. Like the humanities-based approaches, they span the whole spatial spectrum from the global to the local.

Their relevance to the analysis of land use change has to be explored further as they may be more applicable to particular societies and historical periods than in others. In addition, further research may try to make more explicit the interactions and connections between the natural factors emphasized by these theories and the social and economic factors proposed by other theories to provide for truly holistic analyses of land use change.

3.5.3. *Social Sciences-based theories*

This last group of theories is the most "open" of all three groups considered in the nature-society theorization tradition as, first, the Social Sciences may be defined in both a narrow and a broad sense and, second, several of the theories presented before, especially those originating in the Humanities can be included under the Social Sciences heading also. Moreover, the other two **theorization traditions** – the urban and regional economics and the Sociological traditions – are sources of theoretical approaches which are Social Sciences-based theories in a broad sense dealing with the nature-society relationship; as for example, theories from the fields of Environmental Economics, Ecological Economics, and Environmental Politics. The reasons for this breadth of coverage cannot be analyzed here. Suffice it to mention Sack (1990) who notes that in the realm of social relations the forces which control human actions are situated in social, economic and political structures. Hence, theories of the power of bureaucracy (Weber), of market economies (neoclassical economics) and of economic class (Marx) are all relevant in the explanation of how "social relations ... affect social actions and ... propel our transformations of nature" (Sack 1990, 661). Therefore, this section makes special reference to a more restricted set of theories; those originating in Sociology and those characterized by a multi- or interdisciplinary orientation combining concepts and schemata of more than one scientific fields. Environmental Sociology is the particular subfield of Sociology devoted to the study of nature-society interactions (see, for example, Reid 1962). The following discussion is a selective presentation of such approaches.

In the field of Environmental Sociology, Sack (1990) advances a theory of *the mass-consumption culture* to explain social attitudes and values towards nature as shaped by everyday experience in modern societies dominated by the culture of mass-consumption. He bases his theory on a critique of other social theories which underestimate the importance of reflexivity and free will of individuals and place their explanatory schemata within broader structures governing/constraining human behavior (e.g. markets, institutions, social formations) over which people seem to have very little or no control. Giving primacy to reflexivity and human agency, he argues that mass consumption – "divorced as it is in everyday life from the nature-production matrix" (Turner 1990, 656) – creates "a world virtually divorced from the bio-sphere in which it is situated" (Sack 1990, 669). This theory of the culture of mass-consumption provides the framework for explaining why western people have been separated from nature and behave towards it accordingly.

Merchant (1990) adopts a more comprehensive, historical approach which focuses on the significance of social relations of production, reproduction and gender to explain human-environment transformations. She advances the notion of *ecological revolutions* drawing analogies to Kuhn's paradigm of scientific revolutions and paralleling them to Marx's theory of economic revolutions. In Marx's view, "economic revolutions take place when the forces of production conflict with the relations of production.... Periods of social transformations are explained as revolutions in modes of production" (Merchant 1990, 677). By analogy, "*ecological revolutions* can be characterized as fundamental changes in human-environment relations in large part generated by social changes" (Merchant 1990, 677). "In an ecological revolution a number of external introductions or internal 'contradictions' accumulate in a long-accepted 'mode' of interaction between a society and its environment. A period of ecological revolution ensues in which new nature-society relations emerge... In capitalist ecological revolutions internal contradictions (e.g. between land use and inheritance patterns), when combined with market incentives, may propel a society toward the industrial-capitalist mode of interaction" (Merchant 1990, 673-674). In addition to the mode of interaction, Merchant brings to the analysis the issues of reproduction and gender as well as the gender-reproduction relationships. The interactions between production, reproduction and gender are used to explain changing human conditions which give rise to environmental transformations in particular contexts.

All theories in the nature-society **theorization tradition** are basically multi-disciplinary theories as they employ theoretical and analytical constructs and methodologies drawn from more than one discipline to analyze the nature-society relationship and, at times, particular land use-society interactions. A broader family of theories which do not have a distinct name or are not built on explicit theoretical arguments are called here *multidisciplinary* and, although they apply to various spatial levels, they are relevant at larger scales mostly. Most of them employ, in various degrees and under various guises, the notion of "ecological equilibrium" (Coccossis 1991, 441). According to this perspective, a region has four sets of factors – population, resources, technology and institutions that are constantly in a state of dynamic equilibrium. Changes in the spatial structure of the region are the result of changes in the equilibrium between these factors. Extending the argument to the land use change theme, Cocossis (1991) suggests that "in this conceptual framework, changes in land use are the result of changes in the size and the distribution of population, technological innovation and economic restructuring, social organization and policy" (p. 442). He mentions several applications of this notion since the beginnings of the twentieth century to the study of the relationship between the size and spatial distribution of population and social organization (Gras 1922), resources (McNeil 1976), technological change (Simon 1957, Rashevksy 1969) (Coccossis 1991, 442).

Elements of this notion can be traced in several of the approaches that have appeared since the 1970s addressing the issue of the environmental impacts of human activities. Originating in the writings of biologist P. Ehrlich (1968), the shorthand expression I=PAT has been used to operationalize the relationship between environmental impact (I) and its principal determinants: population (P), affluence (A), and technology (T). Various analysts, including Ehrlich and Ehrlich (1990), have used this expression to assess the global level impacts of changes in these three determinants (e.g. Commoner 1972, Harrison 1992). The widely publicized modeling exercises of the Club of Rome and Forrester's world dynamic models similarly have focused on the interactions between population, production, pollution, and resources (Forrester 1971; Meadows *et al.* 1972). When environmental impact is specified as *land use impact*, the PAT expression offers a guide for exploring the land use implications of changes in population, affluence, technology and, consequently, resource use. Several studies have been conducted under this umbrella theoretical structure (not a theory *per se*, though) (for collections of such studies, see, for example, Turner *et al.* 1990, Brouwer *et al.* 1991, Lutz, 1994, Meyer and Turner 1994, Heilig, 1996). In the same spirit, Manning (1988, 1991) has proposed an more detailed analytical framework which considers the interactions among the biophysical and socio-economic determinants of land use and land use change.

The diversity of this last group of Social Sciences-based theories makes difficult a general evaluation. Sack's thesis of the mass-consumption culture approaches the nature-society relationship from the sociological perspective of individual consumers and their behavior in modern societies. It requires further elaboration and integration with other aspects and explanations of this relationship to make it a useful guide to the analysis of the particular ways by which land use changes under the influence of the culture of mass consumption, among other driving forces. Merchant's thesis of ecological revolutions adopts a materialist-historical position which bears some similarities with Massey's (1984) theory of the spatial divisions of labor. Again, this thesis requires further analysis and integration with elements of related and other theories to provide better guidance for the analysis of land use change. Finally, the *multidisciplinary* family of theories represent mostly loose collections of theoretical propositions informed by the urban and regional economics and the sociological theorization traditions as well as by the theories of the nature-society theorization tradition. They are mostly descriptive frameworks and their value lies in considering the role of resources and environmental constraints as limiting factors on development and, consequently, on land use. But they do not delve into the mechanisms of change and the dynamic interactions between these natural constraints and the socio-economic and institutional regimes governing their utilization. To prove useful as explanatory devices of land use change they, too, need to be synthesized with elements from other theories to produce explicit theoretical propositions of the processes by which and the conditions under which land use is transformed from one type to the other at particular spatial levels and within specific time frames and historical contexts.

3.6. A Summary Evaluation of Theories of Land Use Change

This chapter presented and evaluated briefly a broad variety of theories which bear on the subject of land use change either directly and explicitly or indirectly and implicitly. Each theory has its particular merits and shortcomings some of which were outlined in the previous section; the references provided herein contain more detailed analyses for the interested reader. What is important for the present purposes is that each theory brings certain new elements, sheds light from its particular angle on the intricate web of relationships between land use change and its drivers. Each **theorization tradition** specializes more or less on a given spatial and temporal level although it is difficult to say which is the dominant level for each one of them. It seems, however, that the lower the level of reference the more elaborate is the theorizing and more concrete and realistic accounts of the context and the mechanisms of change are given. At higher levels, theorizing is abstract and it may be hard to get from the theory to the real-world counterparts of the context and mechanisms of change.

This section is devoted to a summary evaluation of these theories with the aim to address three larger questions: (a) how well the theories reviewed serve the purpose of providing a comprehensive account of land use change and its determinants at various spatial and temporal levels, (b) what should be done at the level of theory development to provide support for operational model building and to inform decision and policy making, and (c) whether an all-encompassing theory of land use change is desirable and feasible. In the following, the alternative ways by which land, land use, land use change and the drivers or determinants of change have been conceptualized and expressed in the theories reviewed are summarized first. Particular attention is being paid to the issue of explanation – which theories offer valid explanations (and not simply descriptions) of the dynamics of land use change – as well as to the issue of the theories being suitable for supporting operational models of land use change. Lastly, the question of the desirability and feasibility of a general theory of land use change is addressed.

The theories in which land and land use are treated *explicitly* – as areas of the earth's surface with particular, spatially variable properties – are few compared to the large number of theoretical schemata available of which only a limited selection has been reviewed here. The second millennium is over and still von Thunen's and Alonso's remain the most land use-explicit, concise theories/models. This last point is emphasized as there are numerous micro-level studies of land use change – especially in the nature-society **theorization tradition** – which, however, cannot claim the status of theory. But even the two theories mentioned have limitations as they do not (or, cannot) cover the variety of land use types and patterns as well as the diversity of drivers of land use change. This is characteristic of the majority of theories where land use is treated explicitly, i.e. they refer directly only to particular types of land use – mostly residential, industrial, commercial, agricultural, forestry – and not to the full array of existing and potential uses of land. Those which are not the direct object of land use analysis are treated as an amorphous group of uses although the dynamics of change may raise insignificant uses to importance under changing socio-economic circumstances (as it is the case, for example, with tourism development). A large number of theories also – from the urban and regional economics and the sociological theorization traditions – concentrate on the urban level of analysis in advanced capitalist (free market) societies mostly, the latter feature explaining also the particular modes of theorizing. Hence, the land use types considered derive from the nature of the spatial context to which the theories refer – e.g. central city, low-income, suburban, high-income areas, etc. The level of detail used to conceptualize land and land use is influenced significantly also by the spatial level of analysis. Theories referring to higher spatial levels (e.g. the macro-economic and similar approaches) treat land more abstractly than theories concerned with lower spatial levels. These latter theories focus on the behavior of the individual land user where it makes more sense to treat the area of land used for a certain activity explicitly and with direct reference to its particular characteristics. Finally, a considerable number of theories in all three theorization traditions consider land abstractly – even when they focus on individual behavior – as their interest focuses on particular determinants and/or processes of land use change. The point is, however, that a realistic and holistic analysis of land use and its change necessitates treatment of both land use and its determinants at the same level of definitional detail.

It is interesting to note also the small number of theories which specify the particular *patterns of land uses* which result in the process of change. In fact, only the earlier theories – von Thunen's, Alonso's, (sociological) human ecology, environmental determinism – treat this aspect of land use change although under very restrictive assumptions. Several reasons explain this fact. A number of theorization traditions are associated with non-spatial disciplines (e.g. economics, sociology, political science). The purpose and mode of theorizing is not oriented towards producing or indicating the exact spatial forms which result. This is reinforced also by the variability and indeterminacy of the drivers of land use change considered. Characteristically, only descriptive and normative theories deal with spatial patterns. Explanatory theories usually are distanced from this issue. This is perhaps an indication of the limits of meaningful theorizing and of human ability (and risk-taking attitude) to predict exact spatial configurations which result from the intricate relationships between the bio-physical and the socio-economic drivers of land use change.

The *drivers or determinants of land use change* which are accounted for by the theories reviewed here cover the whole range of bio-physical and socio-economic factors. Naturally, not all theories consider all relevant factors; when they do, they do not assign the same degree of importance to all factors considered. In fact, as the preceding presentation shows, the urban and regional economics **theorization tradition** is almost exclusively concerned with the economic determinants of land use change while the sociological tradition with the economic and the social in varying degrees of emphasis between the two. The nature-society theorization tradition provides more comprehensive accounts of a variety of drivers although, again, the relative emphasis depends on the chosen orientation of the particular theoretical framework. The level of detail in which the various drivers are represented depends on the spatial level of reference the theory adopts as well as on the purpose of the analysis. Micro-level, descriptive theories tend to be more specific as to the exact conceptual (and operational) definitions of the drivers taken into account than macro-level theories. It is noted, however, that definitional detail does not imply also definitional completeness. Several theories specify only certain aspects of the drivers (e.g. income as a measure of consumer utility/welfare, price of land as a measure of its attractiveness, floorspace as a measure of attractiveness of a retail area) and exclude others potentially (equally or more) important.

Of particular importance to this project are the *mechanisms of land use change* the various theories propose. Two broad groups of theories can be discerned in this respect, at least. The first group comprises static theories of land use which assume that the land use system reaches an equilibrium position at some point in time when certain factors change. But as regards the explication of the real mechanisms and processes of change, they adopt a "black box" approach where changes in some determinants enter the box and land use change comes out of the box. In this case, the theories simply mention what changes (e.g. demand, product prices, income, population, preferences) and then leave it to the user to reason the "why" of these changes and how they changes produce particular land use results. The second group of theories do not deal directly with land use change but with changes in its determinants. Hence, the question of the mechanism of land use change is not addressed by definition! It seems as if it is left to the user of the theory to explain the specific mechanism of land use change in the particular context of the theory's application. Naturally, this is a matter of spatial level of reference; at higher spatial levels it may be neither feasible nor meaningful to attempt to specify exact mechanisms of change as this change occurs at the lower spatial levels where the users of land – the direct decision making units – operate! Some theories are deceiving also as they appear to address the issue of the mechanisms of change when, in reality, they simply *describe* how change occurs (e.g. human ecology). Explanation of change is telling the land use change story; in other words, it is a matter of reasoning about the processes that lead from changes at the level of the drivers of change, through the proximate sources of change (see, Chapter 1) down to the level of the particular spatial manifestations of their effects.

In general, very few theories explain land use change. Some offer explanations for particular types of change such as industrialization, urbanization, suburbanization, deforestation although the "explanations" they offer may need proper qualification; i.e. whether they provide essential explanation or superficial explanation of observed patterns and regularities. There are several reasons for this explanatory poverty of the theories. Firstly, as mentioned before, many theories do not focus on land use change *per se*; rather they deal with changes of its determinants. Hence, it is not within their prescribed goals to offer the particular type of explanation of interest here; i.e. to explain how changes in the determinants produce particular land use changes. Secondly, many theories are functionalist-structuralist which means that they do not allow a variety of historical, institutional, political, human agency and other deeper factors to enter into the explanatory schemata used (see, for example, Cooke 1983). It seems that agent-based theories which, in one way or another focus on the agents of change – the users of land – as well as on their interdependencies are in a better position to meet the criterion of explanatory power. Such theories include the agent-based theories in the urban and regional economics theorization tradition as well as those theories which adopt historical-**materialist** and realist epistemological perspectives in the sociological and the nature-society theorization traditions (Massey 1984, Sack 1990, Merchant 1990) Third, the descriptive and/or normative focus of most theories, combined with an assumption about system equilibrium, produces static theories mostly which cannot accommodate the dynamics of change which is the quintessence of explanation. This does not mean that dynamic theories have *de facto* explanatory power as this depends on the epistemology they espouse. Several, though not all, theories in the urban and regional economics theorization tradition, for example, are based on a rationalist epistemology which abstracts from experience and transcribes the analysis of the dynamics of change from the real to the mathematical level of analysis. Hence, the explanation of change is in terms of mathematical relationships analyzed and it is critically conditioned by the assumptions made. Finally, the level of analysis plays a critical role also as the actual explanatory mechanisms of change may not operate at the level of reference of a given theory. In addition, explanation may involve factors and processes that operate at various spatial levels within the same or different time scales and frames in specific spatial contexts. For example, the influence of climatic factors on land use change requires a time frame of centuries at the level of **bioclimatic zones** (large regional scale) while the influence of product price changes or of policy instruments can be examined meaningfully within time frames of years and at lower spatial levels. Theories which account for this spatio-temporal complexity do not seems to exist yet.

A related question is whether the theories reviewed here have found operational applications; i.e. whether operational models using real world data have been built based on these theories. The question is considered only for those theories which deal explicitly with land use. To this author's knowledge Alonso's theory has found an operational expression (the Herbert-Stevens model to be described in Chapter 4). Von Thunen's theory has simply been verified in several contexts and at various scales (Grigg 1995) but this is not considered an operational application of the theory. Finally, spatial equilibrium theory (as well as its dynamic versions) is being used as the broad theoretical framework in the development of operational integrated models of land use change which are presented in Chapter 4. It seems that in their present form, several theories cannot filter down to models of land use change which can be used to analyze the impacts of changes in its various drivers. Among the reasons which explain this situation, the following appear to be influential: (1) many theories are cast in abstract terms and operationalization is difficult, (2) the epistemological orientation of several theories is not congruent with formal modeling, (3) modelers do not show an interest in identifying models with particular theories although theoretical assumptions underlie all models built. Most frequently, **positivist** and functionalist theories underlie models of urban and regional spatial structure and change as positivism and functionalism are congruent with the idea of modeling (Sayer 1976, 1979, 1984)

The last, big question is whether a general theory of land use change is desirable and possible. The two issues are interdependent although either question may be considered separately. The desirability question should be addressed first. The answer depends critically on the epistemological perspective adopted. Epistemological perspectives like **idealism**, **postmodernism**, **realism** , etc. which either emphasize the unique and the particular or stress the significance of the context, may never ask this question. In addition, a look at the diversity of real world situations, although pointing to broad patterns of relationships and regularities over space and time, casts doubt on the desirability of a general theory of land use change as this will inevitably abstract exactly over those details which may be critical in particular contexts and circumstances.

At the same time, the possibility of such a theory seems thin. As Turner (1990) observes for the case of a theory of global environmental transformation (change) "our transformation of nature stems from complex mixes of behavioral and structural factors associated with the prevailing character of the scale and the kind of demand, technological capacity, social relations affecting demand and capacity and the nature of the environment in question. *Context matters*. . . ." Understanding transformation. . . from the view of human behavior, requires multiple forms of analysis, and although practitioners of the subject may be on the verge of identifying the more useful analytical forms by scale (both of space and of complexity), it is doubtful that a relatively simple explanation of "why we transform the environment the way we do is forthcoming" (Turner 1990, 657). Similarly, Kates *et al.* (1990) add: "a generally accepted theory of human-environment relationships has not been developed, but its rudiments are emerging. Such a theory . . . . needs to conceptualize the relations among driving forces of human-induced change, their mitigating processes and activities, and human behavior and organization" (Kates *et al.* 1990, 13). In addition, as regards the issue of dynamics, Batty's (1976) observation summarizes the crux of the problem: "the status of theory in urban and geographic systems with regard to time is almost non-existent. . . .. There are severe problems in trying to develop dynamic theory: . . . the observational dilemma and . . . .data." (Batty 1976, 296).

Evidently, the above statements apply equally well to the issue of the possibility of a general theory of land use change. The analysis of concrete cases of land use change can be conducted meaningfully at spatial and temporal levels which are dictated by the particular historical and geographical circumstances. At these particular spatio-temporal levels, diverse factors and processes of change come into play some of which may be broadly derived from related theories while some others are context-specific and can be elicited from a thorough analysis of the case at hand. Hence, it appears more sensible to use a synthesis of theories rather than rely on a single theoretical schema which will inevitably miss some dimensions of the case under study or will be overly complex to be easily understood and useful. To achieve this synthesis successfully, however, it is necessary to examine critically which theories are suitable for which spatio-temporal level.

On this latter point, many of the theories reviewed here are found wanting as they do not make clear the spatio-temporal levels to which they relate best or they use designations which are abstract and can be construed variously. For example, the designations “urban” and “regional” are not clear as, according to Cooke (1983), “(they) reflect a particular, spatially-dominated way of thinking about processes that are not themselves primarily spatial but social (Anderson 1975, Massey 1978)” (Cooke 1983, 132). Similarly, from an applications-oriented point of view, Jongman (1997) draws attention to the fact that the designation “national” is not spatially unambiguous if one compares the national level of, e.g. Spain, Germany, the Netherlands, and Luxembourg. Similar comments apply to the temporal designations short-, medium and long-term. Hence, more concrete spatial and temporal designations are necessary if theories are to make their way towards assisting meaningful and policy-relevant model building.

A last observation should be added. This chapter was necessarily selective in the presentation of theories addressing directly or touching on the issue of land use change. Many more theories may be relevant to the analysis of land use change but these have either not been brought to the fore yet or they have not been adequately synthesized except in particular situations. Such theories include household economics, small holder and peasant behavior, land allocation, technological innovation, fertility change, institutional regimes associated with land resource management, national markets and international accords (LUCC 1999), mobility and migration theories and many more.

Models of Land Use Change

4.1. Introduction

This chapter presents a representative collection of models of land use change. Prior to this presentation, it is necessary, however, to: (a) clarify the meaning or definition of “model” as it will be used in the present context, (b) indicate which models of land use change will be included and which will be excluded, and (c) discuss the need for and the uses of models in the context of the analysis of land use change.

Models are defined variously. They can be considered as the formal representation of some theory of a system of interest (Wilson 1974, 4). More broadly, models can be considered as abstractions, approximations of reality which is achieved though simplification of complex real world relations to the point that they are understandable and analytically manageable. The representation of reality is expressed through the use of symbols. Mathematical techniques are applied for the manipulation of the relationships among the entities represented by these symbols. Hence, the term *symbolic* (or operational or empirical) model is used to distinguish it from other types of representation (e.g. *conceptual* models) (Lonergan and Prudham 1994). It should be noted that the term “model” is used sometimes interchangeably with the term “theory” in the literature both when dealing with theories as defined in the previous chapters and when dealing with mathematical models as defined above. However, the two terms are not equivalent. Theory provides a more general framework of “connected statements used in the process of explanation” while a model is “an idealized and structured representation of the real” (Johnston *et al.* 1994, 385, 622) or “an experimental design based on a theory” (Harris 1966, 258; see also, Romanos 1977, 135). In this author’s opinion, the use of the term “theory” to denote a mathematical, symbolic model is misleading and unsuccessful (despite the fact that the model may be the mathematical expression of theoretical statements and assertions although this is not always the case).

Getting to the second issue, which models of land use change are included in this chapter and which are excluded, a criterion similar to that applied for the selection of theories of land use change is employed. In other words, a broad distinction is drawn between those models which treat land, land use and, more importantly, *land use change explicitly* and *directly* and those where land use and its change are treated in a less indirect and explicit fashion. Certain qualifications as regards this distinction are necessary.

Models which treat land and land use change explicitly are basically those in which the direct object of model building is land use change. In these models, land (and land use) is conceptualized, at a minimum, as “a delineable area of the earth’s terrestrial surface” (see Chapter 1). Land use is characterized by: (a) its areal (stock) and not point character, (b) its relative immobility (compared to a single location), (c) the relative stability of its occupancy (durability), (d) the relatively high cost of change from one type to another (see, for example, Arnott 1986 for the case of residential land use). Hence, models in which land is reduced to a point in space are not considered land use (and change) models here. This is the case with models where supply (production of goods and/or services) or demand (consumption of goods and/or services) have a point representation (for a concise description of the “point” nature of spatial equilibrium analysis, see Takayama and Labys 1986, 171). These models represent more general processes of spatial change – which may imply land use change – as it was the case with theories which did not treat land use explicitly.

As it is the case with all “spatial” models, land use-explicit models employ some type of zonal system for spatial representation. Each zone is characterized by its particular distribution of land use types. The number of zones, however, should be greater than a minimum value to consider the spatial representation offered by the models as satisfactory. This means that models with a two- or three-zone system are extremely crude spatially, at least for the present purposes. The recent trend is, however, towards individual land unit-level models which make the use of a zoning system redundant.

An important distinction which should be clarified is that between “location” and “land use” as frequently they are used interchangeably in the literature or without proper qualifications as to their difference. The distinction is addressed by Beckmann and Thisse (1986) and Andersson and Kuenne (1986), among others, as noted in Chapter 3. Most of the time, “location” refers to a point representation of a (public or private) firm or facility in space. When the term “location” is used to denote “land use” this is usually because the analysis starts from individual location decisions and then proceeds to obtain spatial (location) patterns which represent a market solution, i.e. the result of the aggregate behavior of locators. This contribution refers to models where spatial/areal patterns are used as opposed to point patterns. An additional point about models where space has a point representation is that – at least in the short run – they assume the location of demand and supply points given; hence, they are not models of *change*. Only their dynamic versions may consider potential changes of the spatial distribution of the demand and supply points.

A similar confusion exists frequently in the literature over the terms "spatial pattern" and "spatial structure". The terms may denote either point patterns (e.g. hexagonal, triangular) or areal patterns (however, simplified and abstracted – e.g. disc, etc.) (see, for example, Andersson and Kuenne's (1986) reference to Puu's work). Finally, "market areas" are not considered to constitute necessarily land uses (with the characteristics stated before) although they are expressed as areal entities whose extent is assessed appropriately. The reason is that a market area for a good or service may comprise of several types of land use (e.g. residential, commercial, open space), in general; hence, the exclusion of related models dealing with market areas and their changes.

Models which treat land and land use indirectly or not at all are, in general, these models in which the primary purpose of model building is not modeling of land use change. First, there is a large number of models which deal with changes in some of the determinants of land use (e.g. product or service demand, income, investments, accessibility), they employ a zonal spatial system of reference, and contain a land use component (however crude). In these models, the assessment of changes in land use may be internal or external to the model. These will be considered here although they suffer from incomplete (or, nonexistent) conceptualization of land, land use and its change. Second, there are the "pure" aspatial models which are concerned with broader socio-economic changes that may impinge on, or cause land use change in one way or another –such as the economic base model, the single-region input-output model, economic growth and international trade models, etc. These are not considered here unless they constitute components of larger integrated models.

Based on the above points of clarification, the genre of location models are not considered in this contribution as their emphasis is on particular, *individual* activities locating in space and not on an area of land used for a given purpose by various locators. Indicatively, the following groups of models are excluded: Central Place theoretic models (Christaller, Losch), Weber-problem models, network models, spatial equilibrium models (and related agricultural, energy and mineral models; see, Takayama and Labys 1986). It is noted that spatial equilibrium models may deal with *long-run*, equilibrium land use patterns. However, first, these patterns are not unique (Beckmann and Thisse 1986) and, second, they address a state of equilibrium achieved some time in the future and do not deal with the process of change towards this state; hence, they cannot be considered effectively as land use change models.

From the group of location models, this contribution will consider, however, the residential location models. These models usually start from modeling individual (residential location) choice behavior but then they aggregate over individual choices to derive residential land use patterns (or, segments of the housing market). In addition, residential location models account explicitly for the amount of housing "consumed"; i.e. they incorporate directly the land requirements of residential (housing) demand. Moreover, many of their versions are land use change models as their specification includes explicitly factors causing change such as preferences, prices, mobility. Residential land use has all the features specified for land use above and, among all urban land use types, represents the most land-extensive (and intensive) type.

The interrelated issues of the need for and the uses of models for the analysis of land use change are finally addressed briefly. Land use change is the result of a complex web of interactions between bio-physical and socio-economic forces over space and time. Coping with this complexity for practical purposes, at least – such as policy making and land management for sustainable land use – is impossible without some simplification of the complex relationships to manageable and understandable dimensions. Hence, the need for some model, in general, and for some symbolic model, in particular, which will express operationally the relationships of interest (see, also, Turner *et al.* 1995).

Given the need for models of land use change, the uses of these models are not difficult to derive. A first, general use is to provide *decision support* in various decision and policy making contexts. More specifically, models can be used to *describe* the spatial and temporal relationships between the drivers and the resulting patterns of land uses and their changes. Concise, well specified descriptions grounded on rigorous theory are the cornerstones of understanding and defining the exact problem of land use change decision makers are facing (or, simply, interested in) and acting about it (if necessary). Models of land use change can be used also as *explanatory vehicles* of observed relationships. This is a debatable aspect of model use, however, as it depends on what one means by "explanation". In several operational models explanation is reduced to statistical or mathematical explanation which is not necessarily equivalent to theoretical explanation which attempts to get into the causality of the relationships analyzed and modeled (see, for example, Achen 1982, D. Lee 1973, Sayer 1976, 1979a, 1979b, 1982). Some theories and models have been, in fact, conceived simultaneously in which case the terms "theory" and "model" are used interchangeably to denote a set of theoretical and operational statements about reality (such as von Thunen's and Alonso's theories and models).

Very frequently, in practical situations, models are used to *predict* (or, forecast) future configurations of land use patterns under various scenarios of bio-physical (e.g. climatic) and socio-economic change. Plausible and successful predictions depend, among other things, on the assumptions, specification and theoretical grounding of the models themselves as well as on the scenarios of change from which they borrow the levels (values) of the variables "driving" the prediction. In situations of extremely complex, cloudy and unpredictable futures, simulation is most commonly used in which case theoretical soundness may not be of critical importance.

Models of land use change can play an instrumental role in *impact assessment* of past or future activities in the environmental and/or the socio-economic spheres. This use has two facets; on the one hand, it may concern assessment of qualitative and/or quantitative changes of land use caused by autonomous or planned changes in one or more of its determinants; on the other, it may concern assessment of the environmental and socio-economic impacts of changes in land use (such as land degradation, desertification, food security, health and safety hazards, unemployment, etc.).

Models of land use change have been and are currently being used to *prescribe* "optimum" patterns of land use for sustainable use of land resources and development, in general. In this case, they rest usually on optimization techniques which are used to produce land use configurations which satisfy specified objectives as well as a variety of environmental and socio-economic constraints. One of these constraints is the availability of land. Optimization models are commonly used in planning and management contexts.

Evaluation is a final model use which is associated with the last three uses mentioned – prediction, impact assessment and prescription. Models of land use change for the purposes of evaluation *per se* do not exist as evaluation is an activity which can be performed on any set of alternatives which have to be evaluated on the basis of specific criteria (see, for example, exposition of related methods in Nijkamp and Rietveld 1986, Voogd 1983). Therefore, in the particular case of the analysis of land use change, land use alternatives generated by models (either for the purposes of prediction, impact assessment or prescription) can be evaluated using any of the available evaluation techniques. This topic is not covered in the present contribution. It is noted, however, that the literature refers to particular land use models as evaluation models but this usage is not widely accepted.

The next sections present a selection from the large and variegated pool of land use change models and details certain of them further. In particular, this contribution expands more on models of a more recent origin as past generation models – and especially, the "classics" – are covered by a voluminous literature completely and adequately which will be indicated appropriately. The last section offers a summary account of the main characteristics of the models of land use change presented here.

4.2. Models of Land Use Change – Classification

The literature contains a considerable number and variety of models of land use change where land use and its change are treated explicitly and are the direct object of the modeling exercise. Eight interrelated sources of variation, in a roughly decreasing order of importance, can be discerned in extant models: the purpose for which the model is built, the theory (or, the lack of it) underlying the model (reflecting, in part, the types of the determinants of land use change taken into account), the spatial scale and level of spatial aggregation adopted as well as the degree of "spatial explicitness" of the model, the types of land use considered as principal objects of analysis, the types of land use change processes considered, the treatment of the temporal dimension (which in the case of analysis of change, in general, should be inherent in any project), and the solution techniques used. Hence, there exist:

a. descriptive, explanatory, prescriptive, predictive and impact assessment models
b. micro-economic and macro-economic theoretic models, gravity or spatial interaction theory-based models, integrated models as well as a-theoretic models
c. local, regional, interregional, national and global level models
d. geo-referenced (fully spatially explicit) and non-geo-referenced (incompletely spatially explicit) models
e. urban (mostly residential), agricultural (crop), forest sector models
f. deforestation, urbanization, etc. models
g. static, quasi-static (or, quasi-dynamic) and dynamic models (however counterintuitive static models of *change* may sound)
h. statistical, programming, gravity-type, simulation and integrated models.

It is, thus, evident that, for the purposes of systematic exposition of extant models, it is necessary to adopt a classification scheme as a presentation and discussion vehicle of these models.

The modeling literature suggests several model classification schemes. Wilson (1974) proposes a classification scheme based on the dominant technique used in model building (p. 173-176). Batty (1976) distinguishes between substantive and design criteria for model classification (p.12-15). Issaev *et al.* (1982) mention four possible approaches to model classification: "(a) construction of a list of attributes characterizing aspects of the models, (b) specification of a set of criteria serving as a general evaluation framework, (c) construction of an 'ideal' model as a frame of reference for judging all other models, and (d) cross-comparison of models on the basis of general structure characteristics of these models" (Issaev *et al.* 1982, 4). Stahl (1986) suggests a number of substantive criteria for classifying business location models including issues of theory and model purpose (Stahl 1986, 769-771).

In general, it seems that a general purpose, unambiguous classification scheme of models which can reflect meaningfully the eight sources of variation mentioned previously does not exist for various reasons. The same subject can be modeled at various levels of spatial detail employing corresponding theories (e.g. micro-, macro-economic) as well as within either a static or a dynamic framework. In addition, the same problem a model addresses can be approached by means of more than one modeling techniques and/or model designs. Model specification for the same problem under study may range from very simple to highly sophisticated. Hence, for the present purposes, a decision was made to adopt a classification scheme based on an aggregate, composite criterion, the *modeling tradition* to which a model belongs. This criterion is governed by the dominant feature of model design and solution technique which is more relevant for model building and discriminates among various model types. Moreover, model design is usually associated with particular model purposes, underlying theories and types of land use modeled (and, usually, the discipline where models originate), and spatial and temporal levels of analysis.

Based on this criterion, four main categories of models were distinguished:

a. statistical and econometric models
b. spatial interaction models
c. optimization models, and
d. integrated models.

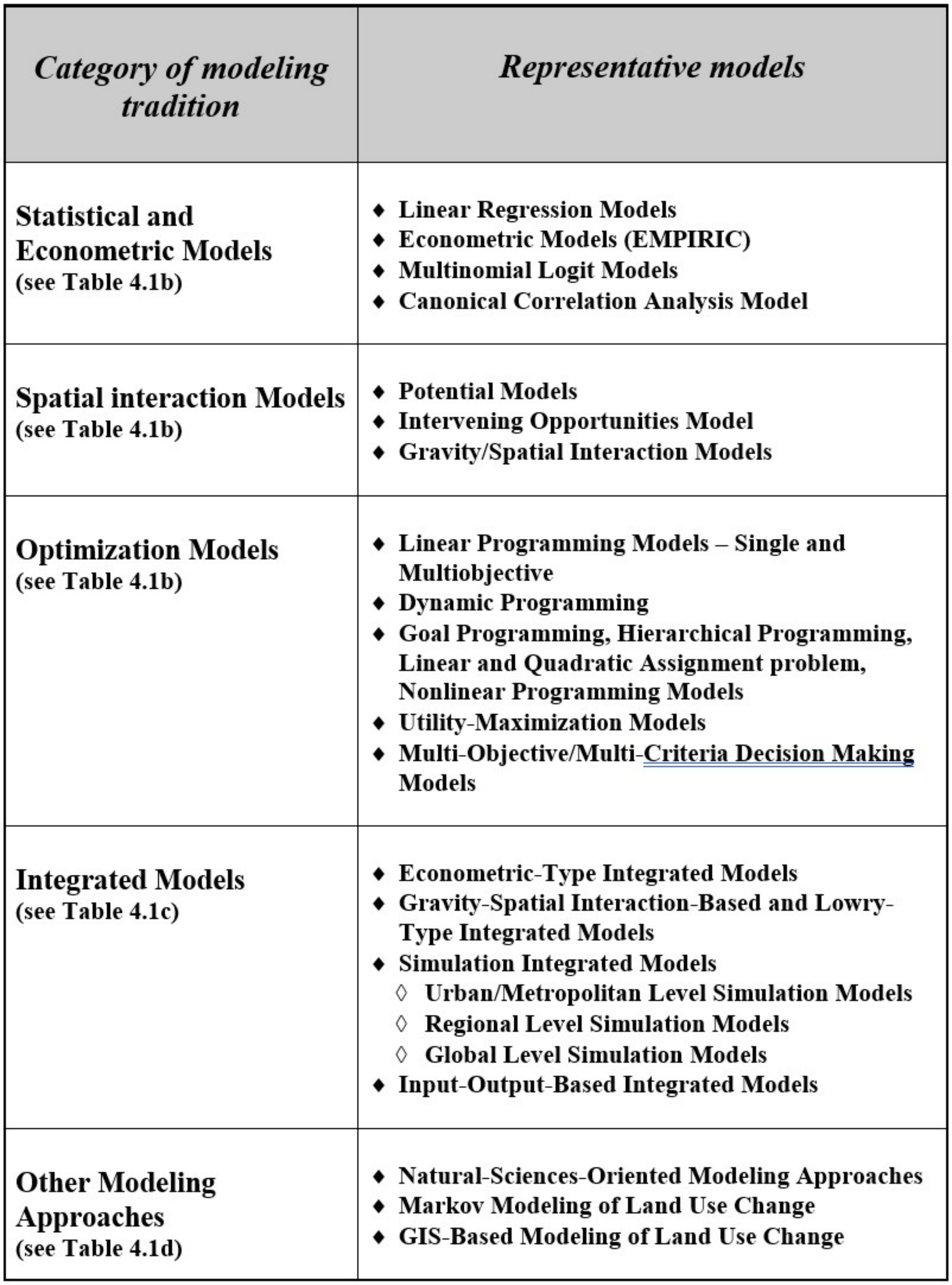
A fifth category has been added which contains those models for which classification is not straightforward as they reflect a variety of modeling traditions. Within each of the above modeling traditions, models are further classified according to criteria particular to this tradition and they are ordered approximately from early to recent models. Because modeling tradition is a composite criterion, it is probable that several models can be classified under more than one category (such as the spatial interaction models which can be considered as simulation or programming models or integrated models which can be classified as simulation models as well).

A selection of models belonging to each modeling tradition is presented and evaluated next based on the following model features/criteria:

- purpose (description, explanation, prediction, prescription, impact assessment)
- aggregation – (a) spatial, (b) sectoral/land use, (c) temporal
- dynamics (static, quasi-static, dynamic) – modeling of change
- underlying theory – conceptualization of the nature of the study area; uses of land (land use types) considered; land use determinants considered as well as their relationships
- model specification/operationalization – spatial representation, types of variables, (including policy variables), operational relationships, solution technique
- data used – spatially-explicit vs. non-spatially explicit, problems of data quality/ availability
- real world application – if any – e.g. for policy support

Table 4.1a contains the principal groups of models which are presented in the following classified according to modeling tradition.

TABLE 4.1a A Classification of Models of Land Use Change



Category of modeling tradition	*Representative models*
Statistical and Econometric Models **(see Table 4.1b)**	◆ **Linear Regression Models** ◆ **Econometric Models (EMPIRIC)** ◆ **Multinomial Logit Models** ◆ **Canonical Correlation Analysis Model**
Spatial interaction Models **(see Table 4.1b)**	◆ **Potential Models** ◆ **Intervening Opportunities Model** ◆ **Gravity/Spatial Interaction Models**
Optimization Models **(see Table 4.1b)**	◆ **Linear Programming Models – Single and Multiobjective** ◆ **Dynamic Programming** ◆ **Goal Programming, Hierarchical Programming, Linear and Quadratic Assignment problem, Nonlinear Programming Models** ◆ **Utility-Maximization Models** ◆ **Multi-Objective/Multi-Criteria Decision Making Models**
Integrated Models **(see Table 4.1c)**	◆ **Econometric-Type Integrated Models** ◆ **Gravity-Spatial Interaction-Based and Lowry-Type Integrated Models** ◆ **Simulation Integrated Models** ◊ **Urban/Metropolitan Level Simulation Models** ◊ **Regional Level Simulation Models** ◊ **Global Level Simulation Models** ◆ **Input-Output-Based Integrated Models**
Other Modeling Approaches **(see Table 4.1d)**	◆ **Natural-Sciences-Oriented Modeling Approaches** ◆ **Markov Modeling of Land Use Change** ◆ **GIS-Based Modeling of Land Use Change**

For each group of models the reader is referred to more detailed Tables (Tables 4.1b, 4.1c, 4.1d) where all models included in the group which this contribution presents are shown.

TABLE 4.1b Statistical/Econometric, Spatial Interaction and Optimization Models of Land Use Change

Modeling Tradition	***Representative Models***
Statistical and Econometric Models	♦ Linear Regression Models (Chapin 1965, Chapin and Weiss 1968, Lee 1973, Veldkamp and Fresco 1996, Verburg *et al*. 1997) ♦ EMPIRIC (Hill 1965) ♦ Multinomial Logit Models (Kitamura *et al*. 1997, Morita *et al*. 1997) ♦ Canonical Correlation Analysis Model (Hoshino 1996)
Spatial Interaction Models	♦ Potential Models (Hansen 1959) ♦ Intervening Opportunities Model (Stouffer 1940, Schneider 1959, Lathrop and Hamburg 1965) ♦ Gravity/Spatial Interaction Models (Niedercorn and Bechdolt 1969, Golob and Beckmann 1971, Lee 1973, Wilson 1974, Batty 1976, Haynes and Fotheringham 1984, Batten and Boyce 1986)
Optimization models	♦ Linear Programming Models – Single and Multiobjective ◊ Herbert-Stevens Linear Programming Model (Herbert and Stevens 1960) ◊ Southern Wisconsin Regional Plan Model (Schlager 1965) ◊ Multiple Objective Linear Programming Model (Du Page County Reg. Planning Commission (Bammi *et al*. 1976) ◊ Linear Programming Models for Agricultural Regions (Campbell, *et al*. 1992, Stoorvogel *et al*. 1995) ◊ General Optimal Allocation of Land Use Model (Latesteijn 1995) ♦ Dynamic Programming (Hopkins *et al*. 1978) ♦ Goal Programming (Lonergan and Prudham 1991) ♦ Hierarchical Programming (Nijkamp 1980) ♦ Linear and Quadratic Assignment Problem (Moore and Gordon 1990), Moore 1991) ♦ Nonlinear Programming Models (Adams *et al*. 1994) ♦ Utility-Maximization Models (Wingo 1961, Alonso 1964, Muth 1961, 1969, Mills 1967, 1972) ♦ Multi-Objective/Multi-Criteria Decision Making Models (Janssen 1991, Fischer *et al*. 1996b)

TABLE 4.1c Integrated Models of Land Use Change

Modeling Tradition	*Representative Models*
Integrated Models	◆ Econometric-Type Integrated Models ◊ Penn-Jersey (Seidman 1969, Wilson 1974) ◆ Gravity-Spatial Interaction-Based and Lowry-Type Integrated Models ◊ The Lowry Model (1964) and early versions (Garin, 1966) ◊ TOMM (Crecine 1964, 1968) ◊ PLUM (Goldner *et al*. 1971) ◊ Urban Stocks and Activities Model (Echenique *et al*. 1969) ◊ Activity Allocation and Stocks-Activities Models (Batty 1976) ◆ Simulation Integrated Models ◊ Urban/Metropolitan Level Simulation Models ∗ San Francisco CRP (Rothenberg-Pack 1978) ∗ UI, NBER, HUDS Urban Simulation Models (Kain 1986) ∗ CUFM (Landis 1994, 1995) ∗ Dynamic Simulation Models • The Dortmund Model (Wegener 1982) • Integrated Land Use/Transport Models ✧ ITLUP (Putman 1983, 1991) ✧ TRANUS (de la Barra 1989) ✧ CATLAS (Anas 1982, 1983) ◊ Regional Level Simulation Models ∗ CLUE-CR (Veldkamp and Fresco, 1996) ∗ Cellular Automata (White and Engelen 1994, Engelen *et al*. 1995) ∗ LUC (Fischer *et. al*. 1996a) ∗ IMPEL (Rounsevell 1999) ◊ Global Level Simulation Models ∗ IFS (Liverman 1989) ∗ IMAGE 2.0 (Alcamo 1994) ● Input-Output-based Integrated Models ◊ Compact I-O models ∗ U.N. World Model (Leontief 1977) ∗ Economic-Ecologic Models (Daly 1968, Isard 1972, Victor 1972) ◊ Modular Models with an I-O Component ∗ PDE Model for Mauritius (Lutz 1994a)

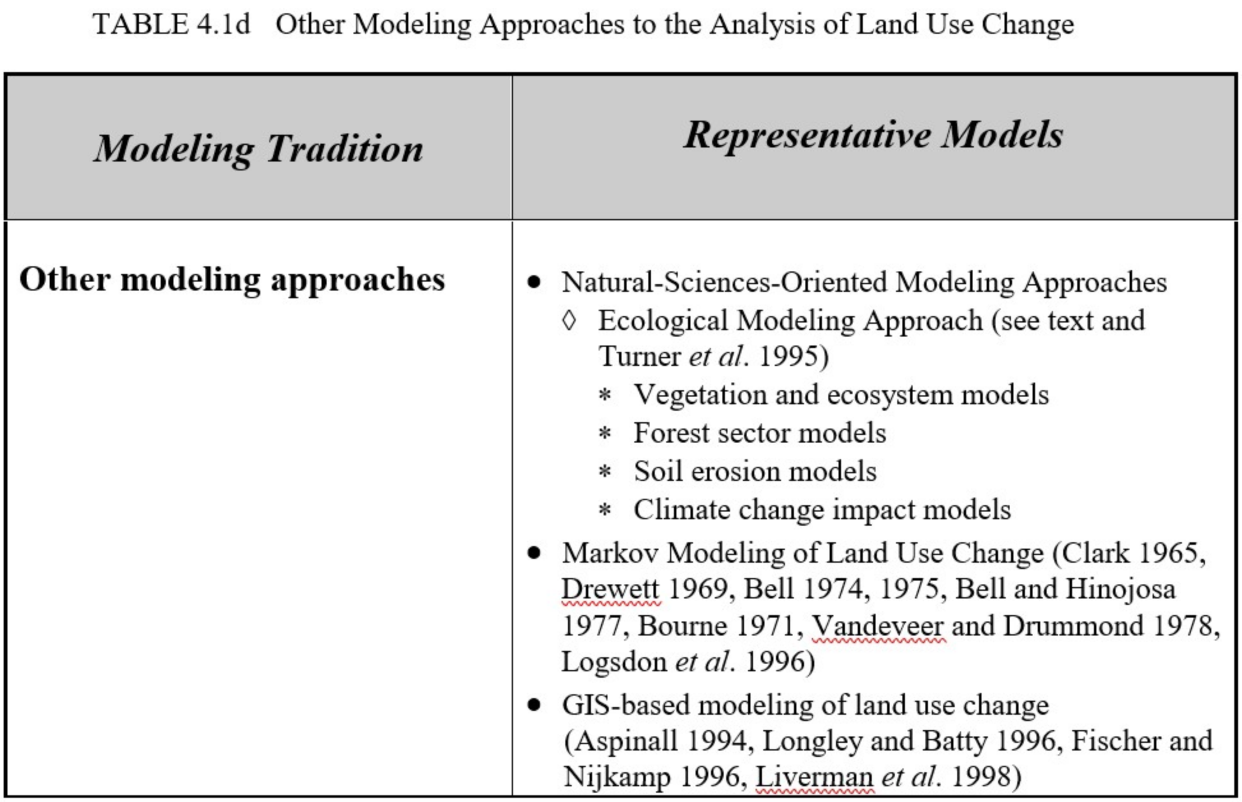


TABLE 4.1d Other Modeling Approaches to the Analysis of Land Use Change

Modeling Tradition	***Representative Models***
Other modeling approaches	• Natural-Sciences-Oriented Modeling Approaches ◊ Ecological Modeling Approach (see text and Turner *et al*. 1995) ∗ Vegetation and ecosystem models ∗ Forest sector models ∗ Soil erosion models ∗ Climate change impact models • Markov Modeling of Land Use Change (Clark 1965, Drewett 1969, Bell 1974, 1975, Bell and Hinojosa 1977, Bourne 1971, Vandeveer and Drummond 1978, Logsdon *et al*. 1996) • GIS-based modeling of land use change (Aspinall 1994, Longley and Batty 1996, Fischer and Nijkamp 1996, Liverman *et al*. 1998)

The presentation of the models which follows is kept simple and not mathematically sophisticated to make it accessible to a wider audience. For several models already built and/or used and for which there is complete documentation the reader is referred to the original sources. More emphasis is placed on models of a recent origin as: (a) they are not as widely publicized and covered in the literature as the past generation models and (b) it is interesting to see whether the more recent models are in a better position to model land use change than was the case with past modeling efforts.

4.3. Statistical and Econometric Models

Application of statistical techniques to derive the mathematical relationships between **dependent** variables and sets of **independent** (or **predictor**) variables is widespread in modeling socio-economic and other systems of interest (see, for example, Colenut 1968, Lee 1973). The most commonly used statistical technique is **multiple regression analysis** (and its variations such as stepwise regression, two-stages least squares) although application of other **multivariate techniques** is not uncommon (such as factor analysis, canonical analysis, etc.). The application of multiple regression techniques to the analysis of problems involving economic demand and supply has given rise to what are known as *econometric models*. Simply stated, these are systems of equations which express the relationships between demand and/or supply and their determinants as well as between demand and supply themselves (for economic/market equilibrium) (Batty 1976, Wilson 1974). A large body of specialized statistical techniques has been developed for estimating their coefficients broadly known as econometric analysis (or, techniques) (see, for example, Judge *et al.* 1982). A selection of models belonging to this modeling tradition are presented in the following (Table 4.1b).

4.3.1. Statistical Models

Statistical models whose direct object of analysis is land use change date since the 1960s at least and they are still employed in several related studies. Frequently, they constitute components of larger models employed for the analysis of land use change and its determinants. A distinction can be drawn between continuous models which treat land use as a continuous variable (area of land devoted to a land use type) and discrete models those which treat land use as a discrete variable (different land use types are distinguished). In the following, the basic structure of a statistical model for land use change is indicated and then existing models are presented and discussed briefly.

In a statistical model of land use change, the study area is usually subdivided into a number of zones (or, grid cells if a grid system is adopted) the size and shape of each cell depending on the level of aggregation chosen as well as the availability of data. (The case where the observation units are individual land parcels instead of zones or grid cells is discussed later.) In the *continuous case*, for each zone, the distribution of land use types (the **dependent variables**) as well as the values of other environmental and socio-economic **predictor variables** (e.g. population, employment, soil conditions, slope, climate (temperature, rainfall, etc.) are given. A multiple regression equation for each land use type is fit to these data (usually referring to a given year). The general form of the equation is:

$$LUT_i = a + \beta_1 X_1 + B_2 X_2 + \ldots\ldots\ldots\ldots \beta_n X_n + \varepsilon \qquad (4.1)$$

where: LUT: is the area of land occupied by land use type i (in each cell) and $X_1, X_2, \ldots X_n$ the predictor variables used. The term "ε" is the error term of the statistical model.

This model form can be used to assess the changes in the area covered by a given land use type for specified changes in one or more of the predictor variables by substituting their values in the equation shown above. Early applications were made by Chapin and Weiss (1968) (see, also, Chapin 1965) in the context of a broader "probabilistic model of residential growth" (known as the North Carolina model) and by Swerdloff and Stowers (1966 cited in Chapin and Kaiser 1979) using the same data set. The **dependent variable** in their model was the attractiveness of a zone of the study region for residential growth measured as (Chapin and Kaiser 1979):

- absolute number of dwellings, or
- increase of dwelling units in a zone (within a planning time period), or
- number of dwellings per unit of available land, or
- acreage of residential land or proportion of land use growth to be allocated to a zone

An exploratory regression analysis was applied first to a larger set of candidate variables which the literature indicated that influenced land use to identify the variables which had a statistically significant relationship to the dependent variable. The **independent** which were included finally in the Chapin and Weiss version of the model were:

- accessibility of a zone to work areas
- availability of sewerage in a zone
- accessibility of a zone to nearest major street
- accessibility of a zone to a nearest elementary school.

The **independent variables** of the Swerdloff and Stowers version of the same model were (Chapin and Kaiser 1979):

- zoning protection at the base year
- percent of total land area in residential use at the base year
- logarithm of accessibility to employment at the forecast year
- dwelling unit density at the base year
- percent of total land in industrial use at the base year.

A similar statistical model is used in the CHANGE module of the CLUE model which is discussed below under the category of integrated models (Veldkamp and Fresco 1996b, Verburg *et al.* 1997). The CHANGE module uses linear regression models to estimate the changes in the area of given land use types which are caused by changes in the values of environmental and socio-economic driving factors projected from other modules of the CLUE model.

Discrete statistical models (or, discrete choice models) are used to represent choice situations in general (see, for example, McFadden 1978, Hensher 1981, Anas 1982). In the case of land use modeling, each land use type is described as a function of a number of characteristics (which usually differ from one cell to another). For each cell, the utility of every land use type is assessed as a function of these characteristics. The probability of choosing a particular land use type in a given cell is calculated as a function of the utilities associated with the land use types considered. The most common mathematical forms used in discrete choice models are the logit and probit models. Examples of this approach are presented next. The discussion of discrete choice model resumes in section 4.6.3A on integrated land use-transportation models.

In the context of a larger modeling exercise for the analysis of land use change in Japan, Kitamura *et al.* (1997) and Morita *et al.* (1997) use a multinomial logit model to assess changes in land use by type. The model assesses the *probability of choice* of a particular land use type in each of the cells in which the study area is subdivided as a function of the values of a set of **predictor/ explanatory variables**. These probabilities are interpreted as land use proportions for each of a specified number of land use types. The mathematical form of the model is as follows:

$$P_{ij} = \frac{\exp(V_{ij})}{\sum\limits_{i} \exp(V_{ij})} \tag{4.2}$$

$$V_{ij} = \left(\sum_{k} \theta_{ik} X_{jk} \right) + C_i \tag{4.3}$$

where:

P_{ij}	the land use proportion of land use type i in cell j
V_{ij}	the utility of the i_{th} land use type in cell j
X_{jk}	the k_{th} explanatory variable in cell j
θ_{ik}	the multiple regression coefficients of the explanatory variables X_{jk}

The above formulation calculates first the utility of each land use type in each cell of the study area as a linear function of the values of a set of **predictor variables** (equation 4.3) and then uses this utility to estimate the probability of a particular land use type occurring in each cell. The predictor variables are shown below. As it was the case with the previous multiple regression model, changes in the predictor variables calculated from other modules of the larger model are fed into equation (4.3) to estimate changes in the utility of each land use type. These changes are then used in equation (4.2) to estimate changes in the proportion of each land use type in each cell of the study region.

Four land use types were taken into account in this study: farmland, forestry land, built-up area, and other land. The dependent variables were operationalized, thus, as: farmland share, forestry land share, built-up area share and other land share. The predictor/explanatory variables used were grouped into three groups: socio-economic driving forces, land use policy and planning factors, natural factors. The socio-economic driving forces category included the variables:

- population density
- percent of population under 64
- farm-household ratio
- percent of full-time farm households
- percent of part-time farm households

- percent of workers in the secondary sector
- percent of workers in the tertiary sector
- percent of female agricultural workers
- percent of employees in the secondary sector
- percent of employees in the tertiary sector
- gross field husbandry product/farmland
- gross animal product/farmland
- average farm size
- per capita gross farm products
- per capita farmland
- number of employees per 100 persons
- number of employees per firm
- distance of Kyoto/Osaka.

The land use policy and planning factors category included the variables:

- car ownership index
- land value
- share of Agricultural Promotion Area
- share of Agricultural Land Zone
- ratio of Agricultural Land Zone to Agricultural Promotion Area
- share of urbanization area
- ratio of urbanization zone.

The natural factors category, lastly, included the variables:

- share of 0-3^o slope area
- share of 3-8 ^{o} slope area
- share of >15 ^{o} slope area
- share of 0-100m elevation area
- share of >200m elevation area
- share of hill area
- share of tableland and terrace
- share of lowland area.

In the framework of the same modeling exercise for Japan, another statistical technique, canonical correlation analysis, has been used to explore the environmental and socio-economic determinants of land use change as well as to test the temporal stability of the land use patterns of the study area in the study period (Hoshino 1996). Canonical correlation analysis (CCA) is a **multivariate statistical technique** used to explore the structure of the relationships between a dependent and a set of independent variables which is especially suitable when the independent variables are correlated with each other. The study area was subdivided in its 138 municipalities which were chosen as the basic unit of analysis. Four types of land use were distinguished as above: farmland, forest land, residential land, other land (public uses, etc.). The results of CCA indicated the relationships between particular land use types and the determinants used in the predictor set.

Recently, discrete choice models have been built where the observation units are individual land parcels. The advantage of these models as compared to those using a zone or grid system is that the observation unit is the *decision making* (the owner of the land parcel); hence, they model the actual land use choice or land use conversion behavior of the individual parcel owner. The independent variables entering the relationship are the actual factors which affect the land use choice or land use conversion decision. These may include policy variables (e.g. land use regulations and restrictions) as well as the physical/ environmental characteristics of the site. Hence, these models allow for more realistic representation of the land use change process. Moreover, the environmental (as well as the social and economic) impacts of land use change at a very disaggregate level – that of the land parcel – can be assessed directly. Models following this approach can be found in Bockstael (1996), Geoghegan *et al.* (1997), Bockstael and Bell (1997), Bell and Bockstael (1999), Irwin and Bockstael (1999).

For example, in Bockstael (1996), Bockstael and Bell (1997), and Irwin and Bockstael (1999), profit-maximizing individuals are assumed to own undeveloped parcels of land and to make decisions to convert them to residential land use. Land conversion depends on expected returns which are assumed to be a function of expected sales price of the land in residential use, conversion costs, and the opportunity cost in terms of alternative uses. The expected price of a converted parcel is assessed as a function of commuting distance to urban centers, provision of public services, zoning restrictions, and indices of surrounding land uses (Bockstael and Irwin 1999). The spatial explicitness of this modeling approach permits also the analysis of the spatial and temporal dynamics of land use change. For example, in Irwin and Bockstael (1999), the theoretical framework of agent-based theories in the urban and regional economics theorization tradition discussed in chapter 3 is used to model: (a) the *attracting effects* among developed land parcels which exogenous features create (e.g. central city, road, public services) and (b) the *repelling effects* rising out of interactions among land users. The authors demonstrate that this model provides a viable explanation of the fragmented residential development pattern observed in urban fringe areas (in the United States where the model has been applied). In fact, fragmented land use patterns can be modeled only at the disaggregate level of land parcels which provides the necessary detail to represent land fragmentation. The authors present also a duration model of residential land use conversion. The land conversion decision is a function of both exogenous landscape features and a temporally lagged interaction effect among neighboring land users (Bockstael and Irwin 1999). A general observation with respect to models in this direction is that they are based on microeconomic foundations providing, hence, theoretically sound models (in an economic sense, at least) of land use change decisions.

Before turning to the econometric models, the statistical models of land use change presented are briefly discussed and evaluated. Their purpose is description, explanation and (conditional and unconditional) prediction of land use changes as functions of selected determinants. They are mostly cross-sectional, static models operating on the basis of annual data. Usually they are national or regional level models based on a zonal system of spatial reference where the zones usually coincide with administrative districts (for which data is available). Exceptions are the recently built models employing parcel level data which can be considered local level models, they do not employ a zonal system, and they may incorporate lagged values of certain independent variables which makes them quasi-static models. Most models consider four to five major types of land use (arable land, permanent crops, pastures and range lands, natural vegetation, other uses); i.e. they employ a rather coarse level of land use detail. Naturally, the spatially explicit land use models can accommodate a finer level of land use detail if available data permit.

There is no specific theory underlying most statistical models except for the broad theoretical claim that land use changes result from changes in environmental and socio-economic driving forces. In other words, they adopt an **instrumentalist** view of theory which has "a rather shadowy, secondary role in providing a source of assumptions on which models .... can be based" (Sayer 1979a, 858). Some of the statistical techniques used (such as CCA) attempt to elicit the structural relationships between land use change and its determinants but this is a mechanistic procedure devoid of theoretical meaning and guidance. An exception again are the spatially explicit, discrete statistical models of individual land user behavior which are grounded in microeconomic theory of consumer behavior (Bockstael 1996, Bockstael and Bell 1997, Irwin and Bockstael 1999).

Model specification in most models rests on **ratio** (quantitative) variables mostly which means that the qualitative aspects of land use change which cannot be quantified and measured do not enter the model. This leaves much to be desired from these models. An exception again are the spatially explicit, discrete statistical models which can accommodate nonquantitative aspects (e.g. personal, cultural, and other characteristics of the land users) of the land use change environment. However, whether the statistical treatment and the operationalization of such characteristics are valid are open questions which should be investigated in the light of recent advances in (and currency of) qualitative analysis. The socio-economic variables include frequently population growth and population distribution among age groups as a proxy measure for several socio-economic determinants (e.g. literacy, demand, etc.). This may not be the best choice given that population has almost always good statistical correlation with many variables including the dependent (land use change) variables. Hence, the models appear to possess significant statistical explanatory power when, in fact, this may be an inevitable numerical result. It has been argued that population has to be considered either as one (but not the primary or the sole) of the **independent variables** influencing land use change or, preferably, it is best to be viewed as an intermediate variable affected by others (see, for example, Sunderlin and Resosudarmo 1999 for an analysis of this issue in the context of forest cover loss). This issue relates to the broader issue of endogeneity of the independent variables. In other words, one or more of the independent variables included in a model may be **endogenous** to land use (the independent variable) in that it is affected by changes in it. An example is the use of the variable "distance to road" as an **explanatory** variable; but when building roads (i.e. changing the value of this variable) may cause land use changes which, in their turn, modify the distance to roads (see, for example, Pfaff 1999).

Multiple regression and related **multivariate** models reveal *correlations* or *associations* among variables, a fact which has nothing to do with *causation*. Causal models require a rigorous grounding on theory which the models discussed previously lack. Most of the statistical models of land use change are *linear* multiple regression models which suffer from the linearity assumption. In other words, a unit change in any one of the independent variables produces always the same level (amount) of land use change of a specific type, an assumption difficult to verify and defend on both theoretical and practical grounds. As regards the particular statistical techniques used, it appears from the model descriptions available in the published literature that the spatial data used are analyzed by means of conventional statistical techniques rather than by spatial statistical techniques. This is a serious, weak point of model estimation as spatial data suffer almost always from **spatial autocorrelation** which should be taken into account and corrected by means of appropriate spatial statistical techniques (see, for example, LeSage 1999). In addition, it should be noted that multiple regression models suffer from **multicollinearity** as the set of **predictor variables** are usually correlated to one another. This is a problem when using the models for explanation but not when using them for prediction.

The data used are rather coarse, aggregate data easily available from population, agricultural and other censuses as well as from governmental agencies. However, they are spatially explicit which offers the models better spatial representation than possible aspatial versions. Lack of a host of other types of (geo-referenced) data, however, limits the utility of the models as several determinants (especially the socio-economic) of land use change are under- (or, mis-) represented by proxy variables while some others are not represented at all. The models presented have been used in real world applications. More specifically, the CLUE model has been calibrated with data from Costa Rica. The multinomial logit model is part of a larger modeling exercise on the analysis of land use change in Japan (this model will be discussed in greater detail in the section on integrated models below). The models by Bockstael (1996), Geoghegan *et al.* (1997), Bockstael and Bell (1997), Bell and Bockstael (1999) have been applied to the central Maryland region in the U. S. The later models present the highest data requirements of all statistical models presented above.

4.3.2. Econometric Models (EMPIRIC)

To this author's knowledge, no econometric models of land use change are known where land use is treated explicitly either as a continuous or as a discrete variable. The common practice in econometric modeling is to estimate changes in some determinants of land use (say, population, housing demand, retail demand, employment) and then convert those estimates to land use requirements (by land use type) with the use of **land use/activity coefficients**. One of the well known econometric models in this tradition is the

EMPIRIC model which is presented briefly in the following as it represents a prototype model built in the decade of the 1960s and was used as a rather simple vehicle to model metropolitan structure.

EMPIRIC is essentially an *indirect* model of land use change as the direct object of model building was not the analysis of land use change but rather, modeling the distribution of employment and population within metropolitan areas. Several publications describe the main features and structure of EMPIRIC to which the reader is referred such as Hill (1965) and Rothenberg-Pack (1978). The latter includes a detailed bibliography on various related documents and discusses the various applications of the model.

EMPIRIC is a regional **activity allocation model** built with the broad purpose of providing future forecasts of population, economic activity and land use patterns in metropolitan areas under various policy (development) scenarios; i.e. it was mostly suitable for impact assessment and policy analysis. More specific and detailed purposes for which the model has been used are found in the related literature, a selection of which are presented here drawing on Rothenberg-Pack (1978). Hill (1965 cited in Rothenberg-Pack 1978, 31), a member of the consulting firm which first developed the EMPIRIC model, concluded in the presentation of the 1965 version of the model: “the model may enable the planner to simulate a chain of events in urban development starting with the variables under public control (such as the transportation system and zoning regulations) and ending with a sufficient and desirable pattern of residential and industrial development.” In its 1967 version (Brand *et al.* 1967 cited in Rothenberg-Pack 1978, 32), EMPIRIC could be used to generate the development pattern (Z) associated with a set of policies (Y) and aggregate growth assumptions (X). Boyce *et al.* (1970 cited in Rothenberg-Pack 1978, 32-33) summarize the model’s uses: “the primary use was seen to be the provision of ‘. . . . . . .forecasts of land use activities which could be input to traffic forecasting’, or ‘forecasts of population and employment for use or input to traffic models and transportation systems analysis’ or, more generally, ‘future year land use patterns for various planning purposes, particularly input to traffic models’. The secondary uses were variously judged to be:‘sufficiently sensitive to public policy inputs to enable use as a design tool producing different future year patterns of land use’ or to be ‘a regional planning tool which will help in the evaluation of alternative regional plans, or, less generally, .. to be applied ‘in testing alternative regional plans for feasibility of implementation as well as for functional utility.” However, as Rothenberg-Pack (1978, 31) observes, “the model can provide inputs to the evaluation stage but cannot carry out evaluation. . . the model does not derive the ‘best’ policy through an optimizing process; rather it simulates the impacts of prespecified policy mixes.” Hence, its uses were more limited than its users and builders had aspired.

EMPIRIC is a spatially explicit model which assumes a study region subdivided into a number of zones. The model consists of three main elements or modules:

a. the activity allocation model

b. the forecast monitoring module, and

c. the land consumption module.

The *activity allocation model* receives **exogenous** population and employment forecasts and distributes them to the subareas (districts) of the study region through a **system of simultaneous equations** . There is one equation for each of four household income classes (and a fifth group of unrelated individuals) and for each of four employment (industry) groups. The **independent (explanatory) variables** are:

a. the base period activity levels (number of households in each income class and number of employees in each industry group)

b. changes of these levels over the forecast period

c. other base period characteristics of each zone such as distribution of land uses, densities, etc., and

d. base period and forecast period values of policy variables (alternative forms of transportation accessibility and availability of water and sewer services).

The model consists of a system of nine simultaneous equations of the general form:

$$R_{ik}(\Delta t) = \sum_{n=1,n\neq 1}^{N} [a_{in} R_{nk}(\Delta t)] + \sum_{n=1}^{N} [b_{in} R_{nk}(t_0)] + \sum_{p=1}^{P} [c_{ip} C_{pk}(t_0)] + \sum_{m=1}^{M} [d_{im} Z_{mk}(\Delta t)] + \sum_{m=1}^{M} [e_{im} Z_{mk} t_0)] + \sum_{m=1}^{M} [f_{im} Z_{mk} t_1)] \qquad (4.4)$$

where,

R_{ik}	denotes change in activity i in zone k
R_{nk}	denotes (simultaneous) changes in other activities by category in zone k
$R_{nk}(t_0)$	denotes the base year values of the activities in zone k
$C_{pk}(t_0)$	denotes base period characteristics of each zone k
$Z_{mk}(t_0)$	denotes initial or base year values of policy variables in zone k
$Z_{mk}(\Delta_t)$	denotes changes in the policy variables over the forecast period in zone k
t_0	denotes the base year and
t_1	denotes the forecast year

$a_{in}, b_{in}, c_{ip}, d_{im}, e_{im}, f_{im}$ are the regression coefficients estimated by fitting the model to available, **cross-sectional**, data usually by means of **Ordinary Least Squares** or **Two-Stages Least Squares**, the latter technique being more appropriate to fitting simultaneous regression equations (Batty 1976).

The *forecast monitoring module* adjusts the initial unconstrained forecast activity allocations generated by the **activity allocation model** to be consistent with preset minimum and maximum activity constraints. Examples of such constraints which could be simulated include: (a) a fair share housing project which required a minimum number of low income households in each district or, (b) an urban renewal policy manifested in counter growth activity locations or, (c) location preferences of certain activities (Rothenberg-Pack 1978).

The *land consumption module*, finally, converts the adjusted activity allocations to land use requirements on the basis of activity-specific density calculations. Following Rothenberg-Pack (1978, 234), "each district is first allocated to an urbanization category based on the proportion of its area which is developed in the base period (four urbanization categories are defined ranging from urban core to fringe). Within each of the urbanization categories, permitted development densities for each activity land use category are specified, based upon the average densities observed in the base period for that type of district. If the land required to accommodate all of the population and employment activity allocated to the district would push the district into another urbanization category or exceeds the initially specified available land for development, then the urbanization category or the average density may be adjusted to reflect development pressures." This basic process may be subject to a number of discretionary policies or "overrides"; i.e. arbitrary changes in the data inputs to the module (the initial land uses, the amount of vacant land, permitted densities), or forced allocations to, or limits upon land for particular uses. Major instruments of land use control (i.e. control of land use change to achieve specific goals such as via zoning or land reservations), i.e. policy variables, are accommodated in the last two modules of EMPIRIC (Rothenberg-Pack 1978).

The version of the EMPIRIC described above is the most commonly used in its various applications. It is a static model where the dynamics of the urban system modeled is implicit. In Batty's (1976) words: "Although certain lags are built into the system, their explanation is also largely statistical and, as the dynamic process which these models are attempting to simulate is implicit, there are few guiding principles in the choice of the time interval. Furthermore, these models do not attempt to identify the mover pool and their equilibrium properties are unspecified" (Batty 1976, 299-300). EMPIRIC lacks an underlying theory, as it is frequently the case with regression models. Batty (1976) notes: "One central problem with .. linear models revolves around their rather inductive bias in that the emphasis upon explanation is completely statistical and lacks little of the causal focus of the activity allocation models" (Batty 1976, 299-300). Rothenberg-Pack (1978) notes that in the activity allocation model itself, "the lack of a theoretical or behavioral base results in the differential specification of similar policy variables in ways which are very difficult to rationalize; moreover, their relationship to some activities and not to others is in many cases difficult to rationalize" (Rothenberg-Pack 1978, 244). Kain (1986) observes that: "relying heavily on the persistence of land use patterns, the model provides very little insight about the forces causing changes in metropolitan structure and is nearly worthless in situations where conditional forecasts are required" (Kain 1986, 850).

Focusing on the land consumption module which is of central interest in this work, policy-induced land use changes are estimated in a simplistic, mechanistic, linear, and additive way by means of **activity coefficients** without due consideration of nonlinearities in land consumption (more households may not consume proportionately more land), the suitability of available land for the forecast uses and the interactions among allocated forecast uses in each district (the positive or negative **neighborhood effects** of development in one zone on the adjacent zones). In other words, the lack of a theoretical framework for assessing future changes in land use as a function of autonomous or policy changes leaves much to be desired of EMPIRIC. An important point as regards the allowable "overrides" to the basic land use calculations is mentioned by Rothenberg-Pack (1978): "(their use)…..has important implications for the subsequent use of the estimated **activity allocation model** (AAM), since the AAM parameter values are very likely to be sensitive to the land use and zoning constraints obtaining during the calibration period" (Rothenberg-Pack 1978, 244). Similarly, the alleged uses of EMPIRIC for policy impact analyses has been seriously questioned on the above and on more detailed grounds.

Despite the various criticisms this model has received, it is one of the few urban models which has had many applications in the "golden age of quantitative analysis" – the 1960s and 1970s. Cities to which the model has been applied include: Boston, Atlanta, Denver, Puget-Sound, Minneapolis-St. Paul, Washington, DC. (for details see, Rothenberg-Pack 1978; also, Kain 1986).

4.4. Spatial Interaction Models

The spatial interaction modeling tradition draws from the original efforts to model interaction of human activities in space based on the analogy of the Law of Gravity in Physics. This was one of the first manifestations of the application of the Social Physics theoretical approach mentioned in chapter 3. Hence, the models included in this group are the well known gravity-type models and their newer versions known more generally as spatial interaction models (Table 4.1b).

These models have been used to model a variety of types of interactions arising out of a host of human activities such as the journey-to-work, shopping, circulation, and mobility, in general. As there are numerous accounts of these models in the literature whose emphasis varies with their purpose and the particular subject studied, the present discussion will be confined mostly to those aspects which bear more closely on how these models handle issues of land use and its change.

"Spatial interaction is a broad term encompassing any movement over space that results from a human process. It includes journey-to-work, migration, information and commodity flows…." (Haynes and Fotheringham 1984, 9). In a generic sense, the study of spatial interaction involves the study of both the interacting entities and the form of interaction between them. In the case of analysis of land use or spatial structure, the interacting entities are individuals residing or engaging in some activity (mostly work or shopping) in origin and destination zones which are characterized by corresponding types of land uses – e.g. residential areas, retail areas, employment areas. Although interaction results from the actions of individuals, i.e. from human activities, the description of these models is commonly worded in terms of interactions between different land use types (e.g. between residential and employment areas). These interactions take several forms such as journeys-to-work, shopping trips, flows of goods and information, etc.

Naturally and logically, the strength of interaction between land use types will depend on the magnitude and nature of the associated activity; hence, changes in activities (which are reflected also in changes in their interactions) may cause some kind of land use change – either qualitative (the amount of land occupied by a given use remains unchanged but its character and intensity change) or quantitative or both. The opposite is also true. Changes in land use may induce changes in the associated activities as well as in the interactions between them. Finally, changes in the ease of interaction between two areas – such as those brought about by changes in accessibility following transport network improvements – may induce changes in the interacting activities and the associated uses of land. This is broadly the rationale for considering spatial interaction models as land use change models. Spatial interaction models have been applied to residential location, retail location, and transportation analyses and they have been used also as components in integrated land use-transportation models (these latter versions are discussed in the section on integrated models.). In the following, the basic structure of these models is presented in a historical context and variations of the original formulation are examined.

According to Carrothers (1956), the origins of the use of the concept of gravitation to explain human spatial interactions are placed in the late 19th century in the work of H. C. Carey which was directly inspired by Newton's Law of Universal Gravitation. Reilly's Law of Retail Gravitation followed tailored essentially on the same idea and applied to the case of retail trade between cities. Three other researchers, working on the gravitational formula from independent angles – Stewart (1948) on demographic gravitation, Zipf (1949) on the principle of least effort in human interaction, and Dodd (1950) on the *interactance hypothesis* for human groups – formulated the first versions of the gravity model applied to modeling socio-economic behavior (cited, among others, in Haynes and Fotheringham 1984, 16; Batten and Boyce 1986, 359ff).

Hansen (1959) proposed a first formulation of a gravity/potential model to predict the location of population in residential zones of an urban region. It is based on the assumption that accessibility to employment is the principal determinant of the location of population and it is concerned with "potential interaction" or relative accessibility of zones (Lee 1973). An *accessibility index* expresses the relationship between population location and employment:

$$A_{ij} = \frac{E_j}{d_{ij}^b} \qquad (4.5)$$

where:

A_{ij}	the accessibility index of zone i in relation to zone j
E_j	total employment in zone j
d_{ij}	distance between i and j
b	exponent of distance reflecting the "friction of distance" between i and j

The overall index for zone i is the sum of all individual indices (all other zones j):

$$A_i = \sum_j \frac{E_j}{d_{ij}^b} \qquad (4.6)$$

Hansen introduced the notion of the "holding capacity" of a zone which is the amount of vacant land which is suitable for residential development. Combining the accessibility index with the holding capacity measure, the "development potential" of a zone is calculated which can be considered as a measure of attractiveness of a zone:

$$D_i = A_i H_i \qquad (4.7)$$

Hansen suggested essentially that the share of total population growth which will be received by any one zone of the study region depends on its attractiveness in relation to all other competing zones. Hence, if the projected population at a future time t is G textsubscriptt, then the allocation of this growth to the each individual zone is given by the allocation formula:

$$G_i = G_t \frac{(A_i H_i)}{\sum(A_i H_i)} \qquad (4.8)$$

This last formula provides a simple, "quick and dirty", way to calculate changes in the allocation of population to zones given changes in either holding capacity and/or the accessibility index of each zone. Evidently, despite the simplicity, spatial explicitness, and intuitive appeal of Hansen's potential model, its lack of theoretical underpinnings, static nature, and the restricted number of ill-defined types of land uses which are considered (residential and employment areas) render it a very naïve model of land use change (if it can be considered as such). In addition, it is not a "complete" gravity model as its operational expression (equation 4.5) includes only one of the two interacting entities – the destination zones whose attractiveness is assessed.

One of the restrictive assumptions of Hansen's model, that of the equal desirability of the total supply of housing to all households independent of income levels, employment type, etc., was relaxed by Stouffer (1940, 1960) who proposed the *intervening opportunities model* in which the total supply of residences was stratified in housing submarkets. Stouffer argued that "the number of individuals (or families) G_r going a given distance r is directly proportional to the number of opportunities Q_r (residences) at that distance, and inversely proportional to the number of 'intervening opportunities' Q" (Romanos 1976, 24). Stouffer's idea was further improved by Schneider (1959 cited in Romanos 1976, 24) who developed an *opportunity-accessibility model.* In this model, "the distribution of population growth is a continuing evaluation of potential dwelling units which are rank-ordered from an urban center serving as the location of employment. These potential dwelling units are the opportunities and are obtained from the product of vacant land available for residential development times the appropriate population density. . . . Similar to Stouffer's model, this formulation describes an allocation of households by starting their search from the center of the city and moving across rings containing the opportunities" (Romanos 1976, 24-25). For a brief mathematical exposition of this model the reader is referred to Wilson (1974, 397-399). Finally, another *opportunity-accessibility model* based on the intervening opportunities concept has been designed by Lathrop and Hamburg (1965) to allocate different activities to zones in a region. The model was tested in Upper New York State. For a brief mathematical exposition of this model the reader is referred to Batty (1976, 52-55).

Before moving to the contemporary forms of the spatial interaction models, a few comments are in order with respect to the first generation gravity models presented thus far from the perspective of the analysis of land use change. All models contain, however simple, some behavioral assumptions concerning the relationship between the location of households (residential land uses), the availability of land for development, the availability and location of jobs (industrial and commercial and other services areas), and accessibility. However, they address the problem of how future population will be allocated to zones *given* the amount of vacant land in each zone. Hence they do not address completely the issue of land use change; this is exogenous to the models. If the amount of available land changes, the models can assess its impacts on the distribution of population to zones but not vice versa. In addition, the models do not contain any equilibrium mechanism and, hence, they do not provide any guidance as to how the interactions of changes in population, employment opportunities and available, developable land will lead to particular spatial patterns.

A contemporary contributor to the spatial interaction modeling tradition is A.G. Wilson (see, for example, Wilson 1967, 1970, 1974, 1985) who avoids the term "gravity" and uses instead the term "spatial interaction models". Here we keep the term "gravity" as a convenient shorthand. Moreover, despite conceptual and operational modifications and improvements, all model versions are essentially similar to the original gravity formula. The gravity model assumes a study region subdivided into a number of zones which are called origin and destination zones. Origin zones are characterized by activities from which flows originate (e.g. residential areas where employees live) to reach destination zones (e.g. employment areas where the employees work). Each zone of the system can be both an origin and a destination zone. The simplest form of the gravity model which parallels the form of the corresponding model in Physics is the following:

$$S_{ij} = k\frac{P_i P_j}{d_{ij}^b} \qquad (4.9)$$

where,

S_{ij}	denotes interaction (flow) from origin zone i to destination zone j
P_i	is the “size” or “mass” of origin zone I
P_j	is the “size” or “mass” of destination zone j
d_{ij}	is a measure of distance between zones i and j
b	an exponent indicating the effect of distance on the interaction between origin and destination zones
k	a constant which is empirically determined and adjusts the relationship to actual conditions

The above formula states that the magnitude of the interaction between zone i and zone j, S_{ij}, is proportional to the product of the “sizes” or “masses” of the origin and the destination zones and inversely proportional to a measure of the distance between them. Measures of the “interaction” term include number of trips between zones, volume of goods transported between zones, migration flows, etc. The “sizes” or “masses” of the origin and the destination zones are operationalized variously depending on the application. In the more common applications of the model – in retail and residential location problems – the “size” of the origin zones is expressed by the population of these areas or the income of the population (a proxy of their purchasing power). The “size” of the destination zones is expressed as retail floorspace or revenues of retail stores or number of employees. Usually, it is taken to reflect the “attractiveness” of the destination zones and alternative, multidimensional measures for this term have been proposed in the literature (C. Lee 1973, Wilson 1974, Haynes and Fotheringham 1984).

The denominator of the formula contains the critical expression of the effect of distance on the interaction between origin and destination zones. This is variously known as “friction of space”, “impedance effect of distance”, “friction against movement”, and so on. The literature contains an extensive discussion of the distance function as regards: (a) alternative ways to operationalize the concept of distance in other than metric units – such as in terms of cost, time spent on commuting between origin and destination zones, multidimensional measures combining time, money, and effort spent in commuting between zones, (b) the values of the exponent of the distance function, known also as the “distance decay parameter” – which varies with the purpose of the interaction (e.g. trip purpose) as well as with distance itself and (c) the use of other functional forms of the distance function instead of the one shown above. As to the latter issue, Wilson (1969) suggested a negative exponential function – $e^{-\beta t}$ which reflects the fact that the exponent (i.e. the magnitude of the effect of distance) varies with distance (C. Lee 1973, Wilson 1970, Wilson 1974, Cliff *et al.* 1974, Caldwallader 1976, Haynes and Fotheringham 1984).

An alternative, simple form of the model shown in equation (4.8) is the following:

$$S_{ij} = kO_i D_j f(d_{ij}) \qquad (4.10)$$

where,

S_{ij}, d_{ij} and k	are defined as above
O_i	corresponds to P_i above (O standing for Origins)
D_j	corresponds to P_j above (D standing for Destinations)
$f(d_{ij})$	a general symbol for the distance function

Sometimes the origin and destination terms are raised to some power (exponientated) to reflect the difference in importance of the “masses” of origins and destinations. O_i can be considered as the total “production” of interaction flows out of zone i and D_j the "attraction" of flows by zone j (Wilson 1974). The above, classical form of the gravity model does not ensure that the aggregate flows modeled will sum to the total flows observed in the study region. This is called the *additivity* condition and it can be expressed mathematically as:

$$\sum_{j=1}^{M} S_{ij} = O_i \ldots\ldots j = 1 \ldots\ldots M \tag{4.11}$$

$$\sum_{i=1}^{N} S_{ij} = D_j \ldots\ldots i = 1 \ldots\ldots N \tag{4.12}$$

Drawing on the above, a form of the gravity model which satisfies the additivity condition for the flows of both the origin and the destination zones is the following:

$$S_{ij} = A_i B_j O_i D_j f(d_{ij}) \tag{4.13}$$

where,

$$A_i = \left\{ \sum_{j=1}^{M} B_j D_j f(d_{ij}) \right\}^{-1} \tag{4.14}$$

$$B_j = \left\{ \sum_{i=1}^{N} A_i O_i f(d_{ij}) \right\}^{-1} \tag{4.15}$$

Based on equation (4.13), four alternative forms of the gravity formulation can be distinguished depending on whether information on the interaction sums O_i and/or D_j is available. When either one or both are not known, O_i and D_j are replaced by "attractiveness" terms W_i and W_j respectively (Wilson 1974). The attractiveness terms W_i and W_j can be operationalized in various ways. Common measures for W_i is the amount of housing available in an origin zone (perhaps of a given quality) and for W_j the number of jobs in destination zones. The four forms of the gravity model are:

(a) unconstrained – neither O_i nor D_j are given. In this case the model takes the form of equation (4.9) where W_i replaces O_i and W_j replaces D_j as follows:

$$S_{ij} = k W_i W_j f(d_{ij}) \tag{4.16}$$

(b) production-constrained – O_i is given but not D_j. In this case the model takes the form:

$$S_{ij} = A_i O_i W_j f(d_{ij}) \tag{4.17}$$

where,

$$Ai = \frac{1}{\sum\limits_{j=1}^{M} W_j f(d_{ij})} \tag{4.18}$$

(c) attraction-constrained – D_j is given but not O_i. In this case the model takes the form:

$$S_{ij} = B_j W_i D_j f(d_{ij}) \tag{4.19}$$

where,

$$Bj = \frac{1}{\sum_{i=1}^{N} W_i f(d_{ij})} \qquad (4.20)$$

(d) production-attraction-constrained (or, doubly-constrained) when both O_i and D_j are known. In this case the model takes the form of equation (4.13) and A_i and B_j are given by expressions (4.14) and (4.15).

The above summary presentation of the basic gravity (or, more generally, spatial interaction) model is discussed in the following in the perspective of the analysis of land use change. The purpose of the gravity models is basically: (a) to simulate the flows between origin and destination zones and (b) to predict these flows when changes in the origins and/or destinations occur and/or when the accessibility between origins and destinations changes (mostly through transportation network improvements). Another stated purpose of the model is the explanation of the interaction observed between origin and destination zones but this issue will be covered below in the discussion of the model's underlying theory. Land use change can, thus, be modeled as resulting from accessibility changes, changes in the destination and/or changes in the origin zones. For example, improved accessibility may lead to increases in residential land in certain zones and to decreases in residential land in some other zones. Changes in income of the population living in the origin zones may generate more flows towards the shopping areas and, hence, produce land use change in the destination zones (increase in shopping floorspace). Changes in the distribution of employment centers in the study region (in destination zones) may induce changes in the distribution of households in the origin zones which may translate into changes in the proportions of residential land in each zone. Moreover, these land use changes are assessed by taking into account the constraints on the availability of suitable land in each zone. It is noted that most of the applications and uses of the model refer to urban/metropolitan areas (and not to agricultural, forestry, open space).

Gravity models are spatially explicit, the degree of spatial representation they offer depending on the number of zones into which the study region is subdivided. There has been considerable debate about the proper number and shape of zones and the effects of the zoning system used on the results of the model (see, for example, Broadbent 1970, C. Lee 1973, Openshaw 1977, Wilson 1974, Batty 1976). The models are static or quasi-static (or, comparative static), at best, which means that they do not account for the dynamics which underlies the observed interactions. In terms of level of detail of the land uses considered as well as of the spatial behavior modeled, the most common forms of gravity models concern two main types of land use – e.g. residential and commercial, residential and employment, residential and recreation. However, to make the gravity model more sensitive to the real world variability of human behavior, an important stream of research effort has been devoted to producing disaggregate versions of the models (depending on the availability of data). For example, residential (origin) areas are disaggregated by income group or types/prices of housing; employment (destination) areas are disaggregated by different wage levels, and types of products; and, interaction has been disaggregated by various modes of transport, trip purposes, and stages (C. Lee 1973, Wilson 1974, Gordon and Pitfield 1982, Batten and Boyce 1986). In the same spirit of improving the ability of the model to replicate real world situations, various model versions employ different expressions for the attractiveness of a destination region, different measures of the "distance" term, different configurations of the transport system, etc. (Wilson 1974, Caldwallader 1975, 1976, Batten and Boyce 1986, Haynes and Fotheringham 1984).

In terms of underlying theory, the gravity model has received heavy criticisms as it reflects a social physics conception of human behavior in analogy to the Newtonian physics prototype model and lacks a grounding on theories of urban (or any other regional, environmental) system behavior (for example, see C. Lee 1973, D. D. B. Lee 1973, Romanos 1976, Sayer 1976, 1979a, 1979b). In other words, it represents a mechanistic and deterministic view of aggregate human behavior interpreted according to the laws governing the motion of particles. It has been argued that this model simply represents and reproduces empirical regularities and does not provide a theoretical explanation of the factors accounting for interaction in addition to accessibility (Romanos 1976, Sayer 1976, 1979a, 1979b). Several attempts have been made to remove the analogy with Physics and provide alternative bases for the explanations offered by the gravity model. Wilson (1967, 1970) derived the gravity model starting from concepts of statistical mechanics and applying entropy maximizing principles which draw from the Second Law of Thermodynamics (the Entropy Law). Entropy measures the probability of a system being in a particular state. The entropy of a system is proportional to the number of assignments which correspond to a particular state. The entropy maximizing procedure Wilson developed seeks to reveal the most probable state (of interaction) of the urban system which corresponds to the largest number of possible (observed) microstates (Batten and Boyce 1986). In this way Wilson arrived at the same operational form of the gravity model avoiding the problem of aggregation by starting at the macro-level rather than at the micro-level (Haynes and Fotheringham 1984). Another interpretation of the entropy approach is that it offers a measure of uncertainty or lack of information in the system and, hence, the model can be cast in probabilistic form. However, even the entropy-based derivation of the model does not avoid the analogy with Physics (the Law of Entropy is a law from Physics), it offers simply statistical explanations, and ignores the body of social theories which explain particular spatial interaction phenomena (although there are arguments to the contrary; see, for example, Batten and Boyce 1986). Drawing on this original effort, several other efforts ensued to refine the theoretical basis of the model on the same entropy-maximizing lines (see, for example, Batten and Boyce 1986).

Other scholars attempted to derive the gravity model on the basis of economic principles of **utility** maximization (Niedercorn and Bechdolt 1969, Golob and Beckmann 1971 cited in Batten and Boyce 1986, 372, Anas 1983). Employing the theory of consumer behavior, an optimal allocation of origins to destinations is obtained by postulating a **utility function** which reflects the relative preferences of people at the origin zones for the attributes of the destination zones. Assuming a collective preference (utility) function, the gravity model form is obtained by maximizing this function subject to a budget constraint (Batten and Boyce 1986, 372). However, as Haynes and Fotheringham (1984) note, this derivation ran into the problem of applying individual level explanations of behavior to a model which describes aggregate outcomes. Other avenues for deriving the gravity model in an effort to refine its explanatory capability are described in Batten and Boyce (1986) among others.

In the light of the land use theories presented in Chapter 3, the gravity formulation appears to miss several of the determinants of land use and its change. The diversity and multiplicity of forces which come into play and shape land use patterns is drastically reduced as the model applies a predetermined functional form to replicate the revealed (observed) patterns (in modeling jargon, the model is fit to the data). In this way, it collapses the intricate web of causal processes into the neutral explanatory mold of "interaction", masking, thus, the real underlying causal mechanisms of urban spatial structure and change. It ignores the contingent nature of the observed interactions as these are influenced by the particular spatial structure of the study area as well as by the socio-economic, institutional, political and bio-physical forces at play. As Sayer (1979a) has argued these models mistake the mechanisms of change for the effects of change (the interactions and the land use patterns modeled). Evidently, they are a-historical models not simply because they are not dynamic but because they ignore the historical circumstances within which land use decisions are made and changed. As Sayer (1979a, 857) puts it: "(the models) turn development and history into something that happens to us, rather than something we make."

Another point to be noted is that, given that they are models of aggregate behavior whose performance has proved to be satisfactory at high levels of spatial resolution, their application to disaggregate data sheds even more doubt on their suitability as operational devices to model human behavior. At lower levels, the diversity of human behavior and of the physical setting of human activities are much higher than at the macro-level. Similarly, the explanatory factors and mechanisms of change are much more variegated, idiosyncratic and, in general, different (at least in importance and priority) from those which are valid at higher levels. The operational form of the model which applies to the aggregate level may not be suitable to particular household groups, industrial sectors (hence, land use types), modes of transport, not to mention socio-cultural and environmental settings other than those of the urban areas of the industrialized countries where most of its applications are made. At disaggregate levels, a variety of social theories exist to analyze and explain meaningfully human behavior which the gravity formulation simply ignores and, hence, cannot accommodate into its overall structure. Hence, the weak and unsatisfactory explanatory ability of the model.

In terms of specification, despite the efforts to disaggregate the characteristics of the origin and destination zones as well as the modes of interaction between them (depending on the application), the model is restricted to representing the interaction between one pair of land uses at a time; hence, it cannot provide an overall picture of the web of interactions among different types of land uses at any point in time. As regards its disaggregate versions, it is observed that, in addition to the theoretical problems mentioned above, the models do not seem to take into account the interactions *between* the disaggregate groupings (e.g. between the location decisions of high, middle and low income groups) – the results of the disaggregate version are added to obtain the final numbers of flows, and the zonal distribution of whatever activity is being modeled. The policy variables which can be introduced in the context of the model's use for impact assessment are restricted to the land use types being represented. One of the heaviest uses of the model (especially when used in the context of integrated models which are discussed in a separate section below) concern the impacts of policy intervention in transportation, the impacts of new retail centers and improvements in residential areas. Constraints on availability of land (or, housing units) within each zone can be introduced. In this way, the model provides an avenue for simulating the impacts of various factors which in one way or another impinge on the availability of land which is suitable for particular purposes (e.g. environmental deterioration).

Despite efforts to improve the functional form of the distance function, the overall results are conditioned by the particular (multiplicative) formulation of the model. For the model to be used in impact assessment or for obtaining conditional predictions of future land use patterns, it has first to be fit (calibrated) to actual data. The model is then used to obtain forecasts using the estimated coefficients under the assumption that they will remain constant and will be the same in the projected date in the future. This is a very restrictive assumption as it implies that the same socio-economic, environmental and other conditions which gave rise to the observed data used to calibrate the model will not change and will apply when changes in the urban or regional system are introduced. This runs counter to the logic of policy interventions which is exactly to change the existing conditions and forms of behavior to achieve better (e.g. sustainable) land use patterns and forms of interaction.

The gravity model is data hungry especially in its disaggregated versions. Given that it is spatially explicit, the higher the level of spatial and land use detail required, the greater the demand for data which may be difficult to meet except in exceptional cases of complete record keeping systems. Otherwise, many data requirements may be compromised, proxy variables may be used and the results may not be those anticipated by the original modeling intent.

The "family of spatial interaction models", an expression commonly used to denote the basic model and its variants, has found numerous applications in various thematic areas – retail trade, market area and commodity flow analysis, transportation analysis and planning, residential location, migration, tourism and recreation analysis, at various spatial levels – urban, interurban, regional, interregional, and by various types of public and private agencies (e.g. transportation planning ministries and boards, planning agencies). Its use for the analysis of land use change is rather secondary and indirect compared to the other thematic uses. An exception is their use in integrated land use-transportation models where the distribution of land uses and of transportation flows are analyzed simultaneously with the main purpose of assessing the impacts of transport/accessibility on land use (see the section on integrated models).

Closing this section on spatial interaction models, a brief evaluation of the ability of these models to deal comprehensively with analysis of land use change is undertaken. Spatial interaction models can deal with only two land uses at a time; hence, their capacity to cover the complete pattern of land uses in urban, rural and other regional contexts appears to be limited. The point is that the incidence of concentrations of particular land use types in certain zones which are included in the model (e.g. residential areas) may be related to other uses which are present in these zones but which are not represented in the model. The land use changes which result from accessibility and other changes discussed before in the context of the gravity model may be modified and conditioned by the presence of these other uses.

Most important, however, is the manner in which these models conceptualize land, land use and its change and which relates to their theoretical basis. Although they are spatially explicit and account for the distribution of land uses in the zones of the study region, they reduce the modeled land use activity to the center of each zone, disregarding, hence, the actual variability of land use intensity within the zone which may affect the resulting changes in important ways. The influence of the shape, number of the zones, and distribution of land uses within each zone on the results of the spatial interaction models have been examined since the early years of their contemporary evolution (Openshaw 1977). It appears questionable, therefore, if these models can represent satisfactorily extensive land uses such as agriculture and forestry especially when the purpose of the modeling exercise is to obtain spatially differentiated land use impacts as well as the environmental impacts of these land use changes. In fact, no applications of spatial interaction models to such uses are known to this author.

In addition, only one characteristic of the land use types modeled usually enters the analysis – e.g. population of the residential areas, or the income of the population, or the revenues of the shopping areas, or their floorspace. The many other environmental and socio-economic characteristics associated with these land uses (and, more importantly, with the *land users*) are not accounted for and the models base their explanations as well as their results on a very limited set of partial aspects of a few (and not necessarily the most important in all contexts and cases) determinants of land use change. Despite efforts to develop multidimensional measures of the origin and destination terms, these models do not capture, in general, the multidimensional character of land use and its change as Chapter 3 on theories of land use change attempted to reveal. In a broader perspective, their weak theoretical foundations and **reductionist** (**deductive**) mode of analysis deprive them of the ability to represent the complex web of interactions among the bio-physical and socio-economic drivers of land use change. As land use changes result from several other causes except from those accounted for by the spatial interaction models, these models, then, have a limited ability to address a host of other (policy) questions related to other determinants of land use change; for example, the land use impacts of climatic change. In this and similar situations, the only way to use these models to analyze the impacts of determinants other than those they account for directly is to assess, outside of the model, their impacts on the origin and/or destination zones and/or accessibility and then use these estimates in the model as usual. However, the question is whether it is theoretically sound and acceptable to manipulate these estimates by means of the functional form of the spatial interaction model. In conclusion, much more research focusing especially on broader conceptualizations of land use and its change is needed to examine if, how, and to what extent spatial interaction models can address the variety and multitude of questions related to land use change.

4.5. Optimization Models

The application of mathematical programming and optimization techniques to urban and regional analysis, spurred by the post-1950s developments in solution techniques and computer technology, has an impressive record and continues to attract significant research contributions as well as to offer significant decision support in various circumstances, notably in planning. As their name denotes, optimization models are exclusively oriented towards producing solutions which optimize certain objectives defined by (interested) users/decision makers. In other words, they are fit to provide support in decision situations where the question is to choose a solution to a decision problem which satisfies one or more objectives and takes into account various constraints. Hence, they are prescriptive models although they are used also as evaluation tools. They have found important applications in the analysis of land use – especially land use planning applications – and, recently, they appear to be useful tools in the search for land use solutions which contribute to sustainable development and use of environmental and human resources. Examples of their use by public and private bodies cover the whole range from the scale of urban regions up to the global scale.

The principal criterion for classifying these models appears to be the particular mathematical programming/optimization technique they employ and this is used in the following presentation. An exception is the group of utility maximization models which are treated as a separate group as they are expressly based on and derive directly from economic theory. Models in this latter group can classified also under the particular programming techniques they utilize. The following principal categories of optimization models are presented below (Table 4.1b):

a. linear programming models

b. dynamic programming models

c. goal programming, hierarchical programming, linear and quadratic assignment, and nonlinear programming models

d. utility maximization models, and

e. Multi-Objective/Multi-Criteria Decision Making models (MODM/ MCDM).

Several of these models are used in the context of larger integrated models also as it will be discussed in the respective section below. As it was the case with the previous model groups, some of the of optimization models are direct land use (and change) models while in some others land use is treated in a more indirect fashion.

4.5.1. Linear Programming Models

Linear programming (LP) is one of the most widely used techniques in model building since the mid-1950s as it is more manageable, understandable and computationally easier than other optimization techniques. Its use in the analysis of land use is marked perhaps by the widely known Herbert-Stevens Linear Programming Model designed for the Penn-Jersey Transportation Study (Herbert and Stevens 1960). Other similar models were built in the same period such as the Southern Wisconsin Regional Plan Model (Schlager 1965) and Britton Harris' Optimizing Model – a modification of the Herbert-Stevens model (Harris 1962, 1966 cited in Romanos 1976, 63). More applications ensued in the following decades up to the present (Bammi *et al.* 1976, Bammi and Bammi 1979, Campbell, *et al.* 1992; Stoorvogel *et al.* 1995; Jansen and Schipper 1995; Latesteijn 1995). In the following, the basic structure of a LP model is presented first and, then, details of its applications drawing on the published literature are offered.

There are two main groups of LP models, the *single* and the *multiple objective* (or, *multiobjective*). The first deal with problems in which there is one objective to optimize and the second address the more realistic situation of finding solutions which satisfy more than one objective. In both cases, the structure of the optimization problem includes one or more (in the case of multiple objectives) *objective functions* and a set of *constraints*. The objective function(s) for land use problems expresses in mathematical form the question: "how much land to allocate to each of a number of land use types in order to optimize objective A (or, B, C, D)." The objectives may be, for example, maximization of (household or individual) rent-paying ability, minimization of environmental impacts, maximization of population income, minimization of the cost of development (or maximization of the benefits of development), etc. The constraints which can be taken into account depend on the case but representative objectives include: lower and upper limits on land use (reflecting, for example, zoning or natural constraints such as land suitability), other constraints on development, availability of labour, and so on. Examples of particular LP models are given below.

4.5.1A *The Herbert-Stevens Linear Programming Model*

The *Herbert-Stevens Linear Programming Model* (Herbert and Stevens 1960) was built with the purpose to obtain optimal distributions of households to available residential land in the context of the larger, comprehensive model of metropolitan structure designed to locate land-using activities for the Penn-Jersey Transportation Study (Wilson 1974, Romanos 1976). It assumes a study region subdivided into zones and it operates iteratively. It receives **exogenous** forecasts of the amount of available residential land as well as of the number of households to be located in the study region within each iteration period. Basic assumptions upon which the model rests include the following:

1. Households choose their location on the basis of an available total budget, a "market basket", and the costs of obtaining those items. The "market basket" is a unique combination of a residential bundle (a house, an amenity level, a trip set, and a site of a particular size) and a bundle of all other commodities consumed annually by a given household group. A household group is a collection of households with similar residential budgets and tastes as regards housing.
2. For each household group, a number of market baskets exists among which the household is indifferent.
3. The household tends to optimize its condition by electing from the set of market baskets the one which maximizes its savings; these are defined as the rent-paying ability of the household for a particular site in a particular area.

The objective to be maximized is the aggregate rent-paying ability which corresponds to maximization of savings of each household. In mathematical form:

$$\max Z = \sum_{k=1}^{U}\sum_{i=1}^{n}\sum_{h=1}^{m} X_{ih}^{K}(b_{ih} - c_{ih}^{K}) \qquad (4.21)$$

subject to:

$$\sum_{i=1}^{n}\sum_{h=1}^{m} s_{ih}X_{ih}^{K} \le L^{K} \qquad (4.22) \text{ and}$$

$$\sum_{K=1}^{U}\sum_{H=1}^{m} -X_{ih}^{K} = -N_i, \text{all} X_{ih}^{K} \ge 0 \qquad (4.23)$$

where,

U	total number of zones of the study region, K=1. . . . . . . .U
n	household groups, $i = 1, \ldots\ldots\ldots n$
m	residential bundles, $i = 1, \ldots\ldots\ldots m$
b_{ih}	residential budget allocated by a household in group I to purchase a residential bundle h
c_{ih}^{k}	annual cost to a household of group i of the residential bundle h in area K – exclusive of site cost
s_{ih}	number of acres in the site used by a household of group i if it uses residential bundle h
L^{k}	L number of acres available for residential use in area K in a particular iteration
N_i	number of households of group i that are to be located in the zone during a particular iteration
X_{ih}^{k}	number of households of group I using residential bundle h located by the model in area K

Its designers as well as its commentators contend that it is a simple, operationalized expression of Alonso's urban land market theory (Wilson 1974, Romanos 1976). The term $(b_{ih} - c_{ih}^{k})$ "represents the bidding power for site rent, which is clearly equivalent to Alonso's bid-price, and so the model maximizes bid-prices subject to constraints in land availability and finding everyone a house. An analysis of the dual shows that, if bid-rent is maximized, actual rent paid is minimized" (Wilson 1974, 198). (Note: Alonso's model is described in this section under the utility maximization models group).

The Herbert-Stevens model has many desirable features such as: (a) the fine level of aggregation with respect to households which allows the inclusion of households of different behavioral characteristics and permits a more realistic land allocation process, (b) the simulation of the market clearing mechanism through a simple linear programming action, (c) the inclusion of policy constraints on the amount of available land, (d) an operational form which makes its real world application possible. However, it has several disadvantages as well. The linear programming formulation imposes the linearity assumption on both the objective function and the constraints which may not be always the case in the real world (a general problem with all LP models). The (good quality) data requirements of the model are heavy. The iterative nature of the model ensures that the allocation of households within the given iteration period will be optimal but it does not ensure that the allocation will be optimal in the aggregate. Overall, these and other constraints such as available time and resources, and the capabilities of available computers and computing methods at the time it was designed, prevented the model from becoming operational (Wilson 1974, Romanos 1976, Kain 1986).

Britton Harris and his students attempted to modify the original Herbert-Stevens formulation to overcome certain of the problems it posed to easy operationalization. To assess the desired or actual allocations of households' budgets to housing and nonhousing goods and services, Harris (1962, 1966 cited in Romanos 1976, 62-63) constructs a preference function following Alonso' theory of the urban land market (see Chapter 3). He uses also the housing preference structure of the population to predict residential behavior and to evaluate the relative differences in utility among consumers under alternative arrangements of the housing stock. However, there is not theoretical justification of the housing preferences (which are assumed to be homogeneous); only the mathematical expression of the preference function. The linear programming part of the Harris's model is similar to the Herbert-Stevens model presented above (Romanos 1976).

The Herbert-Stevens and the Harris' optimizing model can be considered land use change models in the sense that, although they do not assess changes in the uses of land directly, they allocate households to available residential land on the basis of particular behavioral assumptions. The prescribed optimal allocations provided by the models (within each iteration period) can be compared with actual allocations at the base period to obtain forecasts of land use changes of a qualitative nature; i.e. differences in the residential uses of land occupied by household of different socio-economic profiles. Apparently, such assessments are more meaningful in the context of broader models of land use and its change. As regards the Herbert-Stevens model, this was part of the Penn-Jersey Transportation Study model which is presented in the section on integrated models.

4.5.1B *The Southern Wisconsin Regional Plan Model*

Another LP model, the *Southern Wisconsin Regional Plan Model* (Schlager 1965) has an objective function which minimizes the total cost of developing urban land in a given zone of the study area under land availability constraints. More specifically, the model is as follows:

$$\min C_t = \sum_{i=1}^{N} c_i X_i \qquad (4.24)$$

subject to:

$$\sum_{i=1}^{N} d_i X_i = E_k \qquad (4.25)$$

$$\sum_{i=1}^{N} X_i \leq F_m \qquad (4.26)$$

$$X_n \leq G X_m \qquad (4.27)$$

where,

X_i	units of a given land use type in the zone
c_i	cost of developing a unit of land of a given type in the zone
E_k	total land use demand requirement for land use k
d_i	service ratio coefficients which provide for supporting service land requirements necessary for primary land use developments such as streets
F_m	upper limit on land use of a particular type in zone m
G	ratio of land use type n allowed relative to land use type m with the land use types m and n in the same or in different zones

According to its designer, this model is a design aid and makes no claims of modeling personal preferences of families or other aspects of human economic and social behavior (Schlager 1965 cited in Romanos 1976, 61). The model emphasizes mostly the determining effect of development costs (which are affected, among others, by environmental factors such as soil conditions, etc.) on the land use distribution in an area. Romanos (1976) observes that this model, while inheriting all the problems associated with LP models, does not represent any improvement over the Herbert-Stevens models; on the contrary, it lacks the detail and ingenuity of the latter model as well as the economic nature assumptions about individual behavior.

4.5.1C *The Du Page County Regional Planning Commission's Model*

Another linear programming model suggested in Bammi *et al.* (1976) has the basic structure of the prototype LP model and, in addition, incorporates environmental considerations in both the objective functions and the set of constraints, an important omission of past models (see, also, Bammi and Bammi 1979). Bammi and Bami (1975 cited in Bammi *et al.* 1976) developed a *multiple objective linear programming model* for the Du Page County Regional Planning Commission to provide optimal allocations of land use types by simultaneously considering several objective functions and constraints. This land use model has been used in developing the County's Comprehensive Plan for 1990.

The model has seven objective functions each corresponding to one of the following objectives set by the county's planners:

a. minimization of conflict between different land uses
b. minimization of travel distance of new trips to the existing transportation network
c. generation of a fiscally sound plan
d. minimization of air pollution effects
e. minimization of energy consumed by stationary and mobile users
f. minimization of capital expenditures for community facilities, and
g. minimization of the cost to the environment as a result of land development.

The environmental cost of land development was calculated for each of the 147 analysis regions in the county on the basis of their particular topographic, geologic, natural resources, wildlife and floodplain characteristics (Bammi *et al.* 1976).

The constraints taken into account in the multiple objective optimization solution procedure included:

a. efficiency constraints on the individual objective functions
b. lower and upper limits on each type of land use
c. undeveloped acreage by region
d. local commercial zones
e. institutional zones
f. local open-space zones
g. minor floodplains and local open space
h. major floodplains, peat and muck, bedrock outcrops, and regional open space.

The *efficiency of an objective function* was defined as its minimum value divided by its current value for a particular solution; this reflects the requirement that all objective are equally satisfied – i.e. they have the same efficiency. The constraints on upper and lower limits of each land use type are obtained by forecasting population and employment, by choosing a particular mix of residential dwelling units for new housing, and by setting open space standards. The undeveloped acreage in each region is measured by totaling all vacant parcels of land within the region. Local commercial zones relate total (new plus existing) commercial land to total population according to a desired standard of commercial acreage per thousand people. Institutional zones relate total institutional land to total population in the region. Local open space zones and the open space constraints are detailed in Bammi *et al.* (1976). A mathematical formulation of the optimization model and a list of the environmental conditions which were taken into account are included in the same work. It is noted, finally, that the above model has been used by Brill *et al.* (1982) in the context of a broader effort to develop a method (the HSJ – Hop, Skip, Jump) for discriminating among the solutions produced by mathematical programming models which, although they perform equivalently in terms of the modeled objectives, they are associated with drastically different land use patterns.

4.5.1D *Multiple Objective Linear Programming (MOLP) Models*

Multiple objective linear programming models (MOLP) address the question of land use solutions which meet more than one objective. Of particular importance in this context are environmental objectives and constraints. The role of environmental factors in determining the optimal allocation of land uses in a region has always been of high importance in the context of planning in agricultural regions. In addition, the need for detailed information on spatial data as well as for the spatial representation of the optimal land configurations always figured high on the researchers wish lists. Progress on and diffusion of GIS techniques and technology since the 1980s mostly has made possible the use of information of better spatial detail and specificity. Linear programming models for agricultural regions appeared which are sensitive to the distribution of environmental conditions in the study areas and which are linked to GIS to provide for mappings of the optimal solutions produced by the models. Representative applications are found in Campbell, *et al.* (1992), Stoorvogel *et al.* (1995), Jansen and Schipper (1995), and Stoorvogel (1995). In Campbell, *et al.* (1992), the purpose is to match the planned or anticipated demand for agricultural products with the ability of the agricultural sector (which includes its natural resources endowment and land suitability) of the study area to meet the demands. The objective function of the (multiple objective) LP model seeks to minimize the cost of meeting these demands and includes two components: (a) the cost of local production and (b) the cost of imports to complement local production to meet local demand. The assumption is that the economic costs of production determine whether local demand will be met by local production or by imports subject, among others, to the natural resources constraints facing the study region. A summary mathematical formulation of the LP problem, is shown below following Campbell, *et al.* (1992):

$$\text{minimize } \mathbf{CX} + \mathbf{MY} \qquad (4.28)$$

subject to:

$$\mathbf{AX} \leq \mathbf{B}, \qquad (4.29)$$

$$\mathbf{KX} + \mathbf{TY} \geq \mathbf{D}, \qquad (4.30)$$

$$\mathbf{X},\ \mathbf{Y} \geq \mathbf{0} \qquad (4.31)$$

where,

C	a $1 \times n$ vector of variable costs associated with local production on 1 acre of land
X	a $n \times 1$ vector of the number of acres used by each of the local production activities
n	the number of different production technologies for various crops – the technologies depend on farm size, geographic region, soil and environmental conditions
M	a $1 \times m$ vector of unit costs on the m import possibilities
Y	a $m \times 1$ vector of the number of units of goods imported to complement local production to meet local demand
A	the $r \times n$ matrix of input coefficients required to produce 1 acre of local output for the n production activities
K	the $m \times n$ matrix of outputs per acre produced by the n local production activities and by using the inputs in **A**

T	an $m \times m$ identity matrix which allows imports of goods to be added to local production
B	a $r \times 1$ vector of resources available for local production and
D	an $m \times 1$ vector specifying the national demand for agricultural outputs

C, **M**, **A**, **K**, **T**, **B** and **D** are all fixed. The object of the LP model is to choose a set from **X** and **Y** so that the national demands, **D**, are satisfied, the local resources, **B**, are not exceeded and the total cost is minimized. The inputs to the LP problem are obtained from a GIS data base created from map and statistical information using a GIS software. The results of the LP problem, the optimal crop allocations to the regions of the study area, were mapped using the GIS following a rule-based procedure developed for this purpose and using expert knowledge (Campbell *et al.* 1992).

Stoorvogel *et al.* (1995) followed a similar LP modeling procedure with the exception of the specification of the objective function and the set of constraints. The LP model employed is part of a broader methodology developed for the quantitative analysis of land use scenarios and which is operationalized by means of a specially developed software called MODUS. MODUS transforms databases from one of the models or tools to the specific requirements of the others. The study region is subdivided into a number of farms and the objective function of the LP model maximizes farm income in the study area. The constraints of the model describe the availability of resources (e.g. land and labor) and restrictions on sustainability parameters. The latter include the soil nutrient balance and a biocide index.

The study employed a detailed and elaborate methodology for distinguishing LUSTs – Land Use Types of a Specified Technology – which provides a detailed picture of the combinations of land using units, land use types and quantitative descriptions of the technology and corresponding inputs and outputs (Jansen and Schipper (1995). The idea of LUSTs borrows from FAO's methodologies for land evaluation (see, for example, FAO 1976, 1978, 1995). A spatial database was set up using data from farm surveys, field surveys, literature surveys, field experiments, expert knowledge, and maps of the area. The results of the model runs – optimal crop allocations among the farms of the study area – were mapped with the use of the MODUS software. Stoorvogel (1995) provides details on the development of a GIS-models interface which makes possible the translation of the results of external model calculations into a GIS and, hence, the visualization of their spatial distribution.

Another application of linear programming is in producing future land use scenarios and exploring their implications. An example is offered by Latesteijn (1995) who presents a multiple objective LP model which differs from the previous in that has been applied at the level of a group of nations; namely, the European Union (EU). The presence of more than one objectives necessitates the application of special optimization procedures to optimize them, either simultaneously or iteratively. In the case discussed, the latter approach was adopted, called "Interactive Multiple Goal Programming" (IMGP), which allows the optimization of a set of goals interactively. In this way, it is possible to study trade-offs among goals. The core of the procedure consists of an LP model called GOAL (General Optimal Allocation of Land Use). The broad objective of the model's application is to arrive at optimal combinations of agricultural land use types necessary to satisfy an exogenously determined future demand for agricultural and forestry products within the EU. The particular goals which were translated into respective objective functions were the following:

a. maximization of yield per hectare
b. maximization of total labor
c. maximization of regional labor
d. minimization of total pesticide use
e. minimization of pesticide use per hectare
f. minimization of total N-fertilizer use
g. minimization of N-fertilizer use per hectare, and

h. minimization of total costs.

Differing political philosophies and attitudes of the decision makers can be introduced in the model interactively by setting limits to the achievement of particular goals while the others are optimized. In this way, the model can generate scenarios showing the effects of different policy priorities on land use allocation among the land use types considered in the modeling exercise. The model's constraints include the satisfaction of exogenously defined future demand as well as particular socio-economic, land use and environmental constraints applying to particular regional and local situations in the EU.

The model uses a zonal system consisting of 22,000 Land Evaluation Units for the whole area of the EU (at the time of the model's application). The suitability of each unit for various types of farming is assessed using the Automated Land Evaluation System (ALES) and it is accomplished with the use of GIS. Production potentials for suitable locations are also calculated by means of a simulation model which are then translated into cropping systems using the notion of Best Technical Means. Expert knowledge is used to arrive at cropping systems which are acceptable from both an economic and an agronomic point of view. This information is combined with alternative policy priorities, e.g. attaining highest possible yields, reducing the environmental impacts of agriculture, preserving agricultural land in the EU, to define feasible field systems.

Latesteijn (1995) makes clear that the model is not used to produce a forecast. The scenarios generated are meant to explore technical possibilities to attain a set of objectives. Policy instruments, such as price changes and assumptions about the behavior of the actors as well as institutional obstacles are not taken into account. The results of the model indicate the technical limitations associated with policy change. The options explored through the model can be used to determine to what extent current policy can cope with the major developments generated in the scenarios. These include land use changes and their implications such as increasing productivity and decrease in land-based agriculture. In other words the results can serve as guidelines for the development of future policies.

4.5.2. Dynamic Programming Models

Another class of optimization techniques which have found application in problems of land use analysis are offered by dynamic programming models (DP). "Dynamic programming is a mathematical programming technique often useful for making a sequence of *interrelated* decisions. It provides a systematic procedure for determining the combination of decisions that maximizes overall effectiveness... In contrast to linear programming, there does not exist a standard mathematical formulation of "the" dynamic programming problem. Rather, dynamic programming is a type of a general type of approach to problem solving, and the particular equations used must be developed to fit each individual situation" (Hillier and Lieberman 1980, 266). A simplified adaptation of this approach to the case of deciding on the optimal allocation of land uses in a study area is provided below following Hillier and Lieberman (1980).

A study area is subdivided into cells which represent the "stages" of a dynamic programming problem. For each cell, a number of candidate land use types is considered; these represent the "states" of the DP problem. Each of the land use types (states) has certain characteristics such as development costs, environmental impacts, etc. which determine the value of the "policy" (of the objective function) in the DP terminology. One of the states is chosen for each stage of the problem. The solution to this problem seeks to identify the optimum allocation of states to stages (i.e. land use types to cells of the study region) which optimizes an objective such as maximization of development benefits or minimization of development costs, etc. (subject to a number of applicable constraints).

The solution procedure starts with one cell of the study area and finds the optimal "policy" for this cell; i.e. the land use type which maximizes the value of the objective function. It then gradually adds cells, finding the current optimal solution from the previous one, until all cells of the study area are considered. The decision of which land use type to choose for each cell is associated with the choice of land use types in the remaining cells. In other words, given a current land use type in a cell, the optimal "policy" for the remaining cells are independent of "policy decisions" made for the previous cells. The solution procedure starts by finding the optimal "policy" for each land use type of the last cell; a solution which is usually trivial. Then, a recursive relationship is established that identifies the optimal "policy" for each land use type in cell n, given the optimal "policy" for each land use type for cell (n+1) is available. Therefore, finding the optimal "policy" when starting with land use type s at cell n requires finding the optimizing (maximizing or minimizing) value of the objective function for this cell. Using the recursive relationship, the solution procedure moves *backwards* cell by cell – each time finding the optimal "policy" for each land use type of that cell – until it finds the optimal "policy" when starting at the *initial cell*.

It is important to keep in mind that the application of DP is justified when the decision problem involves making a sequence of interrelated decisions. This is the case with determining the optimal allocation of land use types to the sub-basins of a watershed for the purposes of minimizing flood hazard (evidently on the downstream areas of the basin) while maximizing economic rent to land, a problem addressed by Hopkins *et al.* (1978). They applied a dynamic programming formulation which "yields the optimal allocation of uses to maximize economic rent to land net of flood damage, while specifically considering the impact of upstream development on downstream flood levels and the impact of downstream development on the amount of damage given flood levels" (Hopkins *et al.* 1978, 95). According to the authors, the DP can be described mathematically as:

$$f_N(X_N) = \max \sum_{n=1}^{N} r_n(X_n, D_n) \qquad (4.32)$$

subject to:

$$X_{n+1} = t_n(X_n, D_n) \text{ for } n = 1 \ldots\ldots N \qquad (4.33)$$

where,

$f_N(X_N)$	the function yielding the highest aggregate bid price for each final outflow level (or sub-basin)
D_n	the set of possible land uses for sub-basin n
X_n	the set of possible peak inflows to n
r_n	the return function for each sub-basin which is expressed as: $r_n = v_{jn}a_n - c_{jn}^k d_n^k$ (4.34)
where,	
v_{jn}	bid price per acre of use j in sub-basin n
a_n	number of acres in sub-basin n
c_{jn}^k	present worth of flood damage per acre of use j in sub-basin n at depth k
d_n^k	acres flooded to average depth k in sub-basin n

It seems that several land use allocation problems may have a similar structure to the one addressed by the above study, justifying, hence, the application of dynamic programming for finding optimal land use patterns which satisfy economic and environmental objectives.

4.5.3. Goal Programming, Hierarchical Programming, Linear and Quadratic Assignment Problem, Nonlinear Programming Models

Three other programming techniques have been used to build land use optimization models which are discussed in this section but they are not as widespread as those presented before; namely, goal programming, hierarchical programming, linear assignment problem, and nonlinear programming.

Goal programming (GP) is a mathematical programming technique which addresses the issue of striving to satisfy more than one goals simultaneously. According to Hillier and Lieberman (1980) "The basic idea is to establish a numerical goal for each of the objectives, formulate an objective function for each objective, and then seek a solution that minimizes the (weighted) sum of deviations of these objective functions from their respective goals" (p. 172). A simplified presentation of the basic mathematical formulation of a GP problem is presented below following Hillier and Lieberman (1980).

Assume that k objectives are considered, expressed in terms of a number of decision variables $(X_1, X_2, ..X_n)$. For each objective, let c_{jk} be the coefficients in its objective function and g_k the goal for this objective function. The solution being sought is the one that comes as close as possible to attaining all of the following goals:

$$\sum_{j=1}^{n} c_{j1} X_j = g_1 \qquad \text{(goal 1)} \qquad (4.35)$$

$$\sum_{j=1}^{n} c_{j2} X_j = g_2 \qquad \text{(goal 2)} \qquad (4.36)$$

$$\sum_{j=1}^{n} c_{jk} X_j = g_k \qquad \text{(goal k)} \qquad (4.37)$$

Because it is not possible to attain all goals simultaneously, it is necessary to make explicit the meaning of the "as close as possible". In the simplest case, under the assumption that deviations from goals are equally important for all goals, the composite function for the goal programming model takes the following form:

Minimize the sum of deviations from goals:

$$Z = \sum_{k=1}^{K} \left| (\sum_{j=1}^{n} c_{jk} X_j - g_k) \right| \qquad (4.38)$$

Depending on the details of the particular GP formulation, various solution techniques have been developed.

Goal programming models have been applied to private sector decision problems but their application to public sector decision situations (such as those involving issues of land use allocation) has been criticized as, for example, it is not easy and straightforward (nor politically expedient) to specify the values of the goals required for the GP formulation. Nevertheless, they have found applications in forest management, agricultural and recreational resource planning, and industrial and residential location problems (Lonergan and Prudham 1994). Lonergan and Prudham (1994) cite Dane *et al.*'s (1977) application of a goal programming model to "assist with planning decisions for the Mount Hood National Forest in Oregon. The model was able to provide information on the sensitivity of land allocations to combinations of planning goals, the goal constraints that had the greatest effect on model solutions, the sensitivity of allocations to goal priorities, and the trade-offs between goals" (Lonergan and Prudham 1994, 429). Lonergan and Prudham (1994) cite also an application of a similar model they have built for resource management purposes in Eastern Ontario, Canada. The model included 6 planning goals and a set of constraints which referred to: (a) technical and resource constraints, (b) economic efficiency, (c) regional income and employment generation, (d) energy efficiency, and (e) environmental quality. For our purpose, the important aspects of this application are the spatial resolution of the application – the model considered 27 townships in the region and included land use variables as well as land availability constraints.

Hierarchical optimization is a multidimensional (or, multiobjective) programming approach which is appropriate to problems in which the objective functions can be ranked in an ordinal way from, say, "important", to "next most important", etc. The solution procedure is based on sequential optimization of the objective functions according to the established rank order. The set of constraints at each stage of the optimization is co-determined by the optimal results obtained in previous stages (Nijkamp 1980). A formal presentation of the hierarchical programming model is given below following Nijkamp (1980).

Assume a set of objectives which are translated into a set of objective functions: $\omega = \{\omega_1, \omega_2 \ldots . \omega_n\}$ expressed in terms of a set of decision variables $X = \{x_1, x_2, \ldots . x_n\}$. In order to construct a hierarchical programming model, the objective functions have to be rank ordered:

$$\omega_1 \succ \omega_2 \succ \ldots\ldots \succ \omega_n \qquad (4.39)$$

where the symbol $\succ$ denotes "preferred to". The goals are assumed to be conflicting, such that:

$$\omega_n(x_n^0) \succ \omega_n(x_n^0) \text{ for every } n \qquad (4.40)$$

where,

x_n^0 is the $k \times 1$ vector of optimal values of the decision variables related to the maximum of the objective function ω_n.

If a trade-off between the objectives is possible, the purpose is to find compromise values of the decision variables $x, x*$, such that at least the following conditions are satisfied:

$$\omega_n(x^*) \geq \beta_n \omega_n(x_n^0) \quad \text{for every } n \qquad (4.41)$$

where ω_n has to be maximized and where the tolerance parameter β_n should be smaller than or equal to 1. The reverse holds if ω_n has to be minimized.

The parameter β_n is associated with the maximum tolerance deviation from the absolute optimum $\omega_n(x_n^0)$. Therefore, β_n indicates the maximum proportion of the original objective function ω_n which be traded-off against other objective functions. The β_n coefficients are called *trade-off coefficients*. Depending on the specification of the goal priorities and the trade-off coefficients, various solution procedures are available.

Nijkamp (1980) offers an example of the application of hierarchical programming to an industrial land use problem in a newly established industrial area near Rotterdam. Seven candidate activities (related to seven different land use types) were considered. For each activity the following were specified: minimum and maximum land use requirements, employment coefficient (employment per hectare of land occupied) and air pollution coefficient (total emissions per year per hectare). The problem was to find the optimal mix of uses in the area which satisfied two conflicting objectives: maximization of regional employment (ω_1) and minimization of total air pollution (ω_2). In this case, two rank orders of the goals were possible; either $\omega_1 \succ \omega_2$ or $\omega_2 \succ \omega_1$. Hence, two different hierarchical models could be solved. The solution of each model depends on the values of the trade-off coefficients assumed and it is not unique, in general, unless additional information is provided or the coefficients are specified a priori. It is noted that in this example application of hierarchical optimization the model was not spatially explicit.

Linear and quadratic assignment models is another group of programming models which are based on the prototype assignment problem – a special case of the transportation problem in operations research. The prototype problem (adapted to the case of land use) answers the question of how to match available land-using activities to available sites so as to optimize an objective such as minimization of development costs (total or net), maximization of benefits (total or net), etc. In addition to the intuitive appeal of this prototype problem, its suitability to modeling optimal land use allocations lies in that it is suited to analysing efficient allocations of indivisible resources – such as land use, plants, etc. (Koopmans and Beckman, 1957), a condition which is not met by most programming techniques which assume divisible resources (i.e. fractions of the quantities modeled are meaningful in practice). A number of related theoretical model formulations have followed the original contribution by Koopmans and Beckman (1957) which would purportedly assist planners in making land use decisions. However, no real world applications seem to have appeared; only illustrative examples are offered by the authors in the context of the theoretical model formulations. In the following, an elementary form of the linear assignment problem is presented and the most important aspects of the related theoretical model proposals are discussed.

Given a number of n sites into which the study area is subdivided and an equal number of candidate land use types as well as the "costs" associated with each land use type at each site (i.e. given the $n \times n$ matrix cost coefficients), the question is which assignment of land use types to the sites of the study area minimizes the development costs (or, maximizes the benefits depending on the available data and demands of the decision environment). The mathematical formulation of this problem is as follows:

$$\text{minimize } \sum a_{ij} X_{ij} \tag{4.42}$$

subject to:

$$\sum_{i=1}^{n} X_{ij} = 1 \tag{4.43}$$

$$\sum_{j=1}^{n} X_{ij} = 1 \tag{4.44}$$

where,

a_{ij} the cost coefficients

X_{ij} a variable taking the value of 1 if activity i is assigned to site j and the value of 0 if it is not

The problem can be solved either as a linear programming problem by using the SIMPLEX method or as a transportation problem or by means of the more efficient Hungarian algorithm (Hillier and Liebermann 1980, Spivey and Thrall 1970). It has been shown that this particular formulation always has integer solutions (Hillier and Liebermann 1980). The **Lagrange multipliers** associated with constraints (4.43) and (4.44) are denoted q_j and q_i respectively. Their optimal values indicate how quickly the optimal value of the objective function changes as the constraint associated with the multiplier is relaxed. In mathematical programming, constraints usually represent the availability of resources. In the context of land development, these resources are usually land and capital and Lagrange multipliers are interpreted as prices or rents. More specifically, following Moore (1991): "If the owners of land and capital make these inputs available to the plant operator offering the highest bid, then the optimal values of q_j and q_i identify equilibrium plant (land use type in the present contribution) and site rents, respectively… At any location other than the optimal site (or, an equivalent site), the combined land and capital rents determined by the market exceed the **seminet revenues** available, and the plant operator would experience a loss at a suboptimal site. Thus, the configuration that maximizes the system's seminet revenues also implies that there is no incentive for any locator i at optimal site j to consider exchanging locations with anyone else and that all locators are in spatial equilibrium" (Moore 1991, 10). The direct relationship of the assignment model formulation to the urban land market theory (see Chapter 3) is described in Moore (1991): "Plant rents accrue to the owners of the mobile factor (capital) while site rents accrue to the owners of the immobile factor (land). Lind (1973) showed that the standard (Wingo, Alonso, Muth, E. Mills) economic model of urban land use is really a special case of the assignment model in which there are large numbers of bidders and competition of such intensity that all plant rents must be bid for sites. In the case of few bidders and discrete sites it is sufficient for owners of capital (or developers) to outbid a next-highest bidder for a given site and retain any remaining profitability" (Moore 1991, 10).

The linear assignment model does not take into account the influence on a given site of the uses in neighboring sites, an untenable assumption in real world situations. This assumption is relaxed (within the structure of the assignment problem) in quadratic assignment problems which include an "interaction" term and have received interesting interpretations in terms of economic theory as well as in terms of the simultaneous nature of land use and transportation decisions (see, Koopmans and Beckmann 1957, Gordon and Moore 1989). However, although more realistic, these models are not easily applicable given their high data requirements and the computational difficulties associated with their mathematical treatment (stemming from the modeled nonlinearities). Moore and Gordon (1990) offer another extension of the linear assignment model. They develop a model of a decentralized urban development process where land development is represented as a sequence of activity shifts resulting from locators' efforts to maximize net revenues by mitigating congestion costs and other externalities. Their *sequential programming model* involves solving a series of linear assignment problems that track urban land use through time. Briassoulis (1995) uses the basic idea of the linear assignment problem to propose a compromise solution procedure for locating hazardous facilities in an area by taking into account development benefits and risk associated with these facilities.

Non-linear programming models are encountered less frequently in the literature and even less frequently in actual applications given the computational difficulties associated with their solution. Fischer *et al.* (1996a) cite FASOM (Forest and Agriculture Sector Optimization Model) which is a dynamic, multi-market, multi-period, nonlinear programming model for the forest and agriculture sectors of the United States built by Adams *et al.* (1994 cited in Fischer *et al.* 1996a, 6). The model considers 11 supply regions and a single demand region – the nation – and depicts the allocation of land to competing activities in the forest and agriculture sectors. Its purpose was to evaluate the welfare effects on producers and consumers of alternative carbon sequestration policies. However, it pays limited attention to land use and land cover change and to the processes of resource degradation (Fischer *et al.* 1996a). *Utility maximization models* applied to the analysis of land use and its change are discussed as a separate group not because they are based on a common mathematical solution technique but because they all share a common theoretical basis drawing from economic theory. Models in this group have been formulated mathematically usually as linear or nonlinear optimization models. In fact, the models included in this group can be classified under one of the previous model groups presented before. Moreover, utility maximization models constitute the basis for large-scale integrated models of land use change to be presented in a later section. In the following the basic concepts and approaches as well some well-known land use-related models are presented.

Welfare economics (and microeconomic theory, in general), distinguishes between producers and consumers of economic goods and services. Each group aims at maximizing some goal; producers are assumed to strive to maximize their profits from selling the goods and services they produce (the supply side of the economy) while consumers aim to maximize their **utility** from consuming various goods and services (the demand side of the economy). The characteristic feature of welfare economic theories of production (supply) and consumption (demand) and of the models derived from them is their emphasis on individual behavior. *Utility theory* of neoclassical economics is founded upon the principle of consumer sovereignty. The analysis of both producer and consumer behavior starts from the individual and then aggregates over all individuals present in the economic system to derive the aggregate behavior – the economy-wide (or, market) demand and supply conditions. The determining factor of the behavior of any individual is the price of goods and services, the signal to which both producers and consumers respond and adapt their behavior (production and consumption of goods) respectively.

In the analysis of a given economic system, two broad cases are distinguished: (a) partial equilibrium and (b) general equilibrium. In the first case, the analysis seeks to determine the market conditions which are (or, should be) met when either producers or consumers maximize their goals (profits, utility). In the general equilibrium case, the conditions which ensure equilibrium between market demand for goods (consumption) and market supply of goods (production) are sought. In both cases, the equilibrium can be either static or dynamic and competitive or non-competitive. The most frequent assumption made is that of competitive equilibrium.

The role of land and land use in the analysis of consumer and producer behavior has undergone changes over time. The French physiocrats considered the production capacity of land as the main source of welfare (Gould and Ferguson 1980). Classical economists introduced capital and labor as additional factors of production and considered the possibility of stagnant economic development due to limits on available natural resources and, in particular, agricultural land. In neoclassical economics – where the models considered here belong – the emphasis shifted to the productive capacity of labor and capital. Land is not ignored but it is considered as a fixed factor of production and as a special form, a component of capital; land and capital are considered substitutes in several cases (Nijkamp and Soeteman 1991). In this form, land (associated with certain land uses) enters the economic analysis of producer and consumer behavior. In broad terms, changes in the demand and supply of goods and services lead to land use changes. The modeling approaches can be distinguished into demand-oriented, supply-oriented and market equilibrium approaches. In the following, the broad structure of the modeling approaches which have developed in the framework of neoclassical economics are presented.

Demand-oriented modeling approaches are the most widely utilized of the three mentioned above. They draw on the micro-economic theory of consumer behavior and consider the supply of space (e.g. availability of housing, land, resources) as fixed. The individual consumer (usually the household) spends its available income (budget) on various goods, $x_1, x_2 \ldots ..x_n$, bought in the market at market prices. One of the goods purchased is land-based such as housing. The household derives its utility from consuming different combinations of these goods; hence, the assumed purpose of its behavior is maximization of its utility subject to the available budget constraint. This is expressed in mathematical notation as:

$$\max U = U(x_1, x_2 \ldots ..x_n) \qquad (4.45)$$

subject to:

$$w - \sum_{i=1}^{n} p_i x_i = 0 \qquad (4.46)$$

where,

w is available income
p_i is the price of good x_i, and
x_i is the quantity of good x_i being purchased (demanded).

The solution to this maximization problem gives the conditions of household equilibrium. Following Batty (1976), to maximize (4.45), a Lagrangian L is constructed:

$$L = U(x_1, x_2, \ldots x_n) + \psi\left(w - \sum_{i=1}^{n} p_i x_i\right) \qquad (4.47)$$

where,

ψ is the undetermined **Lagrange multipliers**. Differentiating (4.47) with respect to each x_i and setting the resulting equations equal to 0, gives the first-order conditions for a maximum:

$$\frac{\partial L}{\partial x_i} = U_{xi} - \psi p_i = 0, \quad i = 1, \ldots \ldots n \qquad (4.48)$$

By manipulating (4.48), the first-order conditions can be written as:

$$\frac{U_{xi}}{U_{xj}} = \frac{p_i}{p_j}, \quad i \neq j \qquad (4.49)$$

Equation (4.49) represents the well-known result that micro-economic equilibrium occurs when the ratio of the marginal utilities equals the ratio of the prices of goods i and j considered.

This formulation of (individual consumer or household) utility maximization subject to a budget constraint has formed the starting point for a large number of theoretical and modeling contributions in urban and regional economics. In urban economics, most contributions refer to the location behavior of the firm or of the household (see Arnott 1986, Beckmann and Thisse 1986, Stahl 1986) and the resulting patterns when individual behavior is aggregated over the whole urban region. A large number of models concern the housing market – as residential land use is the most extensive, land-consuming use in urban areas. In fact, these are the only land use (and change) models which are discussed here from the large body of (urban) location models as land use is included explicitly in the models as an area of land occupied by housing and not as a point in space. It is reminded that this contribution refers to land use (and the related patters) and not to location (and the related patterns) (see also the introductory remarks of this chapter). At the regional level, the land use types analyzed are mainly agricultural and forest uses. Other important applications of the utility maximization modeling framework include travel choice, shopping behavior, and recreation behavior. It has been employed also in integrated urban and regional land use models which are discussed in a later section. Recall also that the utility maximization framework has been used as a basis for deriving spatial interaction models, hence, providing a less mechanistic, more social-science oriented rationale for their use and interpretation (Niedercorn and Bechdolt 1969 cited in, among others, Batten and Boyce 1986, Haynes and Fotheringham 1984).

The first model to be discussed is the much-celebrated *Alonso model* or the *urban land market* model. The theoretical aspects of Alonso's model have been presented in Chapter 3. The reader is referred to the original work (Alonso 1964) for a complete presentation of the analysis. Here, the focus is on certain quantitative aspects of the model. Alonso's work had been preceded by the research of other economists working on the same problems and in the same direction (Wingo 1961, Kain 1962 cited in Romanos 1976 and Batty 1976) but his formulation of an urban land market model (mainly a residential location model) was the first explicit application of the utility maximization approach to residential location. His model is essentially an applied refinement of von Thunen's agricultural land rent theory (and model). This is true for many other urban models which are similar in structure and theoretical origin to Alonso's model (Miyao 1986).

A monocentric city is assumed and households commute to the city center to shop and work. The distance from the household's residence to the city center is denoted by u. A household spends its total income y to purchase land (for housing) q at a unit price $r(u)$, transport to the city center $T(u)$, and a bundle of all other commodities z (its cost set to 1). Transport costs and unit price of land depend on distance from the city center. Unit land prices decrease with distance from the city center because transport cost increases with distance. The household's utility function is written as:

$$U = U(z, q, u) \qquad (4.50)$$

which is subject to the budget constraint:

$$y = z + qr(u) + T(u) \qquad (4.51)$$

Assuming the utility function has certain properties (see, for example, Alonso 1964, Straszheim 1986), the utility maximization problem involves writing the Lagrangian and setting first-order derivatives equal to zero (see, Straszheim 1986):

$$L = U(z, q, u) - \lambda[z + qr(u) + T(u) - y] \qquad (4.52)$$

$$U_z - \lambda = 0 \qquad (4.53)$$

$$U_q - \lambda r(u) = 0 \qquad (4.54)$$

$$U_u - \lambda\left(q\frac{\partial r}{\partial u} + \frac{\partial T}{\partial u}\right) = 0 \qquad (4.55)$$

$$z + qr(u) + T(u) - y = 0 \qquad (4.56)$$

Conditions (4.53) and (4.54) imply that, at the optimal location, the marginal rate of substitution between the composite good z and land q equals the ratio of prices (at competitive equilibrium):

$$\frac{U_z}{U_q} = \frac{1}{r(u)} \qquad (4.57)$$

Condition (4.55) defines the household's location equilibrium decision which entails a trade-off between the cost of land and the cost of commuting.

The level of **utility** a household experiences depends on the amounts of the three goods it consumes. To represent the land market allocation mechanism, Alonso assumes a competitive land market where households bid for available space and land owners offer land to the highest bidder. He introduces the notion of the "bid rent function" (or curve) which depicts the amounts of land households would bid for in the land market at various distances from the city center to attain a certain level of utility (Figure 3.2b - Figure 6.8 in Hoover and Giarratani 1999). Hence, each household is characterized by a bundle of bid-rent functions, one for each level of utility. (For a mathematical exposition, the reader is referred to Alonso 1964, Straszheim 1986). In the competitive land market, bidders with different bid rent gradients arrange themselves by the height of their bid rent curve, with bidders with the steepest gradient occupying the most central locations. To assess the effects of income on the slope of the bid rent functions requires making additional assumptions about the utility functions (Straszheim 1986).

Given that the supply of space is considered fixed, the equilibrium between the demand for and the supply of space requires determining the margin of development in the city – the maximum radius from the city center – which in turn determines the rent profile according to von Thunen (Batty 1976); this is referred to as the *closed city assumption* (Straszheim 1986). The land rent profile (or, curve) shows how the market price of land varies with distance from the city center (Figure 6.8 in Hoover and Giarratani 1999). Using this curve, and invoking the bidding mechanism, a household's equilibrium is determined by the tangency of the household's highest possible bid-rent curve with the land rent curve. To obtain the equilibrium land use pattern, Alonso's model relies on a number of critical assumptions such as the assumption of monocentricity, of continuous space, of similar housing preferences, assumptions about the mathematical form of the utility function and the budget constraint. Moreover, it treats firms and other users of urban land in a rather simplistic manner.

Muth (1969) presented the most complete analysis of residential location and his model is considered a landmark contribution in this area (Batty 1976, Romanos 1976). Although similar to Alonso's approach, Muth's model differs from it in two ways: (a) it deals with "housing services" (land, size of the house, and other dimensions of the value of housing) and (b) it considers a household's income as one of the determinants of transportation expenditures. Muth bases his analysis on a set of assumptions concerning the housing market, transport costs and the center of economic activity (the monocentric city assumption) (Romanos 1976). A simple mathematical exposition of the basic structure of the model is given below following Romanos (1976).

The household's utility function is:

$$U = U(x, q) \qquad (4.58)$$

where,

x	expenditures on all commodities except housing and transportation but including leisure
q	consumption of housing

The budget constraint is:

$$y = x + p(k)q + T(k, y) \qquad (4.59)$$

where,

y	household income
k	distance from the city center
$p(k)$	price per unit of housing, a function of distance
T	cost per trip, a function of income and distance

Household equilibrium is found by maximizing utility subject to the budget constraint (following a similar procedure to the one shown in the case of Alonso's model):

$$U_x - \lambda = 0 \qquad (4.60)$$

$$U_q - \lambda p(k) = 0 \qquad (4.61)$$

$$qp(k) + T(k) = 0 \qquad (4.62)$$

$$y - x + p(k)q + T(k,y) = 0 \qquad (4.63)$$

where λ is the **Lagrange multiplier**. Solving equations (4.60) and (4.61) yields that the marginal rate of substitution between housing and other commodities is equal to their price ratio (compare to equation (4.57) above). Equation (4.62) states that in equilibrium location, the household's marginal transport costs will be equal to its marginal housing savings. The slope of the bid-rent function for a household can be obtained from (4.62) as:

$$\frac{\partial p(k)}{\partial k} = \frac{-1}{q}\frac{\partial T(k,y)}{\partial k} \qquad (4.64)$$

Equation (4.64) shows that as distance from the city center increases, the household will bid less for each new location.

Muth analyzed also the supply side of the housing market where he treated land as any other factor of production but he did not take into account such characteristics as immobility, indivisibility, durability, etc. Moreover, he made a set of assumptions for the supply side of the housing market, the most important of which were:

a. firms and households are competitive in both the product and the factor markets
b. all firms producing a given commodity (including housing) are identical; they have the same production function and use both land and nonland inputs
c. producers employ quantities of land and nonland inputs which maximize profits at each distance
d. land rents and housing services are set by the markets so that the profits of the housing service producers equal zero everywhere the services are produced (Romanos 1976, 77).

In Muth's analysis, the housing producer chooses the capital-land ratio, k, to maximize profits. A housing production function, Q, shows the relationship between the quantity of housing services provided, $Q(k)$, when k units of capital are applied to a unit area of land. Denoting rents on land at a location by R, unit price of capital by ρ_k, and unit price of housing services by p, the producer's profit maximization problem is written as:

$$\max\, pQ(k) - \rho_k k - R \qquad (4.65)$$

The first order condition for maximization yields:

$$pQ' - \rho_k = 0 \qquad (4.66)$$

This means that capital should be applied to the point where marginal revenue equals marginal cost. Competition among housing producers drives profits to zero and, hence, land rents are:

$$R = p(Q - Q'k) \qquad (4.67)$$

Muth examined the effect of accessibility on housing rent and housing services per unit area of land (housing density) also and derived a set of capital-land relationships under conditions of competitive, long tun equilibrium (Arnott 1986). Despite its shortcomings, such as its simplicity, long-run static equilibrium nature, omission of important attributes of housing (e.g. durability), etc., Muth's model of the housing market "was the first formal, general equilibrium model of the housing market, and almost all subsequent mainstream housing market theory has evolved from it" (Arnott 1986, 969).

To obtain the market equilibrium, Muth assumed that the city extended from its center as far as it was necessary for the demand to equal the supply of housing services; this is *the open city assumption* (Straszheim 1986). A market land rent function is derived in an analogous fashion and a bidding land allocation process is basically followed as in Alonso's model. It is interesting to note that at equilibrium, all households have identical levels of utility, a result achieved through the spatial variation of the unit rental price of housing. For more mathematically elaborate presentations and discussion of Muth's model, see also Straszheim (1986), Brueckner (1986), Arnott (1986).

E. S. Mills' (1967) model of residential location operates in the Alonso-Muth utility maximization spirit. Mills, like Muth, considers land as an intermediate factor in the production of housing, which is the final consumption good (Brueckner 1986) in contrast to Alonso who considered only the land area occupied by a house. Mills (1972) analyzed also the location of employment assuming that the whole urban area is used for the production of a single commodity with an aggregate production function; i.e. he dropped Alonso's assumption that all employment is concentrated at the city center and that all product is produced there. This urban land use (associated with the production of the single commodity) competes with transportation for land. In equilibrium, urban land at each distance from the city center is exhausted in production and transportation. Mills derives the equilibrium rent-distance function, a negative exponential form similar to that derived by Muth (Romanos 1976). Muth and Mills's models have been analyzed in a unified manner by Brueckner (1986). Frequently, also, the literature refers to all three models as the Alonso-Muth-Mills (see, for example, Miyao 1986) or the *classical* or the *standard* model of the urban land market. This is because their analysis: (a) shares the same theoretical basis, (b) employs the same methodological framework of budget-constrained utility maximization to derive the relationships between land use and price of land, (c) arrives at similar bid-rent functional forms (the negative exponential), and (d) employs essentially the same mechanism for allocation of land to its users – the bidding process.

The first generation of this genre of analysis presented above has been criticized, on the one hand, on philosophical/epistemological grounds – the adoption of the utility maximizing theoretical framework and the associated model of the rational economic man – and, on the other, on methodological grounds – the many, frequently unrealistic, assumptions upon which it rests. The later refer to those made to derive equilibrium land use patterns or to perform dynamic analysis of the land market which make it difficult to generalize the results of the analysis to urban areas with many centers of employment and other imperfections in the real market. Representative lines of criticism include:

a. the narrowly rational logic for action these models postulate at a conceptual level (**deductivism**) which is then transcribed unproblematically upon real world processes (Cooke 1983)

b. with their reliance on the concept of utility and its propensity to stimulate action, these models conceive of humans as if they exist to express the utility-maximizing quality and nothing else (Cooke 1983)

c. the excessive emphasis these models place on accessibility as the most important determinant of urban spatial structure and the neglect of many other determinants (see, for example, Romanos 1976, Cooke 1983)

d. the neglect of many important particularities of housing itself and of the neighborhood characteristics (see, for example, Arnott 1986, Straszheim 1986)

e. the assumption of a perfectly competitive land market – i.e. without imperfections such as various forms of externalities (Batty 1976, Cooke 1983)

f. the monocentric city assumption

g. the their static nature, and

h. the assumption that location is continuously variable.

Subsequent studies and models of the housing market and of residential land use patterns in urban areas attempted to respond to these criticisms and alleviate some of the restrictions imposed by the classical model. These studies employ alternative forms of spatial demand and supply and of price and rent functions and dynamize the static versions by introducing dynamic factors such as changes in population, income, transport costs, opportunity costs of land the transportation component (see, among others, Beckmann (1969), Solow (1972), Casetti and Papageorgiou (1971) cited in Batty 1976, 259-261; also, Arnott 1986, Brueckner 1986, Miyao 1986, Straszheim 1986). Moreover, as discussed in chapter 3, attempts have been made to relax the monocentric city assumption as well as to consider the incidence of externalities (Solow 1973, Romanos 1976, Shieh 1987, Engle *et al.* 1992). The development of discrete choice models attempts to provide more realistic representations of consumer choices in the urban land use context and relax the assumption of continuity of location (see, for example, Anas 1981, Anas 1982, Batten and Boyce 1986, Clark and van Lierop 1986, McFadden 1973, McFadden 1978, Quigley 1985, Smith 1975, Straszheim 1986). Discrete choice models are discussed in sections 4.3.1 on statistical models and 4.6.3A on integrated land use-transportation models.

It is also interesting to query, from the perspective of the analysis of land use change, how land, land use and its change are represented in these models. These concepts did not escape the deductive mode of analysis which is applied to all other concepts with which these models deal. Land and land use are treated explicitly but at a very high level of abstraction (even when attempts at disaggregation are made) and with very little differentiation of their intrinsic qualities. Note also that usually land (or housing or housing services) is one item which is consumed together with a bundle of all other items which appear to have no relationship with land and its use, i. e. to be independent of one another. People are behaving as if their choice of a house (or of any "landed" piece of property in other applications of the utility maximization framework) is affected only by the accessibility of its location and the particular mode of transport. The host of other constraints and considerations which enter land use decision making at the individual and the collective level are treated in a limited way or not at all (such as institutional factors like planning, legislation, etc., socio-cultural, and political factors, the heterogeneity of the landscape and the environment). Consequently, land use change is treated in a very limited sense as if it is subject only to the influence of the economic determinants which the land market theory postulates. This may be true for market economies perhaps (to which these models refer mostly) but not for other types of economies where the influence on non-economic factors may be stronger and land use decision making is based on a different rationale and value system. However, even in market economies, the influence of environmental and landscape features, at least, on land use decisions is not negligible and recent modeling efforts in urban and regional economics have started to address this issue (see Bockstael and Irwin 1999).

Despite efforts to model both the demand and the supply sides of the land market, most applications are demand-oriented making the implicit assumption that land will adjust to any magnitude of market demand. When models attempt to simulate market clearing, they rely on the particular mode of land use decision making which is characteristic of these models – the bidding process. Although this may be a rough and intuitively appealing approximation of several real world situations in many market and non-market economies, it is far from a satisfactory representation of the land market as there do exist several types of land markets and various types of landed interests and not simply two undifferentiated categories of landlords and households (see, among many others, Form 1954, Cooke 1983, McNamara 1983, 1984, Piore and Sabel 1984, Harvey 1985, Healey and Nabarro 1990).

From a practical point of view, several of the criticisms discussed above address also the limitations of the Alonso-type urban models to provide explicit formulations for operational models as it is the case with discrete urban models (Batty 1976, Wilson 1974). However, they have provided the theoretical underpinnings and the economic rationale for the development of several (potentially and actually) operational programming models (the Herbert-Stevens and the Harris models being well-known cases). This is true for the broader utility maximization (and profit maximization) analytical approach upon which these models rest which has provided the framework for the development of operational models at larger scales – ranging from the regional to the global – and for uses of land associated with non-urban economic activities such as agriculture and forestry (see, for example, Takayama and Labys 1986, Fischer *et al.* 1996a). The concept of utility consumers derive from purchasing and consuming bundles of goods and services produced by economic activities which are, more or less, associated with given types of land, constitutes the basis for formulating single or multiple objective optimization models which have been discussed previously. In these models, utility has been expressed operationally by means of either mono-dimensional measures such as income (e.g. farmers income or the value of agricultural or forest products) or more composite measures which reflect the multi-attribute nature of utility (including, for example, in addition to economic, other aspects of quality of life, of the environment, etc.). In addition, the bidding process introduced by the utility maximization models is being used in several land use modeling contexts as a land allocation mechanism underlying land use change at least in market (or, approximations of) economies.

Applications of the utility maximization approach on larger scales are made basically in the context of larger, integrated modeling exercises. The FASOM non-linear programming model has already been mentioned previously and other integrated models are discussed in a latter section. The characteristic of the contemporary applications of the utility maximization approaches is that they do not make several of the restrictive assumptions characteristic of the early theoretical models. In particular, they do not assume monocentric and uniform flat plains within which economic activities take place; they account for several of the environmental features of the geographic environment under study; they consider the interactions (e.g. trade) and interdependencies between spatial entities and among economic agents (Anas and Kim 1996, Anas *et al.* 1998, Fujita *et al.* 1999). Frequently, they provide for considerable disaggregation (e.g. by consumer group, product type, land use type) which render them more realistic representations of reality.

More importantly, progress in GIS and spatial data management systems has fostered the building of spatially explicit models which can capture the intricate interrelationships in space between the activities modeled as well as important economic-environmental interactions. In this context, it is possible to estimate *spatial production functions* which provide for greater representation of the variability in the conditions of production and of interactions in space compared with the coarse, aspatial production functions which are commonly used. (see, for example, Keyzer 1998, Keyzer and Ermoliev 1998). This is an extremely important improvement as, in principle at least, it facilitates the inclusion of policy variables and the study of the spatial variability of their impacts in terms of the land use changes they produce. However, all this gain in detail, enhanced representation, and potential greater validity of the model results has a considerable cost; namely, the difficulties of finding appropriate spatial data to use the models in all their detail and the computational difficulties stemming from the nonlinearities of the modeled spatial relationships. Finally, it is worth mentioning that the utility maximization approach has been proposed as an evaluation method and it has found applications in the analysis of the desirability of alternative land use plans (see, among others, Bell *et al.* 1977, Nijkamp 1980, Nijkamp and Rietveld 1986).

4.5.5. Multi-Objective/Multi-Criteria Decision Making models (MODM/MCDM)

The last group of optimization models to be discussed represent a rather recent trend in the analysis of land use and its change which involves the combination of optimization techniques with elaborate, multidimensional techniques of land use assessment/evaluation in a spatially explicit modeling environment. The roots of this modeling direction go back to broader developments in the methods and techniques of multi-criteria and multi-objective decision making methods and their subsequent adoption and application to various fields of the social sciences. Their introduction in the analysis of land use issues dates approximately since the mid-1970s but they gained momentum in the 1980s when improvements in information technology and refinement of the techniques combined to produce more user-friendly and versatile tools for decision making. There are several applications which are impossible to cover in this review, first, because they come from diverse sources and, second, because the developments in this area are very rapid currently (although the main idea on which they are built is basically the same). The interested reader is referred to the major sources of literature cited below for further study. In the following, two applications are presented briefly to illustrate the basic idea of this genre of models.

A note on terminology is necessary as the terms “multi-criteria” and “multi-objective” are frequently used interchangeably although they are not semantically identical. Nijkamp (1980) suggests a distinction: “Discrete models are characterized by a finite number of feasible alternative choices or strategies (for example, in the case of plan evaluation or project evaluation problems); discrete models are often called *multi-criteria models*. Continuous models are based on an infinite number of possible values for the decision arguments and hence for the objective functions; they are usually called multi-objective optimization models” (Nijkamp 1980, 30-31). Nijkamp (1980) indicates also representative models from each category. Moreover, the literature on multi-criteria and multi-objective techniques exhibits also a methodological and philosophical differentiation as regards the development of the associated techniques; the former are usually associated with the “outranking method” school established by B. Roy (1973) at LAMSADE at the University of Paris-Dauphine and the latter with the Multi-Attribute Utility Theory (MAUT) school of R. Keeney and H. Raiffa (1976) (see, also among others, Korhonen *et al.* 1992, Roy and Bouyssou 1993, Steuer 1986). Naturally, several other approaches exist which are not easy to classify in either one of the dominant schools such as Saaty’s Analytic Hierarchy Process method (Saaty 1994).

The first model presented below is a multi-objective model which has been used to support agricultural land re-allocation decisions in the Netherlands (Janssen 1991). It is a representative application of multi-objective optimization techniques to similar land allocation decision problems. The problem this application addresses relates to the choice of the most suitable land development strategy for each of the 118 agricultural regions into which the country has been subdivided. Three land development alternatives were taken into account: change of land use, agricultural use, combined land use. Each region was described in terms of several environmental and socio-economic characteristics stored in a GIS in use at the National Physical Planning Agency of the Netherlands. The factors which determine a region’s suitability for a change in land use were distinguished into “demands” and “opportunities”. These factors were translated into 18 evaluation criteria which were used to characterize each region. The table of scores of each region on each criterion was set up (the effects table according to the authors). For each criterion, weights were determined based on interviews with experts. For each region, a utility index was calculated using the weighted summation technique. This procedure is shown schematically in Figure 4.2a below:

	Regions						
Criteria	1	2	3	...	...	...	118
1	s_{11}	s_{12}					
2	s_{21}						
......	s_{31}						
......					s_{ij}		
......							
18							

Figure 4.2a. The Effects Table

The utility score U_j for region j is calculated as follows:

$$U_j = \sum_{i-1}^{118} w_i s_{ij} \qquad (4.68)$$

where,

w_i the weight for criterion i
s_{ij} the score of region j on criterion i

In order to identify the optimal allocation of the three candidate land use types in each of the 118 agricultural regions of the study area, a linear programming approach was followed. Two LP models were used: a single-objective and a multiple-objective. The single objective LP model took the form of maximization of the total utility of the study area; i.e. the sum of total utilities of the 118 regions. For each region its total utility, TU (not to be confused with the utility score above), was calculated as the sum of utilities of the region for each of the three candidate land use types as follows:

$$TU_j = A_j \sum_{k=1}^{3} b_{kp} p_{kj} U_j \qquad (4.69)$$

where,

A_j the total agricultural land of region j
p_{kj} the decision variable; i.e. the proportion of the agricultural land area of region j to be devoted to land use type k
Uj the utility score of region j as calculated from equation (4.63) above
b_{kj} priority weight of land use type k in region j

The single-objective LP model was written as

$$\max \sum_{j=1}^{118} TU_j \qquad (4.70)$$

The second model used was a multi-objective LP model which, instead of maximizing an aggregate utility function for all 118 regions and the three land use types, it consists of maximizing *simultaneously* the sum of utilities of all regions by land use type. For practical purposes, the 118 regions were aggregated into 14 regions in the multi-objective model which was written as follows:

$$\max \sum_{j=1}^{14} TU_{j1}, \qquad \max \sum_{j=1}^{14} TU_{j2}, \qquad \max \sum_{j=1}^{14} TU_{j3} \qquad (4.71)$$

The solution technique used produced the whole ***efficient set*** ; i.e. the set of *non-dominated (or,* ***Pareto optimal****) solutions.* A solution to a MODM problem is characterized by the set of values of each of the n objectives of the problem. A *non-dominated or pareto optimal solution* is one "in which any further improvement in any one of the n objectives can be achieved only at the price of 'worsening' the value of at least one of the remaining objective functions" (Zeleny 1982, 53). In this case, note that the linear formulation of the objective functions means that the interactions and interdependencies of the allocations produced among the regions are not taken into account, an assumption which may be untenable in the real world. However, the inclusion of interaction effects leads inevitably to non-linear models which present considerable computational difficulties and have heavy data requirements.

The characteristic difference between single and multiple objective models is that the first produce only one, the optimal solution, while the second produce a whole set of solutions among which decision makers can choose depending on their particular preferences and priorities. In the above land use allocation problem, the solutions are characterized by the proportions of each of the three land use types to be allocated to each of the regions. The decision makers can choose those solutions in which the proportions of land allocated to each of the three land use types agree with other (implicit) criteria they may consider. Several variations of the multi-objective LP problem have been devised as regards the generation of the **efficient set** (for another land use decision problem example see, Briassoulis and Papazoglou 1993). In addition, because usually the efficient set contains a large number of non-dominated solutions, it is not practical for decision makers to have to inspect the whole set in order to indicate their preferred solution. This was one of the reason for the development and application of interactive optimization techniques which have found applications in land use allocation problems (see, for example, Rietveld 1977, Nijkamp 1980, Voogd 1983). A more advanced, contemporary application of a multi-objective optimization model with an interactive component is presented below.

The second model presented here is part of a Decision Support System (DSS) developed for Sustainable Agricultural Development Planning at the International Institute for Applied Systems Analysis (IIASA) at Laxenburg, Austria, in cooperation with FAO (Fischer *et al.* 1996b). It combines a multi-objective model with the AEZ methodology developed by FAO for land evaluation purposes (FAO 1976, FAO 1978; see also Chapter 1). Application of the AEZ methodology in a study region produces a spatially explicit inventory of its land resources – i.e. land resources by Agro-Ecological Zone – which can be used to produce a land productivity raster (or, grid cell) data base (see, Fischer *et al.* 1996b for the case presented here as well as for other related applications). This data base is used to provide data used in the formulation of the optimization model.

The multi-objective model considered 10 objectives (i.e. it had 10 corresponding objective functions) whose decision variables included: (a) the land use proportions in each cell of the study area devoted to a cropping, a grassland, or a fuelwood activity, (b) the number of animal units of a given livestock system kept in a given zone, and (c) the feed ratio of a given feed from a given crop allocated to a particular livestock system in a given time period in a given zone. The constraints specified included "the preferred demand baskets, crop specific production targets, risk aversion, economic constraints, land use by individual crop, crop mix, input use, quality of human diet, environmental conditions, seasonal feed demand-supply balances, feed quality, and distribution of livestock systems" (Fischer *et al.*1996b, 9).

The particular methodological approach followed to apply the above multi-objective model (MODM) is called Aspiration-Reservation Based Decision Support (ARBDS) method. Its main purpose is to provide a mechanism by which the large number of non-dominated solutions contained in the **efficient set** produced by the MODM is reduced to a set with certain properties which satisfy the preferences of the decision maker. These preferences are defined interactively by the decision maker who expresses aspiration and reservation levels for each criterion. A summary of the ARBDS as a two-stage approach is given below following Fischer *et al.* (1996b).

The first (preparatory) stage consists of specifying and generating a *core model* which contains the objective functions and those constraints which express logical and physical relationships between the decision variables of the model. These variables should include also variables which are potential evaluation criteria (e.g. goals, performance indices, etc.). Initially, the decision maker selects a set of criteria from these variables and specifies whether it is minimization, maximization or a goal criterion (i.e. if it minimizes as deviation from a given value). Then the DSS performs a series of optimizations to produce the Utopia (best value) and the Nadir (worst value) points for each criterion. It also computes a *compromise* solution which corresponds to a problem for which the aspiration and the reservation levels are set to the Utopia and the Nadir points respectively.

At the second stage, during an interactive procedure, the decision maker specifies goals and preferences, including the values of the criteria (s)he wants to achieve or to avoid. The vectors composed of these values are called *aspiration* and *reservation* levels. These are used to define *achievement functions* which are used to select a Pareto optimal solution from the whole efficient set produced by the optimization model. This is achieved by generating additional constraints and variables which are added by the DSS to the core model. Thus, an optimization model is formed which produces non-dominated solutions which are as close as possible to the user-specified aspiration levels. The interactive procedure is repeated with the decision maker revising the aspiration and reservation levels each time after inspecting the solutions and selecting those s/he prefers. The procedure stops when a satisfactory solution is found or when the decision maker wants to discontinue it.

The above modeling procedure is one of the many efforts to develop interactive modeling packages to assist the decision makers in making land use allocation decisions, in the present case. Other versions have been designed also which handle group decision making as, normally, there is not a single decision maker in any decision context (see, for example, Levandowski 1988, Majchrazak 1988, Krus *et al.* 1990). The successful implementation and use of these packages depends on many factors among which the availability of appropriate data, the training of the users of the model, the cooperation and real interests of the decision makers, and the availability of high-technology computer facilities feature high.

Closing the section on optimization models for the analysis of land use change, a few general remarks are in order. First, all these models are normative or prescriptive; i.e. they indicate desirable (according to the specified objectives, preference structures, decision variables, and constraints) future land use patterns (either in a static or, less frequently, in a dynamic fashion). By comparing these future with current patterns it is possible to specify the amount and direction of change in various land use types which should take place to obtain the desirable state. For this reason they are frequently used in planning and policy making contexts as aids to making decisions about future allocations of land to alternative uses (which are frequently in conflict).

The level of detail of the prescriptions offered depends on the level of aggregation of land use types, socio-economic data and the spatial explicitness of these models. In theory, it is possible to achieve a very high level of detail in all respects but at sharply rising computational difficulties, not to mention the capacity of the human mind to conceive of all the detail offered by very disaggregate models. The level of detail offered depends critically also on the theoretical/behavioral basis supporting these models. Broadly, these are based either on neoclassical economic theory of utility maximization (normative theory) or on simplistic behavioral and other assumptions about the factors which have been observed or are assumed to impinge on land use and cause its change (the instrumental approach to theory referred to in (Chapter 3). In the static versions of the models, time is implicit and they offer no guidance about the trajectory of the system which leads to the prescribed patterns. Dynamic optimization models are extremely difficult to build given the data and computational difficulties mentioned before.

Optimization models are necessarily selective as regards the environmental, social, cultural, and political factors which they include in their specification. However, they do not account for the interactions among these factors and the processes through which they combine in certain places, and within particular contexts to produce changes in land use. In other words, the prescriptions they offer do not account for the dynamics which operate to bring the land use system from the present to a desirable state. The future states prescribed are assumed to be affected by the factors taken into account in the specification of the models (mostly prices, costs, distances in the more conventional and utility maximization models) but the particular processes through which these states are generate are treated as a "black box". The more recent versions of optimization models include more detail and account for many more factors in addition to the economic ones but they still rely on either a positive or a normative theoretical framework which governs their structure. Overall, optimization models offer rough guides of desirable land use futures (usually different from the current ones) and they should be used prudently by decision makers when deciding what actions to take to achieve them. Finally, it should be noted that optimization models are frequently used as components of integrated models which are discussed in the next section.

4.6. Integrated Models

Integrated models of land use change are diverse as integration takes on different meanings in different contexts. They are called also *comprehensive* or *general* models although the term "integrated" has come to dominate the literature since the 1980s. In the present context, integrated models are those models which consider in some way the interactions, relationships, and linkages between two or more components of a spatial system – be they sectors of economic activity, regions, society and economy, environment and economy, and so on – and relate them to land use and its changes either directly or indirectly (see, Wegener 1986b, on the feature of integration of integrated models). The emphasis here will be mostly on those integrated models which contain an explicit land use component or treat land use directly as it was the case with the previous model categories. However, several other integrated models which relate to land use indirectly will be mentioned where appropriate. It is noted that, to this author's knowledge, the purpose of model building in most of the integrated models presented in this section, was not modeling of land use change but modeling of some other aspect of a spatial system of interest. Integrated models whose direct purpose is the analysis of land use change are of a very recent origin as discussed below.

Integrated models, in general, appeared in the 1960s during the “quantitative revolution” in urban, regional and geographic analysis. The first efforts included land use explicitly and integrated models which continue in this modeling tradition keep this feature or have improved upon it. Several integrated models have been developed starting from the decade of the 1960s onwards which are aspatial; i.e. they consider interactions between several aspects of a spatial system but without an explicit spatial frame of reference (for example, demographic-economic, energy-economic, environmental-economic, etc.). One instance in which these integrated models include the spatial dimension is when they are formulated in an interregional or multi-regional context (see, for example, Issaev *et al.* 1982). Aspatial integrated models do not account for land use change in most cases.

A common characteristic of integrated models, in addition to their emphasis on integration, is that they are mostly large-scale models. In fact, an inspection of the literature on large-scale models reveals that, most of the time, these are integrated models (see, for example, Batten and Boyce 1986, Boyce 1988, Wegener 1994). The range of spatial levels covered starts from the urban/metropolitan and reaches the global. The spatial coverage of integrated models is closely related to their purpose, focus, and other structural and design characteristics as shown in the following presentation. As regards the latter aspect of model structure, a broad distinction can be drawn between “compact” or “unified” and “modular” or “composite” model forms (see, for example, Briassoulis 1986, Wegener 1994). The first form refers to integrated models which are described by a single operational expression which contains all the arguments whose integration is represented; for example, a single equation, an input-output model, etc. The second form refers to integrated models which combine several separate models of the components of the spatial system which are being modeled. The second form is more common in recent versions of integrated models.

The meaning of integration varies with the model purpose and is reflected in the structure of the integrated model. Five dimensions of integration can be distinguished broadly:

a. *spatial integration* – where the horizontal and/or vertical interactions among spatial levels are emphasized with respect to a phenomenon being modeled

b. *sectoral integration* – where the model represents the linkages and relationships between two or more economic sectors of the spatial system of interest such as retail, housing, transportation, industry, agriculture, etc.

c. *land use integration* – in which the model accounts for the interactions between more than two types of land use such as residential, commercial, manufacturing, transportation, etc.; this dimension of integration may be equivalent at times with the sectoral integration

d. *economy-society-environment integration* – where the model represents the linkages between at least two of the several components of the spatial system such as economy-environment, economy-society (e.g. population), economy-energy, etc.

e. *sub-markets integration* – where models show how different sub-markets of the whole economy relate to one another; a related type of integration may be considered that between supply and demand. In this latter case, the related economic models are distinguished into partial equilibrium (referring to either demand or supply) and general equilibrium models.

The temporal dimension is not considered as one of the dimensions of integration. Models which incorporate the time dimension are called dynamic, in general, and may concern either simple or integrated models although the latter case is less frequent given the many difficulties associated with building conceptual and operational dynamic integrated models.

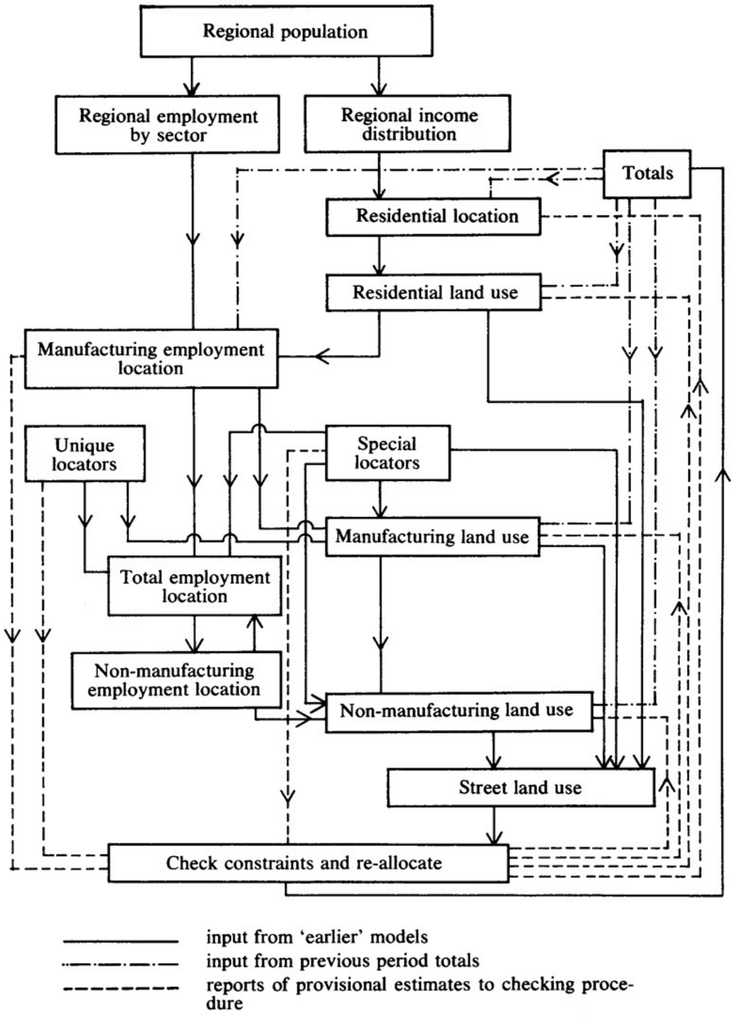
The five main dimensions of integration are not mutually exclusive; in fact, any integrated model may combine more than one of these dimensions. The modern trend in integrated model building is to account for several dimensions with a special emphasis on the spatial dimension – especially in modeling land use or environmental characteristics and issues. This latter feature has been greatly facilitated by the rapid developments in information and spatial data management technology. Note, however, that the higher the degree of integration, the greater are the difficulties, on the one hand, to conceptualize and support theoretically the relationships of interest and, on the other, to operationalize and use the respective models.

The integrated models which are presented in the following have been grouped on the basis of their most characteristic feature which is the main modeling tradition in which they belong (Table 4.1c).

More specifically, the model groups are: (a) econometric-type integrated models, (b) gravity/spatial interaction-type integrated models, (c) simulation models, and (d) Input-Output-type integrated models. In all these models, land use is either accounted for directly by the model or the land use implications of the models' results can be assessed outside the model.

4.6.1. Econometric-Type Integrated Models

The most well known econometric-type integrated model which accounts explicitly for various types of land use is the *Penn-Jersey model* (Seidman 1969, Wilson 1974, Romanos 1976). It is a modular model which adopts an aggregate, macro- approach to modeling the components of a metropolitan economic system. It consists of seven main sub-models as shown in Figure 4.2b which is Wilson's (1974) interpretation of the model's structure.



The Penn-Jersey model

Source: Wilson (1974) – Reprinted with the permission of J. Wiley and Sons

Figure 4.2b

It operates sequentially through a series of 5-year periods. A brief description of the model is offered below following Wilson (1974) where the reader is referred for a complete and concise description of the model's basic equations (the econometric model) and operation.

The model assumes a study region subdivided into zones. A *regional demographic model* "drives" the rest of the sub-models. It applies **cohort-survival analysis** to produce population projections by age, sex and race. The output of the demographic model is fed into two models separately: a regional employment and a regional income distribution model. The *regional employment model* calculates the total labor force by multiplying the population projections by age-sex specific activity rates and assumes a constant (6%) unemployment rate. The total labor force is allocated to different employment sectors using a linear regression model.

The *regional income distribution model* is based on the results of an income projection model whose task is to predict future median income and the new income-class boundaries based on historical evidence which had shown that the distribution of income among different income quartiles had remained reasonably constant over time. The population projections from the regional demographic model are fed into the income distribution model which produces the allocation of the total population to income groups (which are assumed to each have different locational behavior).

In the *residential location model*, the population projection for each income group is allocated among the zones of the study region. Original allocations may be amended later when the constraints are checked. The allocation formula by income group used is an accounting equation which calculates the population of a zone (for a given income group) as the sum of the population of the previous period plus the projected change. The projected population change is the sum of net migration to the zone plus the zone's share of total population growth. Migration from a zone is assumed to be proportional to the population of the zone, its residential desirability, and the zone's "effective area". The latter is calculated as the minimum of residential land plus available land and prevents a zone from doubling its residential area in a single projection period. As the population projections allocated are expressed as number of households, these are converted into actual number of people by multiplying the number of households by the average household size for the zone.

The *residential land use model* assesses the amount of residential land in each zone by income group. This is expressed as the product of the projected population (by income group) of the zone (the output of the residential location model) times the amount of residential land consumed by household in the zone. This quantity is estimated from an econometric equation as a function of the zone's median income, expenditures on transport, and accessibility to opportunities of type 1 (the connection with Alonso's model). This model estimates also the price of a household plot of land in each zone as a function of the same variables as above using an econometric equation.

The *manufacturing employment location model* employs the same mathematical framework as the residential location model. The amount of manufacturing (by sector) and retail employment in a zone is assessed as the sum of employment in the previous period plus change in employment. The change in employment is calculated as a function of the employment of the zone in the beginning of the projection period and net migration to the zone. The latter is assessed as a function of the initial employment, the desirability for manufacturing and retail location of the zone, and the zone's effective area which is calculated as in the residential location model.

The *manufacturing land use model* employs simple trend projection formulae as good econometric equations were difficult to identify. A distinction is made between zones where manufacturing employment is declining and those where it is increasing. For the latter case, all zones are divided into five concentric rings and the rate of increase in manufacturing land use is taken to be proportional to the change in employment in all zones of the ring of which a particular zone is a member.

The *service employment location model* is a cross-sectional model which employs a mixture of intervening opportunities and gravity model concepts. The main variables are: (a) service activity generated in a zone in a given sector from the households in this zone and (b) service activity generated from workplaces. Conversion coefficients are used which convert activity measures, such as turnover, to employment for each of the above types of service activity. Retail activity is assessed from a spatial interaction (gravity) model which, however, takes into account the ordering of zones so as to account for jobs which remain in a zone or pass from a zone to another. In other words, an intervening opportunities model form is employed. According to Wilson (1974), this was an extremely ambitious model whose successful development, calibration, and use was a substantial achievement of the Penn-Jersey model.

The *service land use model* employs simple trend projection formulae for the same reasons as it was the case with the manufacturing land use model. Zones where service employment is increasing or decreasing are distinguished as in the case of manufacturing. Finally, the *street land use model* employs a simple linear regression model to assess the amount of land for streets in the projection period after the land consumed by residential, manufacturing, and service activity has been estimated.

All the estimates provided by the above sub-models are provisional and they are subject to feasibility checks. These checks include: (a) avoiding negative values of obviously positive quantities and (b) observing the maximum values of rate of growth or decline in individual ones or groups of zones. Excess amounts of activity are re-allocated through rather complex procedures as Seidman himself had admitted (Wilson 1974). Finally, it is noted that the model described here was used to allocate land use and activity to the zones of the study area. These were used subsequently in a transportation model which was the original purpose of the Penn-Jersey Transportation Study.

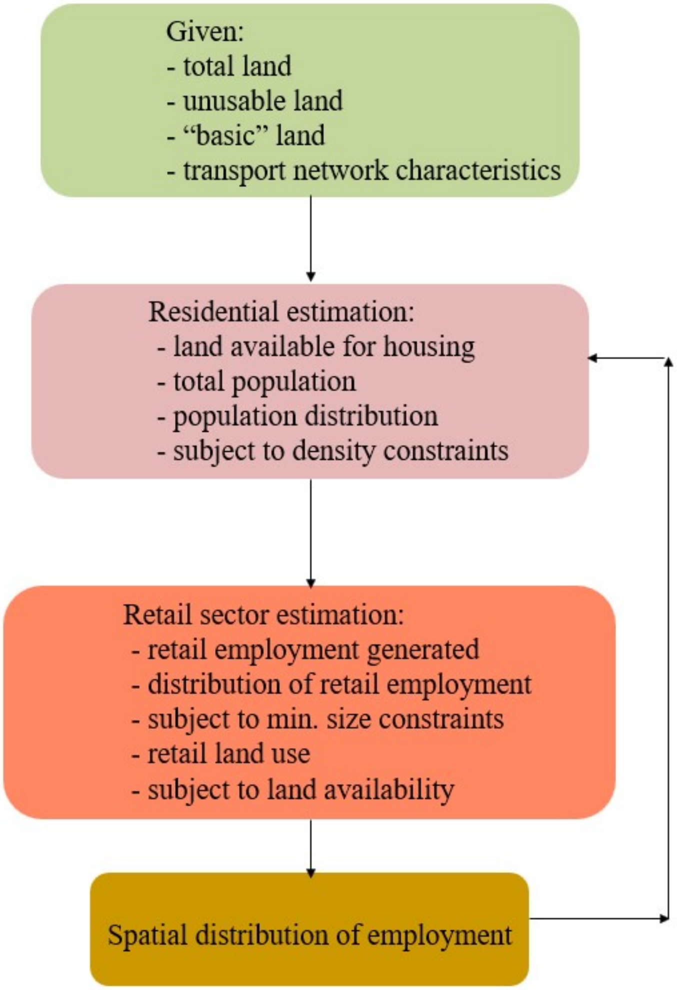
Econometric-type integrated models of land use such as the Penn-Jersey model presented above provide elaborate, although mechanistic, tools to assess land use change as a function of change in the independent variables they take into account: population growth, income changes, employment changes, etc. However, in order to cope with the complexity of the system being modeled, they need to rely frequently on mechanistic calculations which are not supported by a theory of land use change. In addition, the econometric estimates they produce through the systems of equations they employ use, inevitably, historical data. This means that the coefficients reflect the past state of affairs of the urban system modeled which may not be congruent with a future system where several changes, among which, land use change, have taken place. The linear operational forms used present another drawback of these models as several of the changes may be nonlinear such as changes in service employment and changes in the area occupied by the various land use types. The lack of rigorous theoretical backing of these models contributes to these weaknesses. Moreover, they do receive several **exogenous** inputs which would be better assessed endogenously in a comprehensive treatment of land use change.

4.6.2. Gravity/Spatial Interaction Type Integrated Models

The gravity model, or the family of spatial interaction models in Wilson's (1974) more comprehensive terminology, has offered a less mechanistic framework to build integrated models of land use compared to the econometric models. Given that it is based on certain, however controversial, theoretical principles and it has been shown to be in agreement with the welfare economic concept of utility maximization (see section 4.4), it has been used as a central modeling device in integrated models of land use allocation.

4.6.2A The Lowry Model and Garin's versions

The landmark model in this group is the *Lowry model* designed by Ira Lowry in 1964 for the Pittsburgh metropolitan region and revised several times later on. The model describes the structure of the urban spatial system in terms of activities and corresponding land uses as follows: population-residential land, service employment-service land use, and basic (manufacturing and primary) employment-industrial land use. The model assesses the levels of activities which are then translated into area of land uses by means of **land use/activity ratios**. It assumes that the study area is subdivided into a number of zones. The basic structure of the model is shown in Figure 4.2c.



Structure of the Lowry model

Source: Adapted from Wilson (1974)

Figure 4.2c

The exogenous information provided to the model consists of total land, unusable land, “basic” land (for the location of “basic” activities to be defined below), “basic” employment (to be defined below), and characteristics of the transport network. The constraints included in the model concern: (a) allowable amount of land use to be accommodated in each zone, (b) population density per zone, and (c) minimum size of service employment for one of three categories – neighborhood, local or district, metropolitan. Using this information, the model performs two separate sets of calculations: one for the characteristics of the residential sector and one for the retail sector of the urban region. The location of basic activities is assumed to be independent of the location of population and service employment. After allocating the predicted levels of activities to zones, the model performs also consistency checks of the predicted distribution of population against the distribution used to compute potentials to find out if they coincide. In case they do not, the model re-iterates the whole allocation procedure until the two distributions coincide (Batty 1976). A simple presentation of the basic mathematical expression of the Lowry model is given below following Wilson (1974) and Batty (1976).

First, the calculation of the population of the urban region is shown given the magnitude of basic employment which is provided to the model exogenously. The Lowry model borrows from the **economic base model** in order to perform this calculation (see, for example, Wilson 1974, Hoover and Giarratani 1984, 1999). Total employment in an area is considered to be the sum of basic and service (or, population-serving or local) employment. *Basic employment* is associated with the production of goods (and services) which are exported out of the region while *service* (or, *population-serving* or *local*) *employment* is associated with the production of goods (and services) destined to be consumed locally, within the region. The identity expressing the relationship between total, basic and service employment is:

$$E = E^B = \sum_k E^{Rk} \qquad (4.72)$$

where,

E^B	the exogenously given basic employment
E^{Rk}	service employment in the k^{th} service (retail) sector (summed over all k service sectors)
E	total employment

It is assumed that total population, P, is proportional to total employment as follows:

$$P = fE \qquad (4.73)$$

where,

f is an inverse activity rate (persons per employee in the basic sector)

It assumed also that total employment in the k^{th} service (retail) sector is proportional to the population as follows:

$$E^{Rk} = a^k P \qquad (4.74)$$

where,

a^k is a constant (one for each of the k retail sectors)

Solving equations (4.72)-(4.74) gives the magnitudes of total employment, population and retail employment:

$$E = \frac{E^B}{1 - f \sum_k a^k} \qquad (4.75)$$

$$P = \frac{fE^B}{1 - f \sum_k a^k} \qquad (4.76)$$

$$E^{Rk} = \frac{f a^k E^B}{1 - f \sum_k a^k} \qquad (4.77)$$

Given these calculations, the rest of the model solution procedure is as follows:

The amount of land available for residential use in each zone j, A_j^H, is given by:

$$A_j^H = A_j - A_j^u - A_j^B - A_j^R \qquad (4.78)$$

where,

A_j total land of zone j

A_j^u unused land in zone j

A_j^B land for basic industries in zone j

A_j^R land for services in zone j

Given the estimate of the total population, this is allocated to the zones of the study region according to a potential model (see section 4.4.) which can be considered as a simple spatial interaction model with only one “mass” term. More specifically:

$$P_j = P \frac{\sum_i E_i f^1(c_{ij})}{\sum_i \sum_j E_i f^1(c_{ij})} \qquad (4.79)$$

where subscript i denotes the destination zone (where employment is located) and $f^1(c_{ij})$ is a generalized travel cost function from origin (residential) to destination (employment) zones.

Equation (4.79) ensures that the sum of the population of all zones equals total population. Moreover, for each zone, a check is performed to find whether the maximum population density constraint is exceeded:

$$P_j \leq z^H A_j^H \qquad (4.80)$$

where, z^H is the population density of the zone

As mentioned above, in equation (4.74), total employment in retail sector k, E^{Rk}, is assumed to be proportional to total population. This is allocated to the zones using a potential model similar to that used for the household sector:

$$E_j^{Rk} = E^{Rk} \frac{\sum_i g^k P_i f^2(c_{ij}) + q^k E_j}{\sum_i \sum_j g^k P_i f^2(c_{ij}) + \sum_j q^k E_j} \qquad (4.81)$$

where,

g^k and q^k	are empirically determined coefficients which express the relative importance of population and employment in the index of market potential
$f^2(c_{ij})$	is a generalized travel cost function for the retail sector.

Residential, industrial and retail land use in each zone is calculated using land conversion ratios for population, e^P, basic employment, e^B, and retail employment, e^R, using the following simple, general formula:

$$L_i = e^1 X_i^1 \qquad (4.82)$$

where,

e^1	is e^P or e^B or e^R
X_i^1	is ^{P}, or E_i^B or E_i^R

Consistency checks on the calculated amount of land by land use type are performed to ensure that the constraints on each land use type are met.

The Lowry model is solved by iteration for a single period. Both Wilson (1974) and Batty (1976) provide an exposition of the iterative formulation of the model which shows how the equations are executed. The iterative process stops when the predicted distribution of population coincides with the distribution used to compute potentials in the beginning of the solution procedure.

The original version of the Lowry model has been subjected to several improvements and its variants have served as core land use forecasting models in a large number of land use and transportation studies in several countries (mostly the U.S., Canada and the U.K.). Batty (1976) credits Garin (1966) as having reinterpreted the Lowry model in two important ways: "first, the potential models have been replaced by production-constrained gravity models and second, the expanded form of the economic base mechanism has been substituted for the analytic form" (Batty 1976, 63). With respect to the first point, Wilson (1974) shows also how the inclusion of an "attractiveness" term converts the simple gravity-type models of the original Lowry model into gravity models proper. Garin offered also a matrix formulation of the Lowry model (Garin 1966 cited in Wilson 1974) leading to several methodological and solution insights.

4.6.2B TOMM (Time Oriented Metropolitan Model)

The first use of the Lowry model framework was made by Crecine (1964 cited in Batty 1976, 62 and Batten and Boyce 1986, 851) who designed TOMM (Time Oriented Metropolitan Model) for the Pittsburgh Community Renewal Program. This model kept the basic Lowry model structure but provided for: (a) incremental, and not single-year, solutions introducing, thus, the time element in forecasting which accounts for the fact that all changes predicted by the model do not take place in the forecast year but a certain proportion of activity remains stable and (b) disaggregated population into different socio-economic groups in the hope of improving the explanatory power of the model. Another version designed also by Crecine for East Lansing, Michigan (Crecine 1969 cited in Batty 1976, 62) is used as an educational device in the METRO gaming simulation exercise at the University of Michigan (Batty 1976).

4.6.2C PLUM (Projective Land Use Model)

Another application of the Lowry framework is PLUM (Projective Land Use Model) designed by Goldner (1968 cited in Batty 1976, 63 and Batten and Boyce 1986, 851-852) for the San Francisco region. The modifications and improvements made include programming changes to incorporate zones of different sizes, the use of an intervening opportunities model to allocate population and employment, disaggregation of the model's parameters by spatial unit (the nine countries of the Bay Area), use of zone-specific activity rates and population-serving ratios. For further description and discussion of this model's use, the reader is referred to Rothenberg-Pack (1978). PLUM has been used by Putman (1983) in building ITLUP -- an integrated land use/transportation model – which is discussed later in this section.

4.6.2D Activity Allocation and Stocks-Activities Models

From the other side of the Atlantic, Echenique and his colleagues at the University of Cambridge in the U.K. (see, Wilson 1974, Batty 1976) developed the *Urban Stocks and Activities model*, an adaptation of the Garin formulation of the Lowry model framework, which operates at the town scale. They have fitted this model to several British towns and a version has been applied to Santiago Metropolitan area (Echenique *et al.* 1969 cited in Wilson 1974, 242, Batty 1976, 75-79). One of the important changes this model introduced was the use of floorspace as a measure of location attraction on each iteration of the model. As floorspace is reduced so is the measure of location attraction. The use of floorspace introduces, however crudely, the supply-side mechanism of the urban land market which is not present in the original Lowry formulation. The stocks of floorspace serve as constraints on the demand for space by various activities seeking to locate in a zone (Wilson 1974, Batty 1976). More recent integrated land use-transport models designed by Echenique and his colleagues use also floorspace as a measure of location attraction (Echenique *et al.* 1990; see also, SPARTACUS 1999).

A more general family of urban models originating from the parent Lowry model have been built by various modelers in the 1970s which Batty (1976) calls *Activity Allocation and Stocks-Activities Models*. These models are variations of the spatial interaction model which are used to allocate population and employment to the zones of an urban/metropolitan region while the Stocks-Activities models operate at the town scale where they translate the activity allocations to land uses. Batty (1976) describes the operational forms and technical details of these models and provides information on their applications in the U.K. as well as intermodel comparisons.

To close the discussion of the Lowry model, a brief evaluation of the first generation of Lowry-type models is in order. The main purpose of these models is to forecast (or, predict) future changes in the distribution of the population, employment and land uses in urban (mostly) areas given exogenous changes in basic employment. In other words, they are basically demand-driven models in which the supply side of land is under-represented in the best case. From the analysis of land use change point of view, this is an important drawback as various aspects of the supply of land (economic, environmental, institutional, etc.) play a crucial role in determining the direction and amount of change which comes about with changes in the demand for land by space-consuming activities (among others). This drawback is further reinforced by the static nature of all these models (despite efforts to produce dynamic versions – see, Crecine 1968, Batty 1976) which does not capture the dynamics of land use change which may be either demand-, or supply-related or, most possibly, may result from their interaction. In addition, from a policy impact analysis viewpoint, these models do not include many policy variables so that they can be used as decision and policy support tools for the large variety of policy interventions through which land use change is effected (see, also, Rothenberg-Pack 1978).

Another drawback relates to their theoretical foundations which borrow from the economic base theory (and model) and the gravity theory (and model). Both have been heavily criticized for their **positivist** orientation, their many omissions of critical factors related to urban growth (especially the supply side), the mechanistic view of real world phenomena they advance (see, section 4.4), and their poor explanatory power all of which bear importantly on the issue of land use change. Overall, both pieces of theory emphasize, in a rather rudimentary way, the economic determinants of land use change while, as it is being repeatedly stressed, land use change results from much more involved processes even in the economic markets. Besides these deficiencies, the Lowry-type integrated models miss many other aspects of integration, important among which is the impact of the transportation network, a theme which was addressed in the decade of the 1980s by the development of integrated land use-transportation models.

Finally, and most importantly in the perspective of the present project, the treatment of land use is rather simplistic. The land conversion ratios are crude measures (quick and dirty techniques) of the amount of land demanded when changes in economic or population activity take place. They do not account directly for technological variations (low-, vs. high-rise buildings, land use intensification through space-saving technologies), socio-economic and cultural differences (especially when the models are transferred to other cultural settings) in the use of space, non-linearities in the use of space especially those arising out of the interactions among adjacent land uses (demand for space may not be proportional to changes in the space-demanding activities). Moreover, their uniform application over space disregards the supply-side of land use change; i.e. the constraints which the natural and built environment may impose on future changes. The supply side is taken into account by imposing allowable space limits on land use types but the adjustment process the models apply when these limits are exceeded is mechanistic. Evidently, the use of these linear land conversion ratios masks all potential variations in the use of space and makes the assessment of land use change by these models a mechanistic (and mostly self-fulfilling) process.

4.6.3. Simulation Integrated Models

Many of the integrated models of land use can be classified basically as simulation models if simulation is defined broadly as a modeling activity aimed at analyzing impacts or making conditional predictions using some form of operational expression of a system's components and of their interrelationships. Batty (1976) notes that "All mathematical models which involve the use of large-scale computational facilities are referred to as simulation models" (Batty 1976, 294). However, as a modeling technique, simulation has a more precise meaning. According to Wilson (1974), simulation techniques involve "a set of rules which enable a set of numbers to be operated upon, usually in the computer, although the rules and the consequences of applying them cannot be written down as a set of algebraic equations. . . . Sometimes, the simulation technique lends itself naturally to a problem. This happens, for example, when the underlying theory consists of a set of statements involving conditional probabilities . . . .We resort to simulation techniques for situations which are too complicated to be handled by more straightforward algebraic techniques" (Wilson 1974, 175).

Batty (1976) clarifies further the meaning of simulation by distinguishing between analytic and simulation methods of modeling: "*Analytic methods of modeling* involve the use of mathematical analysis to arrive at explicit equations representing the behaviour of the system. *Simulation methods* are used to derive the behavior of the system when the system is too complex to be modeled using the more direct analytic approach" (Batty 1976, 294). He further cites Elton and Rosenhead (1971) who point out the essential characteristic of simulation when they say "... one does not arrive at explicit equations expressing the behavior of the system of this general type; rather one achieves a number of potential histories of the system from which the effects of possible modification to the system can be predicted" (Batty 1976, 294).

The simulation integrated models which are presented here are grouped according to the spatial level to which they refer as there is a close relationship between spatial level of analysis, theoretical background of the model, and level of aggregation used (or, possible). Most models are based on economic theory – either micro- or macro. Microeconomic models are also distinguished according to their adopting a continuous utility maximization framework or a discrete, random utility theory framework. Three groups of models are discussed: (a) urban/metropolitan level simulation models, (b) regional level simulation models, and (c) global level simulation models.

4.6.3A Urban/Metropolitan level simulation models

The first simulation models to be considered are urban/metropolitan level models. The application of, more or less, **heuristic techniques** to provide answers to land use forecasting questions which arise naturally in the context of planning dates back to the 1950s when elementary, plan-based forecasts were generated by means of such techniques. The Detroit Metropolitan Area Transportation Study and the Chicago Area Transportation Study (CATS) were among the first efforts which had the greatest influence. The former is credited with introducing "what has come to be known as the Urban Transportation Planning (UTP) model ... which operationalizes the concept ... that urban trip-making is a derived demand depending on land uses and that future travel could be derived from forecasts of future and uses" (Kain 1986, 848). The CATS model (Hamburg 1960 cited in Kain 1986, 848) "devised an ingenious land use forecasting model based on the concept of development capacity" (Kain 1986, 848) utilizing floor area data and historical information on population densities and vacant land. However, (computer) simulation techniques emerged in the early 1960s when more refined modeling techniques started to develop and information technology was making rapid progress. In fact, this latter development is one of the reasons for the flourishing of simulation techniques in the following decades up to the present.

Among the first, large-scale applications of simulation were models of the housing market. Although these are not integrated models of land use change proper as they concentrate on a particular subsystem of the urban spatial system, the housing market, and not on land use, they attempt some kind of integration in the sense that: (a) they examine the demand for housing and the allocation of households in each housing submarket (in a way similar to many gravity-type integrated models discussed previously), (b) they consider the interaction between demand and supply of housing, and (c) they disaggregate the housing market considerably to capture (within the constraints of the models applied, of course) the spatial variability of the housing market. The following models which belong to this category are presented here:

- The San Francisco CRP model, and
- The UI, NBER, HUDS urban simulation models
- The CUFM model

Adopting a broader perspective on integration, other modelers attempted to simulate the relationships among more components of the urban/metropolitan system. The literature calls these models *dynamic simulation models*. Two examples of this line of integrated modeling are given:

- The Dortmund model and
- A selection of the well-known integrated land use/transport models.

The San Francisco CRP model

The earliest housing market simulation model was the San Francisco CRP model designed by A .D. Little (Rothenberg-Pack 1978, Kain 1986) whose primary focus was less on forecasting than on evaluating various housing and community development programs. It represents a pioneering effort to model the behavior of both housing demanders and suppliers and to relate their decisions in a rudimentary market clearing framework. It was concerned with the *central city* (and not with the wider metropolitan region) and it did not consider competition between the central city's housing market and that of the rest of the region. It required **exogenous** forecasts of population by household types according to demographic characteristics and income. It represented 114 types of households (defined in terms of income, family size, race and age), 27 types of dwelling units (defined in terms of structure type, tenure, number of rooms and conditions), and 106 neighborhoods. It developed housing supply models which assumed profit maximizing housing suppliers and made supply decisions according to projected market rents and estimates of the cost of new construction (Kain 1986). For a variety of reasons whose discussion is beyond the scope of the present project, this model did not become fully operational (for details see Rothenberg-Pack 1978).

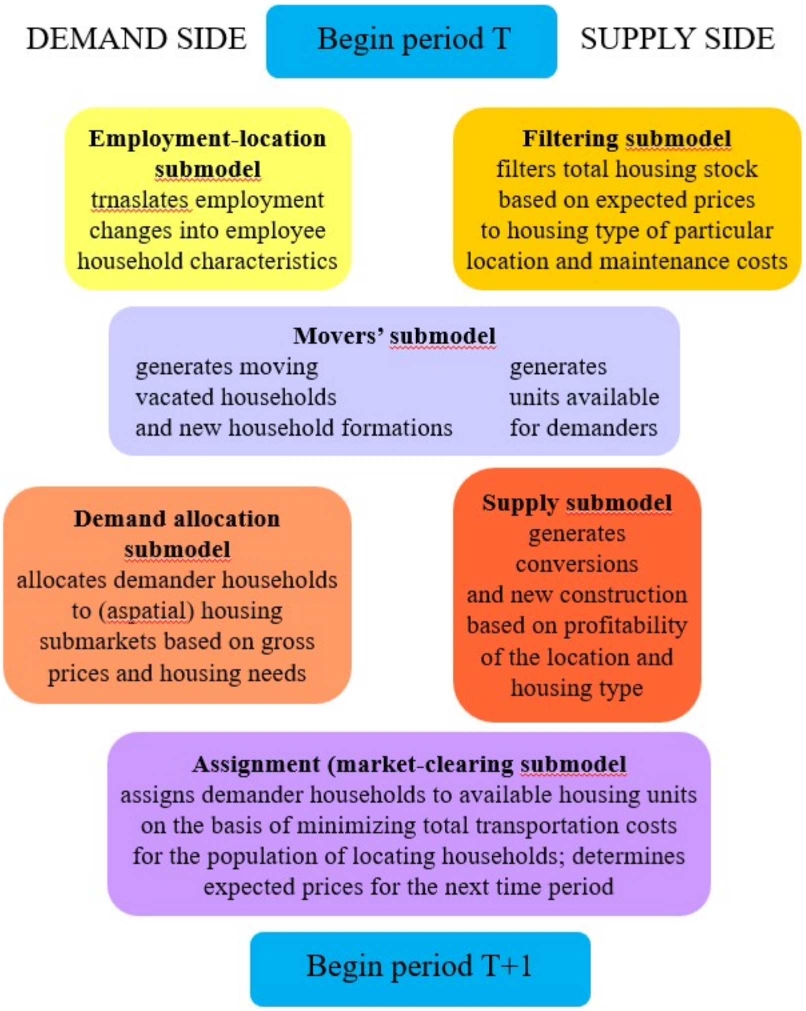
The UI, NBER, HUDS urban simulation models

Three other simulation models of the housing market, developed in the 1970s, are widely known: the Urban Institute model (UI), the NBER (National Bureau of Economic Research) Urban Simulation model and the HUDS (Harvard Urban Development Simulation) model (Kain 1986). All three models provide modeling of demand for housing, supply of housing, and a housing market clearing mechanism.

The *UI model* produces long run equilibrium solutions of housing quantities and prices based on a **Walrasian** auction mechanism for a 10-year simulation period (Kain 1986). *Housing demand* is modeled on the basis of utility theory. Households seek to maximize their **utility** subject to a budget constraint; the housing services demanded depend on quantity of housing services consumed, quantities of other goods consumed, employment accessibility, average journey-to-work travel time for each zone of the study area, relative wealth of the zone, racial composition of the zone. The utility functions assume that the optimum quantity of housing services demanded is independent of neighborhood characteristics.

Housing supply is modeled similarly following the economic theory for producers; i.e. assuming profit maximization. The housing production functions express current level of housing services in terms of initial level of services and a quantity of newly added capital inputs (including housing depreciation). These housing supply functions are calibrated from historical data. The UI model provides for less spatial (six zones) and household detail compared to the NBER-HUDS models which are discussed next.

The *NBER-HUDS models* is essentially a family of three models starting from the Detroit Prototype moving to a second version used to study the market effects of housing allowances as part of the Experimental Housing Allowance Program (EHAP) and ending with HUDS which was designed and used to evaluate the impacts of spatially concentrated housing improvement programs (Kain 1986). The structure of the basic NBER model is presented below based on Chapin and Kaiser (1979) and Kain (1986). The characteristics of the housing and demand models of NBER and HUDS are discussed together (following Kain 1986) as both belong to the same family.



The NBER Submodels

Source: Adapted from Chapin and Kaiser (1979)

Figure 4.2d

The NBER-HUDS models provide annual housing market clearing solutions in contrast to the UI model which assumed a 10-year simulation period. They employ a disequilibrium framework for clearing the housing market which is modeled by means of linear programming. Housing is modeled in great detail as a multidimensional bundle of housing services described in terms of structure type, neighborhood quality, and quantity of structure services households must consume as an indivisible package at a particular location. The structure of the prototype NBER model is presented in Figure 4.2d.

The description which follows reflects the characteristics of the two versions of this original prototype. Six submodels are included corresponding to the demand and the supply side of the housing market. The *first submodel* is a *supply-oriented dwelling unit-filtering submodel* which estimates changes in housing quality either downward due to aging or upward due to renovations on the basis of expected housing prices in the zone and **exogenous** maintenance costs. The output of this submodel is a distribution of expected housing prices by dwelling type and zone and an aged and renovated housing stock.

The *second submodel* is a *demand-oriented employment location model* which receives as input exogenously determined revisions of employment levels and composition (by industry) at each workplace. It translates these changes into changes in employee household characteristics – age of the head of the household, family size, income, education, race – for each of 96 household types. The *third submodel* is called a *movers' submodel* which generates mover households that enter the housing market as demanders of housing. It introduces new household formation as well. The moving households generate vacancies that enter the supply side as available housing units.

The *fourth submodel* is a *demand allocation submodel* which allocates housing demanders (the 96 household types) at each workplace to one of 50 housing submarkets defined as 50 housing bundles based on five neighborhood quality levels and 10 structure types. The allocation is operationalized by means of econometrically estimated multinomial logit demand functions and takes into account the relative minimum gross prices of the 50 housing bundles. The demand function expresses the probability that a worker employed at workplace j will live in residence zone i and the conditional probability that he will commute by mode m, given the choice of residence i so as to minimize travel costs which include both time and money costs. Note that this is not a spatial allocation but an allocation to housing type.

The *fifth submodel* is a *supply submodel* which estimates demolitions, conversions, and new construction for each zone. The housing supply functions are similar to the UI's supply functions but are more elaborate and detailed reflecting, among others, expectations of the housing suppliers of future changes in prices, investments, etc. The last submodel is the *market clearing assignment model.* After each housing market participant has been assigned to a housing submarket, a linear programming algorithm is used to assign them to residence zones. The same algorithm produces estimates of location rents which are used as price signals and, in combination with other information, are used to calculate market prices for each of the 50 housing bundles in each of the 200 residence zones (of the Chicago area application of HUDS). Taking into account the distributions of both housing and household characteristics at the start of the simulation period, the output of this model is the distribution of these characteristics at the end of the period (a year).

The NBER-HUDS models are more detailed spatially and in terms of household types than the UI model. All three models are restricted to urban areas and to housing, employ economic theory of profit and utility maximization to estimate housing supply and demand, and they are suited to analyzing impacts of housing policies. The analysis of land use change with these models is constrained by the above features and lacks a host of other explanatory factors (environmental, social, cultural, political, institutional). In fact, these models are not explanatory models as they are fitted with historical data and start with a predetermined theoretical schema, that of utility maximization. Interactions with other types of land use are implicit at best. The emphasis of these models on accessibility as one of the explanatory factors of household housing choice behavior is characteristic of the functionalism of modeling activity in the 1960s and 1970s.

The CUFM model

The California Urban Futures Model (CUFM) developed by Landis (1994, 1995) is a more recent modeling effort to provide a model of the housing market which could be used in a planning context for the analysis of alternative plans. It has a diverse heritage as its designer notes (Landis 1995) of which the Lowry and the NBER pieces are of interest here. It has several innovative features with respect to both past and contemporary models of the housing market. First, it focuses on private land developers as the most influential agents in the context of urban development. These are assumed to be profit maximizing individuals who decide to develop a site if it has a high development potential. Second, CUFM models the supply side of the housing market explicitly by adopting a spatial system of reference based on the notion of Developable Land Units (DLUs) which may be individual sites or groups of sites with similar characteristics (with respect to residential development). DLUs are stored and manipulated in a GIS environment. The solutions generated by the model are, thus, depicted in greater spatial detail on a site by site or DLU basis in contrast to zone-based integrated models. Third, the purpose of CUFM was to simulate the development effects of locally-based land use and development policies, the latter constituting an important input to the operation of the model.

CUFM consists of four linked submodels: (a) the Bottom-Up Population Growth Submodel, (b) the Spatial Database, (c) the Spatial Allocation Submodel, and (d) The Annexation-Incorporation Submodel. The *Bottom-Up Population Growth Submodel* represents the demand side of the whole model. It generates five-year population growth forecasts for every city and county as a function of city size and growth history, outward expansion potential, and the adoption of specific policies intended to promote or retard growth. It consists of two linear regression equations one for cities and one for counties (Landis 1994). The *Spatial Database* represents the supply side of the whole model and includes the geometry, location and attributes of each

DLU. It consists of a series of map layers that describe the environmental, land use, zoning, current density, and accessibility attributes of all sites in the study region. The *Spatial Allocation Submodel* allocates the projected population growth to the DLUs of the study area with the use of certain rules and procedures. Its main function is to "clear the market" by matching the demand for developable sites to the supply of such sites. DLUs are developed in decreasing order of their expected profitability (to private developers). Finally, the *Annexation-Incorporation Submodel* consists of a series of procedures for annexing newly developed DLUs to existing cities or incorporating clusters of DLUs into new cities.

The profit potential of a DLU, measured as per acre residential development profit (i, j, k) is calculated as the difference between the net home sales price (i, j, k) and the following cost items:

- raw land price (j, k)
- hard construction costs (i, k)
- site improvement costs (i, j, k)
- service extension costs (k)
- development, impact, hookup, and planning fees (k)
- delay and holding costs (k)
- extraordinary infrastructure capacity costs, exactions, and impact mitigation costs (j, k).

The subscripts used denote:

i the size and quality level of a typical new home in each community
j the slope, environmental characteristics, and specific location of the home site (or DLU)
k the jurisdiction in which the home is located

Although CUFM provides a spatially explicit integrated model of the housing market which can be used to analyze various policies as well as to incorporate the environmental variability of a study area, it has several shortcomings in the view of more holistic integrated models. First, although it rests on the assumption of profit maximizing land developers, it lacks a firm theoretical grounding on economic as well as on sociological or other theories on land development. Second, it does not take into account the interaction of land use with the transportation network which has proven to be very important in metropolitan areas at least. Third, it does not include feedbacks from development or excess demand on housing prices. Fourth, it does not deal with the allocation of other uses such as industrial, commercial, etc. In fact, it ignores the important, "driving" influence of the location decisions of various types of employment on the subsequent development (including housing) of an urban region; i.e. it does not model the jobs-housing balance. Finally, the "journey-to-work" variable (i.e. accessibility) which is central in several past and contemporary integrated models is of secondary importance and does not affect directly the allocation of development. This is not necessarily a negative feature of the model as, in fact, the emphasis of several models on accessibility as a determining driver of urban development has been criticized frequently as it downplays the importance of other determinants of urban spatial structure and growth (namely, the location decisions of producers or, equivalently, of capital).

Dynamic simulation models

Simulation techniques have found important applications in modeling dynamic urban and regional systems given the complexities of modeling these systems as well as the tremendous (if not infeasible) data requirements. Among the first widely known urban dynamic models are J. Forrester's (1969) simulation modeling exercises which, however, were aspatial and, hence, did not deal with land use at all. Several dynamic urban and regional models have been proposed and the interested reader is referred, among others, to Andersson and Kuenne (1986), Bennett and Hordijk (1986), and Miyao (1986). Wegener (1994) reviewed and compared briefly 12 operational urban models built in the 1980s and 1990s of which several account for land use such as POLIS (Prastacos 1986), CUFM (Landis 1992), ITLUP (Putman 1983, 1991), TRANUS (de la Barra 1989), LILT (Mackett 1983), MEPLAN (Echenique *et al.* 1990), IRPUD (Wegener 1982, 1985, 1986a). The presentation of all these elaborate models is beyond the scope of this contribution. The reader is referred to recent reviews for further information (Southworth 1995, Wegener 1994). In this section, only a few selected models are presented which relate closely to the analysis of land use change and they are representative of the modeling tradition in this area. These are:

- The Dortmund Model, and
- The Integrated Land Use/Transportation Models

The Dortmund Model

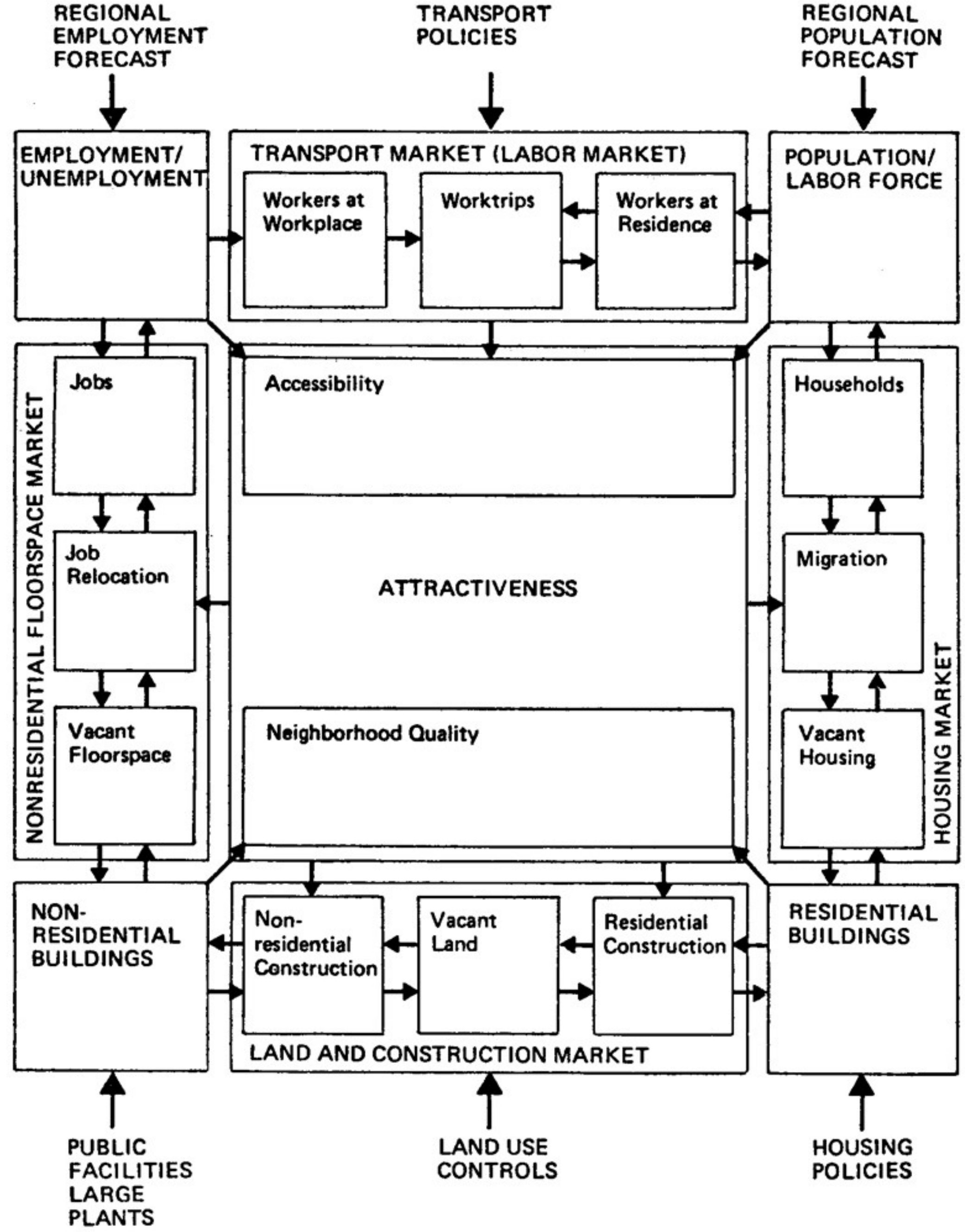
Wegener (1980, 1982) developed a multilevel dynamic simulation model of the economic and demographic development of the Dortmund region, Germany, to capture urban growth and decline processes. Its purpose is to simulate the location decisions of industry, residential developers and households, the resulting migration and commuting patterns, land use development, and the impacts of public programs and policies in the areas of industrial development, housing and infrastructure. The model is operational for the city of Dortmund (consisting of 30 zones and 40 subregions).

The general subject of the model is the study of the **endogenous** adaptation of urban regions to changing **exogenous** conditions through public and private decisions. It starts from the observation that several national and multiregional models (of the late 70s-early 80s when the model was designed) cannot capture the essential causes of urban decline because they lack the spatial resolution necessary to take into account agglomeration diseconomies and scarcity of resources, most notably of land. Most models of urban spatial development have been built to allocate growth and have failed to address the issue of urban decline. Only a few of them consider some causes of urban decline such as an aging population, economic recession, outdated infrastructure, and scarcity of buildable land. One of the reasons Wegener advances for this drawback of urban models is the lack of a theory of spatial decision behavior of urban actors such as enterprises, households, individuals and considers his model an attempt to contribute to such a theory.

The Dortmund model is organized at three spatial levels: (a) state, (b) urban region, and (c) city. The *first-level model* is a multiregional, demo-economic (i.e. demographic-economic) model of the state. Its regions are functionally defined as labor markets. It predicts how regions compete to attract industries and migrants under **exogenous** preconditions. State policies are taken into account such as public subsidies for industrial development, housing programs, infrastructure investment in specific regions, large scale location or relocation decisions by major industrial corporations. The model yields forecasts of employment by industry and population by age, sex, and nationality in each of the 34 labor market regions as well as migration flows between them.

The *second-level model* subdivides the urban region into 30 zones. It predicts intraregional location decisions of industry, residential developers and households, resulting migration and commuting patterns, land use development, and impacts of public programs and policies in the areas of industrial development, housing and infrastructure. The outputs of the model are employment by industry, population by age, sex and nationality, households by income, size, age and nationality, dwellings by size, quality, tenure, and building type, and land use by land use category for each of the 30 zones plus the volume of migration and commuting between them. Finally, the *third-level model* receives as input the output of the second-level model to allocate further the projected activities within each of the 30 zones of the second level. The rest of the presentation of Wegener's model refers to the second-level model - the urban region – which concerns the modeling of the spatial distribution of activities in the urban region.

The basic structure of the model is shown in Figure 4.2e.



The Dortmund Model

Source: Wegener (1982) – Reprinted with the permission of Sage Publishers.

Figure 4.2e

It is a recursive, spatially disaggregated simulation model of the urban region. It operates at 2-year increments up to a time horizon of 20 years. It receives as input from the first-level model zonal data on employment (40 industrial sectors), population (20 5-year cohorts), 30 categories of households (characterized by nationality, age of head, income, size), 30 types of housing (characterized by type of building, tenure, quality and number of rooms), industrial and commercial buildings, public facilities, 30 land use categories 10 of which relate to built-up areas), and transportation networks. Urban growth and decline are modeled in terms of the spatial distribution or redistribution of three major urban activities: employment, housing and population.

The *employment model* simulates the effects of major economic and technological developments such as recession, sectoral changes, productivity increases which cause changes in demand for industrial and commercial floorspace and eventually buildings and land affecting, thus, the spatial structure of the region. This model treats each of the 40 sectors as separate submarkets and makes no distinction between basic and non-basic sectors. At the beginning o the simulation period, it starts with employment in sector s at time t in zone $i, E_{si}(t)$. This employment can change in six ways as follows:

(a) sectoral decline calculated by the following equation:

$$^{rs}E_{si}(t, t+1) = E_{si}(t)[1 - E_s(t+1)/E_s(t)] \qquad (4.82)$$

where,

rs	stands for redundant sectoral workers
E_s	denotes total employment

(b) lack of building space is calculated by the following equation:

$$^{rb}E_{si}(t, t+1) = [E_{si}(t) -^{rs} E_{si}(t, t+1)][1 - b_{si}(t)/b_{si}(t+1)] \qquad (4.83)$$

rs	stands for jobs to be relocated because of lack of space
$b_{si}(t)$	is existing floorspace per workplace at time t
$b_{si}(t+1)$	is the projected floorspace per workplace at time $t+1$

(c) closing down of large plants which is considered as a “historical event” for which there is no model and, hence, it is exogenously determined (as number of workers and vacated space)

(d) new jobs in vacant buildings which is estimated by a pro rata rule

(e) new jobs in new buildings modeled as extra demand accommodated in new buildings through an allocation function

(f) demolition where the last two steps are reiterated to account for the relocation of jobs caused by demolition.

The *housing model* assesses changes in housing stock in three different ways:

(a) filtering, where the housing stock filters down in quality each simulation period expressed by the following equation:

$$R(t+1) = h(t, t+1)R(t)d(t, t+1) \qquad (4.84)$$

where,

R	an $M \times K$ occupancy matrix (M number of household groups, K number of housing types)
h	an $M \times M$ matrix of transition rated of households
d	an $K \times K$ matrix of transition rates of housing types

(b) public housing which is exogenously determined (as a form of policy)

(c) new housing construction which considers additions to the housing stock usually in a subset of the 30 housing types (submarkets).

The demand for new housing is estimated as a function of price changes in a given submarket compared with other investment alternatives (i.e. as a function of relative profitability). This demand is allocated to vacant residential land through an allocation function which accounts for the capacity and attractiveness of a zone.

The *population model* consists of two distinct but interrelated parts. The first projects existing population of each zone by age, sex, and nationality. The second projects the same population in terms of households by size, income, age of head, and nationality. The relationships between population aging, household formation, migration of households, and migration of persons are modeled as a sequential probabilistic process. For population aging, standard cohort-survival population projection techniques are used. A portion of foreign population is transferred to the native population. Household formation is calculated by using transitions between household states as in the case of transition between age groups. They are aggregated to 30 household types and matrix $h(t, t+1)$ used in equation (4.84) is formed. Consistency checks between aging and household formation are performed also. The migration of households is modeled by an elaborate housing market submodel which represents the interaction between supply of housing (by landlords) and housing demand (by households). A micro-simulation probabilistic approach using the Monte Carlo technique is employed to simulate the housing market as a sequence of search processes of households looking for a house and landlords looking for a tenant. Finally, the migration of persons translates the results of household migration into numbers of persons by taking into account the age distribution of households by type.

Integrated land use/transportation models

An important class of urban/metropolitan models, known as integrated land use/ transportation models, were built in the decades of the 1970s and 1980s and their development continues up to the present. Their common purpose is to model the simultaneous nature of land use and transportation interactions and decisions in urban/metropolitan areas and, thus, be used to analyze the spatial (land use) impacts of changes in the transportation system and/or the location of activities. The land use- transportation connection remains always important because, even in the present information age, the transportation system provides the physical links between the various land markets of the urban system. Before discussing particular representative models, the main features of the integrated land use/ transportation models are briefly presented first.

Until the time research on integrated land use/ transportation models began, transportation and land use modeling and planning moved on separate tracks. A transportation study would assume as *given* a future land use pattern consisting, mainly of the spatial distribution of residences and workplaces, to design a system of transportation facilities that would serve adequately this pattern. The spatial distribution of activities offered input to procedures for estimating: (a) the total number of trips from and to each zone or subarea of a region and (b) the origin-destination (OD) trip matrices between pairs of zones (split by transport mode if possible). Given the various sets of OD trip matrices, the trips would be “loaded” on the transportation network to test whether the configuration of the transportation system could serve adequately the *given* spatial pattern of activities.

In the same vein, forecasting the future spatial distribution of activities in an urban area would assume the transportation network as *given*. Other inputs necessary in this context included: (a) description of the base year spatial distribution of activities (mainly, residences and workplaces) and (b) regionwide population and economic forecasts. Some kind of simulation model was (or is) used to produce the future spatial distribution of activities served by the *given* transportation network. These future land use patters were evaluated against various planning goals.

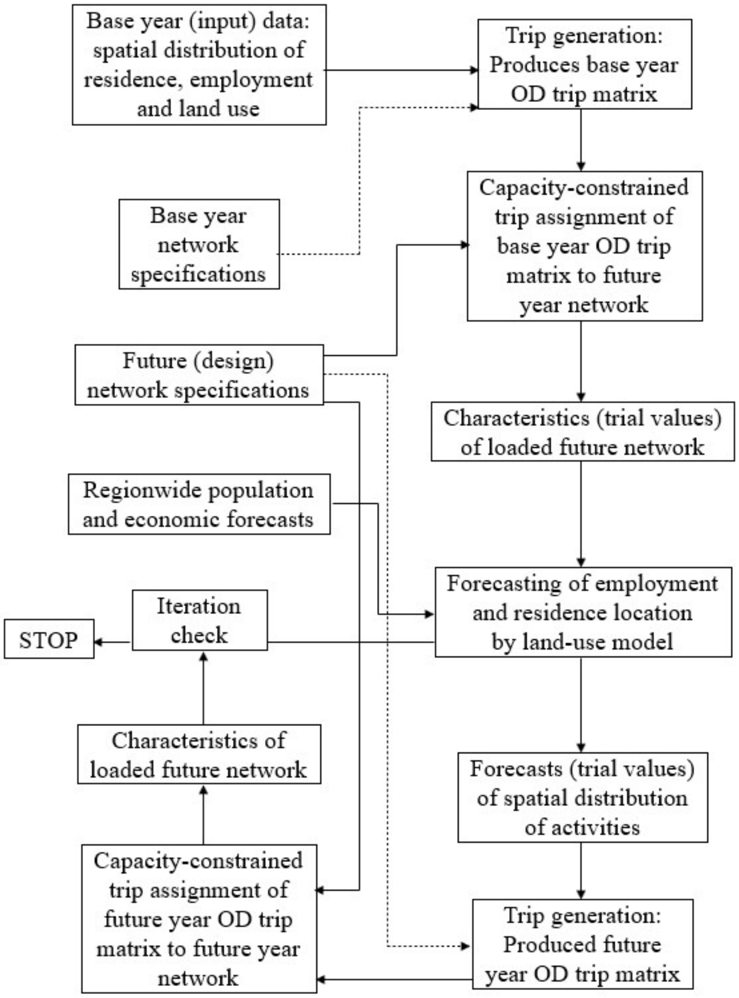
As it may have become evident from the above, the main shortcoming of the separate modeling of the land use and the transportation systems is that it ignores the feedbacks between them. The transport system may induce the spatial redistribution of activities – rearrangements of population and employment in space. In their turn, the changed patterns of activities impact on the transportation system (causing, e.g., congestion). In this way, a “chain reaction” is set in motion within an urban area. As Gordon and Moore (1989) put it: “both approaches to urban model building (the activity location and the transportation modeling) though clearly complementary, are equally deficient. . . . Congestion costs are determined within the process of land use allocation and, in turn, affect this allocation. It is intellectually inconsistent to accept either transportation costs or land uses as fixed” (Gordon and Moore 1989, 1196). This shortcoming attempts to alleviate an integrated land use/transportation model.

The first line of development of integrated land use/transportation models grew out of the gravity or spatial interaction models as recast by Wilson (1967) as entropy maximization models. These models can be used either as transport models which predict transport flows between origin and destinations or as allocation models which allocate population and employment to zones. Coupling these two aspects of the spatial interaction models provides a means to model in an integrated fashion the linkages between two or more sub-systems of the urban or regional spatial system. According to Wegener (1986b): “The general idea is to formulate the relationship between two subsystems as constraints of one process on the other and then solve the spatial interaction system under these constraints. Examples of this kind of integration effort are models linking transport and location (Boyce 1977, Los 1978), or models linking two or more urban activities (Brotchie 1978, Coelho and Williams 1978, Sharpe and Karlqvist 1980, Leonardi 1981)” (Wegener 1986b,18). The resulting models are usually non-linear constrained optimization models (see Batten and Boyce 1986 for an exposition of the evolution and mathematical formulation of these models).

Another line of integrated land use/transportation models consist of coupling an activity allocation with a transportation model for the simultaneous modeling of the land use-transport connection. Of the several integrated land use/transportation models built since the mid-70s along this line, three are presented briefly below: (a) ITLUP, (b) TRANUS, and (c) CATLAS. ITLUP employs location and transport models of the spatial interaction variety while the other two employ models based on the framework of random utility (or, discrete choice) theory. The recent trends and developments in integrated land use/transportation modeling are presented at the end of this section.

ITLUP – Integrated Transportation Land Use Package

Among the first and most celebrated of those models which have been built upon the Lowry modeling formulation is Putman’s Integrated Transportation and Land Use Package – ITLUP (Putman 1983). ITLUP grew out of a research project which was commissioned by the U.S. Department of Transportation for the study of the interrelationships of transportation development and land development. Based on the description provided by its developer, a schematic representation of ITLUP is shown in Figure 4.2f.



A schematic representation of the Integrated Transportation-Land Use Package (ITLUP)

Source: Adapted from Putman 1983

Figure 4.2f

Inputs to the model are: (a) base year descriptions of the spatial distribution of employment and residences and (b) the characteristics of the unloaded base year transportation network. These data are used to generate a preliminary estimate of trips in the metropolitan area. These estimated trips are loaded on the *future* transportation network so that its characteristics (travel time and cost) reflect the traffic volumes that would be on the network if the base year spatial distribution of activities had not changed. These characteristics of the network together with the base year spatial distribution data and the forecast regionwide control totals are used to produce a trial estimate of the spatial distribution of activities in the projection year. These are, then, loaded on the future transportation network whose modified characteristics can be used to reallocate the projected spatial distribution of activities. This is compared to the first trial estimate. If there are no differences, an equilibrium has been reached and the model run is ended. If there are differences, new trips are generated and loaded on the network and the procedure is repeated. Evidently, this type of land use/transport modeling takes into account the feedbacks among the two components of the urban system – land use and transport. In the following, the land use and the transportation models employed in the context of the integrated model are presented first followed by a discussion of their integration.

The *land use model* which was originally selected for ITLUP was the Projective Land Use Model (PLUM), a derivative of the Lowry model (see section 4.6.2.). PLUM accepts as given the spatial distribution of basic employment and then produces the spatial distribution of the population (residences) and nonbasic (basically retail) employment. The general form of the residential location model employed is given by the following equation:

$$N_i = g \sum_j E_j p_{ij} \qquad (4.85)$$

where,

N_i	is the number of persons living in zone i
E_j	is the number of employees working in zone j
p_{ij}	is the probability that a person who works in zone j will live in zone I, and
g	is a scaling adjustment factor

The probability p_{ij} is the central element of this equation and it is considered as having two components: a trip function and an attractiveness measure. In the earliest versions of PLUM there was no attractiveness term. The trip function used in all versions of PLUM had the following form:

$$p_c = \frac{\beta}{c^2} \exp\left(\alpha - \frac{\beta}{c}\right) \qquad (4.86)$$

where,

p_c is the probability of a trip of length (i.e. travel time or travel cost) c and α and β empirically derived parameters.

In a later version of PLUM, two modifications were introduced in the calculation of the travel probabilities. The first was to modify the original calculation of the probability of traveling to a zone; instead of dividing the probability of traveling to an **isochronal annulus** by the number of zones in the annulus , the probability of traveling to an annulus was divided by travel cost to the annulus . The second modification was to include a measure of attractiveness the residence-zone end of a work trip, essentially a residential holding capacity or, a measure of “opportunities”, as it was called, given by the following expression:

$$U_i = L_i^v \frac{H_i}{L_i^r} \qquad (4.87)$$

where,

U_i	is a measure of opportunities for new residential development in zone i
L_i^v and L_i^r	are, respectively, residential land acreage and vacant (nonindustrial) acreage in zone i, and
H_i	is the number of housing units in zone i

Modifications of the above measure of attractiveness were introduced later to better reflect the state of existing infrastructure which influences the development potential of a zone.

To better estimate the trips generated in the zones of the urban system, a disaggregated residential allocation model (DRAM) was developed after the first version of ITLUP had been completed which accounted for the following types of trips: (a) work-to-home, (b) work-to-shop, and (c) home-to-shop (Putman 1983). By normalizing trip probabilities (i.e. dividing each p_{ij} by the sum of trips from all origin to a destination zone), the residential location model that resulted is basically a singly-constrained spatial interaction model (see section 4.4). Further improvements of this model resulted in the final formulation of the DRAM model which combined a multivariate attractiveness measure of a zone to residential locators (by type of locator) and a two-parameter trip function (for details, see Putman 1983).

To account for the location of non-basic (or, population-serving) employment, a singly-constrained spatial interaction model was formulated also of the form:

$$S_{ij} = A_i Y_i W_j^R f(c_{ij}) \qquad (4.88)$$

where,

$$A_i = \left[\sum_j W_j^R f(c_{ij}) \right]^{-1} \qquad (4.89)$$

S_{ij}	is the number of persons living in zone i and shopping in zone j
Y_i	is the purchasing power of consumers living in zone i
W_j^R	is the retail “attractiveness” of zone j
$f(c_{ij})$	is the generalized cost function of a trip between i and j

The reader is referred to Putman (1983) for details on the treatment of the projections of the location of basic employment in ITLUP (which in the Lowry-type models is assumed to be exogenously given).

Turning now to the *transport models* used in ITLUP, the transportation model package which had been developed by the Planning Sciences Group of the University of Pennsylvania was used. This package contained procedures for network coding, tree tracing, and several traffic assignment procedures. The typical transportation analysis includes four steps: trip generation, trip distribution, trip assignment and modal split. The trip assignment procedure involves taking an **exogenously** calculated origin-destination trip matrix and determining the paths these trips take over the transportation network. The trip assignment procedure used in ITLUP was more sophisticated employing alternative algorithms for trip assignment and allowing for modal split (different modes of transport).

The critical aspect of the integrated model is the *integration* of the land use model with the transportation model. In ITLUP this is done via *trip generation*. More specifically, the land use models produced the distribution of residences and nonbasic employment to the zones of the urban system. From these distributions, a set of trips – the origin-destination (OD) matrix – was produced for input to the transport network model. The person-trip matrices thus generated are then converted by means of some procedure to vehicle-trips to be loaded on the transportation network. To illustrate the linkage between the land use and the transportation models, the simple, original form of the land use model shown in equation 4.85 is used. This is as follows:

$$T_{ij} = g E_j p_{ij} \qquad (4.90)$$

where,

T_{ij}	is the number of trips from zone i to zone j

Because the trip probabilities, p_{ij}, used in the final form of the land use models are normalized – leading to a singly-constrained spatial interaction model form (equation 4.88), it is assured that the sum of trips thus generated equals exogenously estimated future totals of population and employment. The joint calculation process employed in ITLUP results in a trip matrix consistent with the spatial distribution of trip makers, their trip origins, and trip destinations.

ITLUP has been used in a series of policy analyses which are discussed in Putman (1983). These include analysis of the impacts of: (a) redistribution of basic employment, (b) high-speed road links, (c) land use controls, (d) regional growth or decline, (e), regionwide changes in transportation costs. Additional procedures were developed also which used the results of ITLUP to assess the impacts of transportation, location, and land use policies on air quality. ITLUP has been used by several planning agencies in the United States as an aid in making land use and transportation decisions (Putman 1983). A similar, Lowry-type model like ITLUP is LILT (Leeds Integrated Land Use/Transport) developed by Mackett (1983) for the Leeds Metropolitan Area which was then applied to several other British and foreign cities.

TRANUS (Transportation and Land Use System) and CATLAS
(Chicago Area Transportation Land use Analysis System)

Sharing the common purpose of all integrated land use/transportation models, the models discussed below differ from the previous ones in that the land use and transport models they employ are discrete choice models drawing from the random utility theory instead of the classical gravity or spatial interaction theoretical framework. Random utility theory (McFadden 1978) aims "to explain and forecast the behavior of urban actors such as investors, households, firms, or travelers. Random utility models predict choices between alternatives as a function of attributes of the alternatives, subject to stochastic dispersion constraints that take account of unobserved attributes of the alternatives, differences in tastes between the decision makers, or uncertainty or lack of information" (Wegener 1994, 24). It is a more suitable approach to modeling phenomena where the variables under consideration are not continuous (like residential choice, land use, shopping behavior); hence, marginal analysis (characteristic of the classical continuous utility maximization models) cannot handle them satisfactorily. For example, in the Muth-Mills equilibrium models, housing prices reflect marginal productivity conditions consistent with long-run competitive equilibrium (Straszheim 1986, 746), which may not be the case in the short run or when the capital stock is durable as it is the case with housing. Discrete choice models drawing on random utility theory model utility maximizing choices as a problem in random utility functions (Straszheim 1986, 746). A brief exposition of the basic characteristics of discrete choice models is offered below followed by the presentation of the TRANUS and the CATLAS models.

Starting with the individual case, the perceived utility an individual s associates with the choice of option k, u^{sk}, in a decision situation, is defined as:

$$u^{sk} = U^s(X^k, S^s) \qquad (4.91)$$

where,

X^k represent the measurable attributes of option k
S^s the socio-economic characteristics of the individual s

Even in this individual case, the utility function is not deterministic because individuals behave differently each time in choice situations. In the aggregate case of a group of individuals, the variations in the utility functions become even larger as aggregation introduces many sources of variability. Thus, for the group as a whole, a distribution of perceived utilities.

An aggregated utility function of the utility, u^{sk}, for a population s (of the same socio-economic characteristics) as regards a choice option k is given by the following expression:

$$u^{sk} = U^s(X^k, \zeta) \qquad (4.92)$$

where,

X^k represents the measurable properties of option k, and

ζ the random variation in the utility function

The utility function shown in equation (4.92) is divided into two components, a deterministic and a stochastic component. The deterministic component represents the fixed and measurable aspects of utility, V^k, or, the *strict utility* of an option. The stochastic component, μ, reflects the probabilistic nature of the utility within the population. The probability that population group s will choose option k, p^{sk}, is defined as the integral of the cumulative joint probability function, $\tau^k(t)$ expressing the variation within the population with respect to option k:

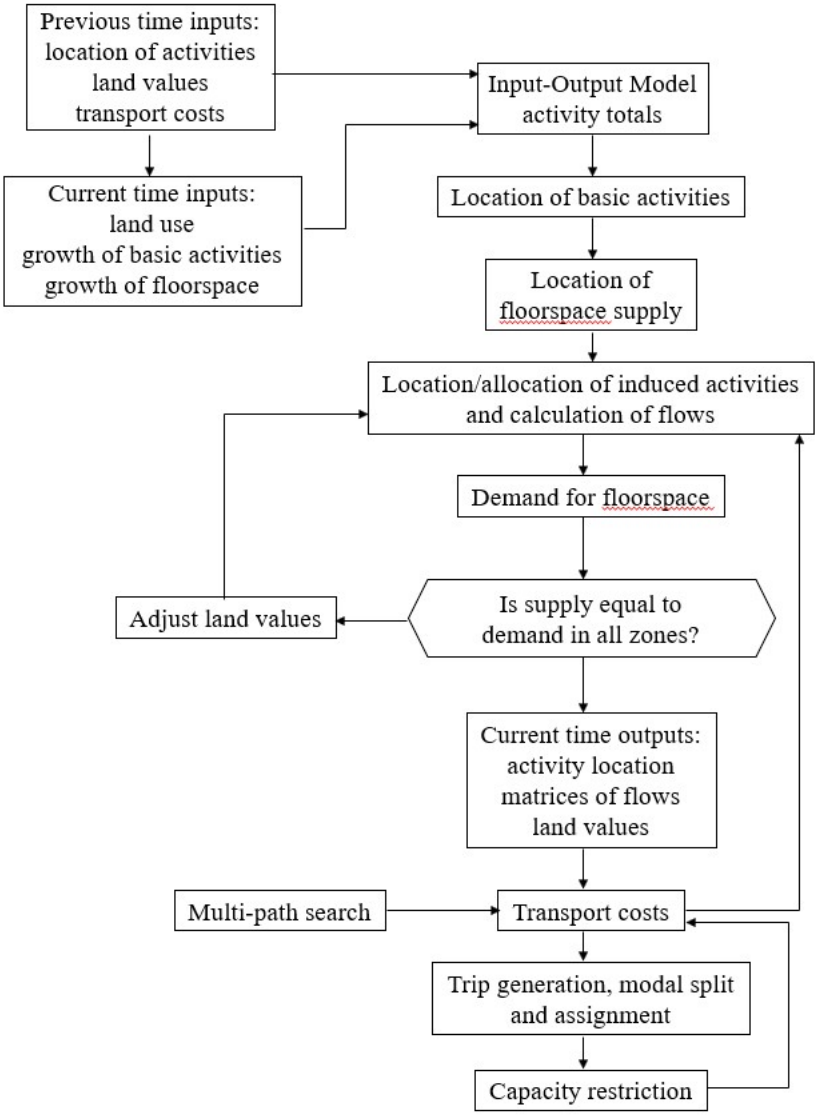
$$p^{sk} = \int_{-\infty}^{+\infty} \tau^k(t)dt \qquad (4.93)$$

Depending on the particular mathematical function chosen for $\tau(t)$ equation (4.93) produces alternative mathematical expressions. A common expression is the multinomial logit model:

$$p^{sk} = \frac{\exp(\beta^k V^k)}{\sum_k \exp(\beta^k V^k)} \qquad (4.94)$$

This model form has been already presented in the section on the statistical models of land use change. It is used in several other applications of random utility theory as shown below. At this point, it is important to note that Anas (1983b) showed the convergence of the random utility and the entropy maximizing theory. More specifically, the above multinomial logit model resulting from random utility maximization is, at equal levels of aggregation, equivalent to the entropy maximizing (gravity) model.

TRANUS is an integrated model employing the random utility theory framework for the land use and transportation models of which it is comprised. The following discussion borrows heavily from the description offered by its developer, Tomas de la Barra (1989). A schematic description of the model structure is shown in Figure 4.2g.



A schematic representation of TRANUS

Source: Adapted from de la Barra 1989

Figure 4.2g

The upper part of the Figure depicts the dynamic interactions of the land use with the transport models for time periods $t_1, t_2, \ldots . t_n$. The bottom part of the Figure shows the working of TRANUS within a single time period. In the following, the land use, or activity location/allocation, model, the transport model and their integration are discussed.

The *activity location procedure* requires the following inputs:

a. A set of **technical coefficients** a^{mn} of an aspatial Input-Output model where a distinction is drawn between final demand (basic) and induced sectors. The definitions of basic and induced employment correspond to those used for basic and service (or, nonbasic or population-serving) employment in the description of the Lowry and the ITLUP models. In the context of TRANUS, the conventional terminology of **Input-Output Analysis** is modified; commodities and economic sectors are substituted for "activities", where the latter may stand for number of workers, residents, etc. (de la Barra 1989).

b. Previous time inputs: the location of activities in the zones of the urban system, land values, and transport costs

c. Current time inputs: land use, growth of basic activities, and growth of floorspace.

The procedure starts with the determination of totals of induced employment and population given an **exogenously** determined level of total basic employment. The increments of basic employment and floorspace forecast for the current period are allocated to the zones of the urban system. The location of the increments of basic employment can be estimated by means of a simple probabilistic model or can be set by the user (reflecting, e.g. the location of new major plant). The location of the increments of floorspace is more elaborate as it takes into account the amount of floorspace in the previous period, land values, and potential floorspace. The user can predetermine the location of floorspace in the zones also.

The location of induced activities and floorspace in the zones of the system is the next step. The following equation is used for the allocation procedure as well as for the estimation of flows between pairs of activities:

$$ {}^{r}X_{ij}^{mn} = {}^{r-1}X_i^m \alpha^{mn} \frac{\exp(-\beta^n V_{ij}^n)}{\sum\limits_j \exp(-\beta^n V_{ij}^n)} \tag{4.95} $$

where,

${}^{r}X_{ij}^{mn}$	is the number of activities (e.g. jobs) of sector n in zone j generated by activities in sector m in zone i; r denotes iteration number
${}^{r-1}X_i^m$	is level of activity of sector m in zone i
V_{ij}^n	is the utility function associated with activity of sector n
β^n	is an empirically estimated parameter

The utility function takes the form:

$$ V_{ij}^n = c_{ij}^n + \tau^n r_j \tag{4.96} $$

where,

c_{ij}^n	is the composite cost of transport for activity n between zone i and zone j is a parameter regulating the effect of land values on the location of
τ^n	n activity which combines with β^n for the effect of the composite cost of transport
r_j	is the value of land in zone j

Once all activities have been allocated to zones, appropriate floorspace demand functions are used to estimate total demand for floorspace in each zone. This is, then, compared to the current fixed supply of floorspace. Land values in each zone are adjusted appropriately to produce an equilibrium between supply and demand of floorspace.

The main outputs of the activity allocation model described above are: (a) the location of activities in each zone, (b) the supply of floorspace, (c) (equilibrium) land values, and a set of X_{ij}^{mn} matrices which represent the functional relationships between zones and sectors. These are input to the transportation model.

The *transportation model* adopts the random utility theoretical approach also. The interested reader is referred to de la Barra (1989) for the details of this model. Basically, it follows the structure of a typical transportation package consisting of the following sequence of procedures: trip generation, modal split, and network assignment. The important link between the land use and the transport component of the integrated model is trip generation (as it was the case also with ITLUP). The demand function for transport, which converts the flows between sectors and zones calculated by the activity allocation model above, to number of trips from zone i to zone j by sector n, T_{ij}^n, is given by the following equation:

$$T^n_{ij} = X^n_{ij}\lfloor \alpha^n = b^n \exp(-\beta^n c^n_{ij} \rfloor \qquad (4.97)$$

where,

X^n_{ij}	is the total activity level of sector n between zone i and zone j; it is found by summing X^{mn}_{ij}over all m sectors
α^n	is the minimum number of trips sector n must perform and $\alpha^n + \beta^n$ is the maximum
c^n_{ij}	is the generalized composite cost of travel

The number of trips by sector are then distributed to different transport modes by means of a multinomial logit model of the form shown in equation (4.97). Trips by transport mode are distributed over the paths of the transportation network by means of another multinomial logit model where the utility function takes account the cost of transport on the particular path. By applying vehicle occupancy rates, trips are transformed into number of vehicles in each link of the network.

At the end of the iterative process, travel speeds and waiting times change as a function of demand/capacity ratios. This leads to an adjustment of travel and waiting times and, then, to a new estimation of travel cost in each link. The new travel costs affect trip generation, modal split and assignment as well as the location of activities in a future time period.

TRANUS has been used in several applications such as: (a) the design of an urban development plan for the island of Curacao, (b) the design of a land use plan for La Victoria (Venezuela), (c) a study for the extension of the Caracas metro system, (d) the design of the Caracas-La Guaira motorway, (e) the design of the central railway system in Venezuela, (f) the evaluation of motorway projects in Venezuela, and (g) the evaluation of alternative energy scenarios in urban regions (de la Barra 1989). Several other integrated models sharing the structure of TRANUS and employing the random utility theoretic framework have been developed such as MEPLAN (Echenique *et al.* 1990; see also, Wegener 1994, Southworth 1995) and they have been used in various applications (see, for example, SPARTACUS 1999). It is interesting to note that most integrated land use/transport models of the 1990s, either new models or developments of past models, adopt the random utility theoretic framework.

CATLAS (Anas 1982, 1983) is another model in the category of integrated land use/ transport models which is restricted to the housing market as opposed to TRANUS which was a more general model for any type and number of activities in an urban or a regional system. Its purpose is to model the joint choice of housing, residential location and mode of travel. Anas utilizes also the theoretical framework of random utility theory as housing and travel mode choice are not continuous but discrete choices.

The model developed by Anas (1982) is called CATLAS (Chicago Area Transportation Land use Analysis System). It is a dynamic simulation model which employs a nested multinomial logit model, consistent with utility or profit maximization, where choices are represented as a sequential choice probability structure (i.e. the probability of a household choosing a house type and location is represented as a product of conditional probabilities – i.e. as the product of the conditional probability of choosing a house type given the choice of location times the marginal probability of choosing a location) (Straszheim 1986). CATLAS consists of four behavioral submodels: (a) a demand submodel, (b) an occupancy submodel, (c) a new construction submodel, and (d) a demolition submodel.

The *demand submodel* is a sequential choice model which computes the probability that a worker employed at workplace j will live in residence zone i and the conditional probability he will commute by mode m, given the choice of residence zone i. A single equation is estimated for all households. The *occupancy or existing housing stock submodel* estimates the probability that the average dwelling in each zone will be offered for rent in a particular year as a function of the average rents in that zone and various zonal attributes. It simulates changes in the housing stock and the rent of each zone as well as changes in the age distribution of the housing stock by zone. Market clearing is achieved by solving for each year's clearing rent vector, assuming the number of households assigned to each residence zone must equal the number of units supplied in each year (Kain 1986, 859-860).

Recent developments in the area of integrated land use-transportation modeling (or, *integrated urban modeling* as it is called also) follow particular directions based on an experience of more than two decades with this type of models. In particular, emphasis is placed on the behavioral aspects of the land use-transport (or, activity-travel) system. Activity-based travel analysis recognizes that travel demand is derived from the needs of people to engage in out-of-home activities. Hence, activity-based travel analysis is most appropriate for modeling the land use-transportation interactions. In this context, the appropriate unit of analysis is the individual (or, the household) and, at this disaggregate level, modeling attempts to capture the variability and diversity (and causality) of human mobility. Relevant aspects of activity-travel patterns on which research is focusing include:

a. activity-time allocation (Levinson and Kumar 1995, Golob and McNally 1997)
b. activity episodes (Ettema *et al.* 1995, R. Kitamura *et al.* 1997)
c. activity scheduling (Ettema *et al.* 1993, 1996)

At the same time, more appropriate mathematical tools are being developed to provide for more satisfactory modeling of individual behavior. Microsimulation, in particular, is considered, the principal tool for behavioral modeling. As Miller (1996) defines it, microsimulation is an approach to modeling systems that are both dynamic – i.e. evolving over time – and complex. Recent development in computer programming – more specifically, from structured to object-oriented programming (Booch 1994, Booch *et al.* 1999) – has led to the development of object-oriented microsimulation. This modeling approach permits a one-to-one mapping between objects in the real world and objects in the simulated world (Miller and Salvini 1998, Kanaroglou 2000). Overall, the trend is towards developing models which are more sensitive to reality and towards modeling techniques capable of representing this reality.

The preceding brief presentation of the dynamic urban simulation models does not permit a complete and documented assessment of the strengths and weaknesses of this class of integrated models of land use. The interested reader will find such evaluations in the references provided. However, from the particular perspective of the analysis of land use change which is the present focus, certain observations can be made as regards the most notable characteristics of these models. Firstly, they embed the study of land use change in the broader context of changes in population and employment in urban/ metropolitan areas which are assumed to be the important determinants of land use change in these contexts. Not all of these models are really comprehensive as they emphasize selected (and not all) aspects of the urban system modeled (Wegener 1994). This characteristic carries on the particular types of land uses they consider which, with a few exceptions, are usually residential and commercial uses.

In terms of theoretical underpinnings, all models rely on some version of micro-economic theory (Alonso's urban land market theory mainly) and/or random utility theory. In other words, they are **deductive**, **functionalist** models moving in the same theoretical tradition as the earlier urban economic models. This means that, as regards the quality of explanation of the urban phenomena – including land use change – they offer, the same criticisms as those directed to urban modeling of the 1960s and 1970s potentially apply (Sayer 1976, 1979a, 1979b). More generally, in view of the diversity of the theories of land use change which have been presented in Chapter 3, which reveal many more determinants and processes of change in addition to the economic ones, the theoretical basis of these models appears to be rather limited. On the other hand, several of them adopt the random utility theoretical framework which appears to be more flexible and capable of accommodating and handling a variety of behavioral/theoretical assumptions compared to the continuous utility maximization frameworks which governed certain of the earlier microeconomic urban models. In particular, the operational forms of discrete choice models provide for the inclusion of many factors which theory suggests as being important determinants of individual choice behavior and, consequently, of potential spatial change. Several of these factors are discrete (e.g. cultural values, environmental conditions, institutional regimes) which makes the random utility theoretical framework particularly suitable for including them in land use change models. Future research and analysis of these models will reveal their ability to include many more aspects of land use change than their current versions.

4.6.3B Regional level simulation models

Turning now to *regional level integrated simulation models*, a greater diversity of simulation approaches and model applications is encountered. Even the expression "regional level" is somewhat misleading in terms of the actual spatial coverage of the relevant models as it may refer to an assembly of urban regions, to a collection of contiguous subdivisions of a large nation, or the nation itself considered as a collection of regions (variously defined), or to a group of nations. The most characteristic differences of the regional level from the urban level simulation models are rooted in "the difference that space makes" (note: title of an essay by A. Sayer 1985). The change from the lower to the higher level of the spatial scale implies: (a) changes in the nature of the spatial entities under study and the related processes of change; other land use types are included – mainly agriculture and forestry – which were not very relevant at the urban level; other types of agents are involved and other decision making are relevant, (b) other determinants of land use change obtain importance at higher levels such as environmental (climate, geomorphology), political, macro-economic, etc., (c) the complexity of the system to be modeled increases as both the numbers of the interacting entities increase as well as their variations, and (d) other patterns of spatial structure and change are visible and are amenable to modeling (mainly, coarser and less detailed). The models which are presented below have been selected, first, because they are representative of a more contemporary genre of models of the economy-environment-society interactions and, second, because their direct purpose is modeling of land use change. This latter feature reflects the recent interest on the critical role of land use and its change in triggering larger scale environmental change.

Several reviews of integrated modeling efforts of the economy-environment-society interactions as well as of those factors with land use have been undertaken. Most of them conclude that the number of models in which land use change is adequately modeled is very small (see, for example, Turner *et al.* 1995, Fischer *et al.* 1996a, Lonergan and Prudham 1994). One of the possible explanations is that the purpose of most modeling exercises was not modeling of land use change until recently. For example, Fischer *et al.* (1996a) cite a model built to study the effects of global climate change on U.S. agriculture (Adams *et al.* 1993 cited in Fischer *et al.* 1996a, 5). It is a combined bio-physical and economic spatial optimization model which represents production and consumption of 30 primary agricultural products including crop and livestock commodities. It consists of a set of micro- or farm level models integrated with a national sector model. Production behavior is described in terms of the physical and economic environment of some 63 production regions of the United States. Regional level supply curves determine the availability and use of land, labor and irrigation water. However, except for the direct effects of climate change on U.S. agriculture, the model "did not investigate other driving forces such as urbanization nor possible implications and feedbacks of land use change on the dynamics of the resource base such as the potential for competing demand for water" (Ficher *et al.* 1996a, 6).

Four integrated models – or, better, modeling approaches or frameworks – which can be classified as regional level simulation models are presented below which address the analysis of land use change directly:

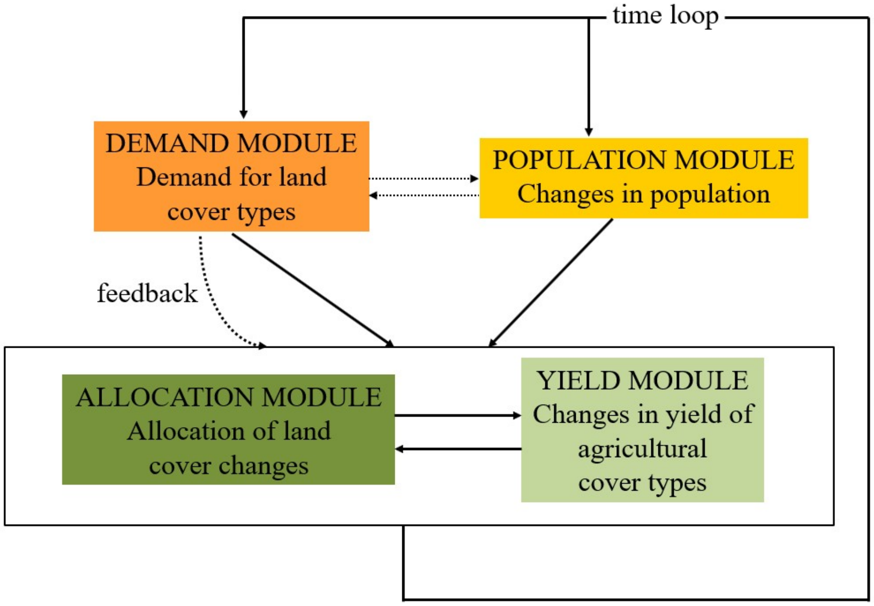
- The CLUE modeling framework
- The cellular automata modeling framework
- IIASA's LUC (Land Use Change) model, and
- The IMPEL model

The CLUE modeling framework

The CLUE modeling framework (Conversion of Land Use and its Effects) is being developed at the Wageningen Agricultural University in the Netherlands to model land use changes as a function of their driving factors (Veldkamp and Fresco 1996a, 1996b, 1998, Verburg et al. 1997, de Koning et al. 1998, Verburg *et al.* 1999). It has been applied to analyze land use/cover changes in several countries such as Ecuador, Costa Rica, Java, and China. A basic outline of this framework follows based on the several publications of the CLUE research group.

The CLUE modeling framework is a spatially explicit modeling framework for the analysis of land use/cover dynamics at various spatial scales. Its most recent versions incorporate also dynamic analysis of feedbacks of land use changes on the local environment, the population, etc. as it is the case, for example, of agricultural over-use or unsuitable use in sensitive areas. In other words, the CLUE framework can be described as an integrated, spatially explicit, multi-scale, dynamic, economy-environment-society-land use model. According to members of the CLUE group, it is a cross-disciplinary model as it integrates environmental modeling and a geographic information system (Veldkamp and Fresco 1996b).

The modeling procedure consists of two consecutive steps. First, past and present land use patterns are analyzed at various levels of spatial aggregation using multiple regression analysis to determine the most important bio-physical and socio-economic determinants of land use at each level of aggregation as well as the quantitative relationships between them and the area of various land use types (the linear regression models used in module CHANGE to perform these analyses were presented in section 4.3.2.). The second step uses the results of the analysis of the first step to explore possible future land use changes within a spatially explicit framework using scenarios of future socio-economic development (de Koning *et al.* 1998). The CLUE modeling framework has a modular structure as shown in Figure 4.2h. Modeling of the supply side is taken up by the *Yield Module* while modeling of the demand side is taken up by the *Demand Module*. The Population Module provides input to the Demand Module as changes in population modify the demand for different commodities. The Allocation Module allocates the projected needs (demands) for land use of various types to the grid cells in which the study area is subdivided to produce the actual patterns of future land use which will result from the projected changes in its drivers.



The CLUE modeling framework

Source: Adapted from de Konig *et al*. 1998

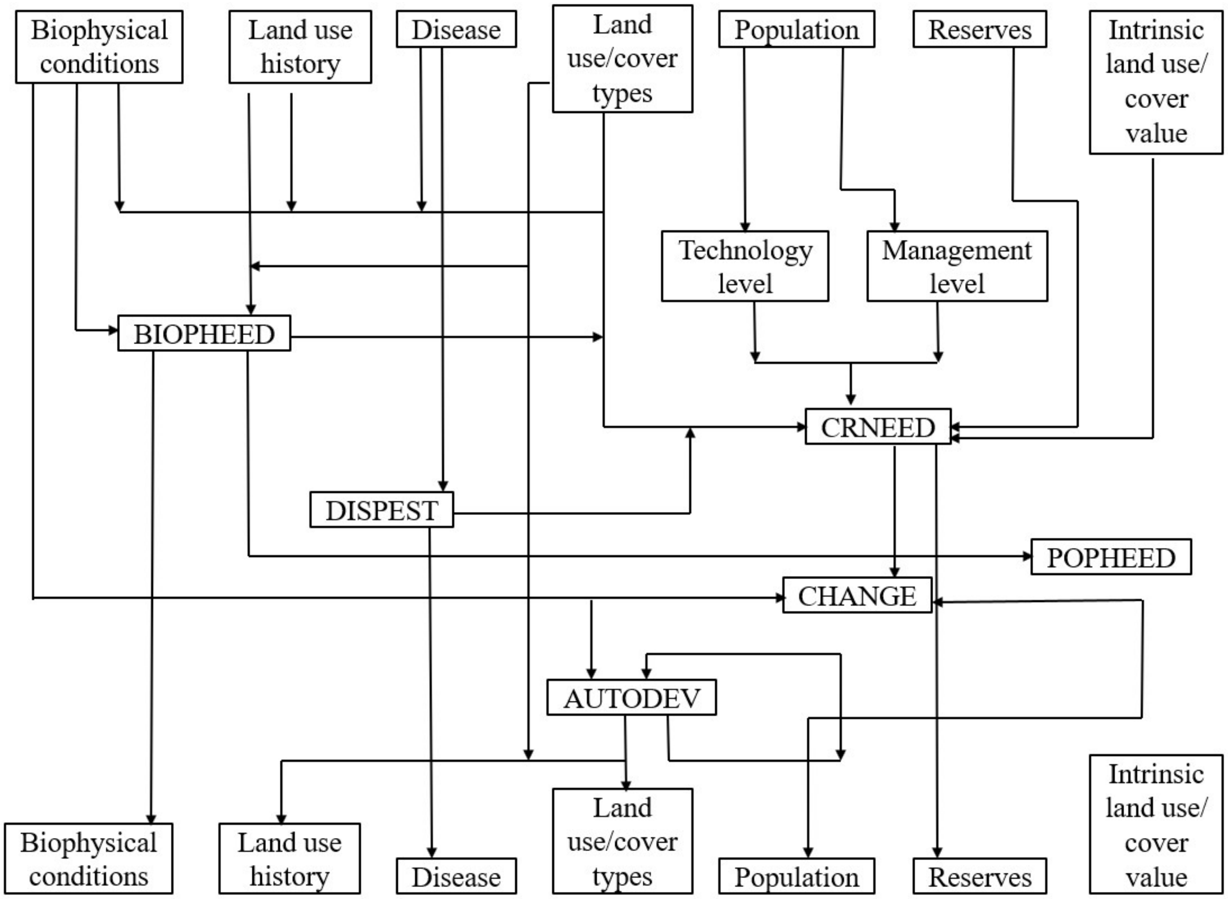
Figure 4.2h

The *Demand Module* calculates the demand for various types of land use based on the national level demand for various commodities. National level demand consists of domestic consumption and exports. Exports are assessed exogenously and they are related to international prices and national subsidies. Domestic consumption is assessed as a function of population size, composition (urban and rural) and consumption patterns. The Population Module provides the necessary demographic input to the Demand Module. Consumption patterns may be related to macro-economic indicators like GNP, purchasing power and price levels. Demand functions for separate commodities are estimated based on historical data. To account for difficult-to-predict changes in demand, alternative scenarios are formulated which take into account various population projections and changes in diet patterns. The production volumes demanded for the separate commodities are translated into areas of the corresponding land use/cover types using crop specific yield coefficients (for animal products, production per animal and stocking densities are used). The areas calculated for separate crops are aggregated to broader land use/cover types to obtain the demand for land at the level of these aggregate types.

The *Yield Module* assesses the yield of each of the main land use/cover types as a function of their surface area (in each cell of the study area), bio-physical conditions, technology level, management level and their general intrinsic cover value. The bio-physical conditions considered are: slope, altitude, soil drainage, and climate. The technology level is simulated by using urban population as a proxy. The management level is simulated by using rural population as a proxy (Veldkamp and Fresco 1996b). Finally, the *intrinsic cover value* is a dimensionless indicator (a numerical value for each land use/cover type) which reflects the relative value of a land use/cover type (which may be affected by changes in market demand and supply of the associated commodities).

The *Allocation Module* provides for the actual allocation of the demand for land by land use/cover type generated by the Demand Module to the cells of the study area in accordance with the ability of land in each cell to support the actual demand as assessed by the Yield Module. The CLUE modeling framework applies a nested scale approach for this allocation drawing on the idea that local land use change is the product of changes in both the drivers of land use at higher scales as well as of changes in local bio-physical and socio-economic conditions. The basic allocation procedure is as follows. The national demand for each land use type is allocated first to the cells at the higher spatial aggregation level to establish the comparative advantages between higher level regions of meeting the demand. Within these higher level cells, then, local changes in all land use types in the lower level of aggregation cells are calculated based on their bio-physical and socio-economic conditions (obtained from the Yield Module) taking into account also the conditions of the larger level cells. The actual calculation of the land use changes at each spatial level are made by using the regression equations estimated from the first step of the modeling procedure. If a cell has less area than that demanded for a certain land use type, then an increase in the area of this land use type is considered within the limits sets by the supply side. The actual fraction of land use change assigned to each cell is determined iteratively and simultaneously for all land use types taking into account competition among land use types within each cell (de Koning *et al.* 1998). This allocation procedure attempts to integrate top-down with bottom-up demands and constraints to simulate the effects of future changes in the drivers of land use.

The CLUE model version applied to the case of Costa Rica (CLUE-CR) has a structure similar to the basic one described above but it incorporates more detail and feedbacks as shown in Figure 4.2i.



The CLUE-CR model

Source: Adapted from Veldkamp and Fresco 1996b

Figure 4.2i

This version is characterized by the authors as a discrete finite state model written in PASCAL (Veldkamp and Fresco 1996b, 233). It simulates the following (exhaustive) land use/cover types: arable land, permanent crops, pastures and range lands, natural vegetation and a residual group (secondary vegetation, towns, roads, bare rock, etc.). It makes a number of assumptions the most important of which are: (a) a dynamic equilibrium exists between population and agricultural production; trade is not ruled out but assumes a minor role, (b) agriculture is the main employment and income generator in the rural areas of Costa Rica, (c) the smallest unit of analysis is a grid-cell which, despite its biophysical and socio-economic uniformity, may accommodate all five land use types, (d) land use change occurs only when bio-physical and human demands cannot be met by existing uses of land (note: the authors mean probably *quantitative* land use change), (e) food and money reserves incorporated in the model for a two-year period imply that seasonal and annual yield fluctuations do not have a direct effect on land use changes.

The modules of the CLUE-CR are similar to those of the CLUE model shown in Figure 4.2h. In particular, CRNEED corresponds to the demand and yield modules and the CHANGE module corresponds to the allocation module in Figure 4.2h. AUTODEV is a module which accounts for autonomous land use change (independent of national demand) in the case national demands do not give rise to land use change as well as in the case certain cells are not selected by the allocation procedure described above. In the next time step, the autonomous land use change calculated is fed back to CRNEED and CHANGE to simulate bottom up effects of local to the regional and national levels. BIOPHEED is an optional module which simulates feedback effects of agricultural overuse or unsuitable use in sensitive areas (e.g. erosion-prone arable land). DISPEST is another optional module designed to simulate the spatial and temporal effects of pests and diseases on land use/cover dynamics. The model's input data as well as its output are geo-referenced and managed in a GIS system.

According to the CLUE research group, the modeling framework they propose requires further elaboration to become a reliable policy support instrument. These include high spatial resolution data, linkages to farming systems analysis, land evaluation systems (e.g. FAO's system already mentioned in this contribution), and optimization planning models. To assist in the assessment of climate change impacts, CLUE has to be linked to GMCs (General Circulation Models) with the application of proper upscaling procedures.

The CLUE modeling framework is a worthwhile attempt to address the land use change issues as it is sensitive to the requirements of integration along all dimensions with a special emphasis on the critical spatial dimension. It adopts a macro-, aggregate approach to the analysis of land use change and it is intended primarily to serve as a predictive tool in analyzing the land use impacts of future development scenarios at large scales – regional and national. It is relatively simple to comprehend and functional to use but its explanatory capability is seriously limited exactly because of these characteristics. Several points should be made about this. First, the application of statistical procedures to identify the most important drivers of land use change is questionable for three reasons at least: (a) statistical associations do not imply causal relationships which is what the search for the drivers of land use change is about; (b) statistical analysis – at least of the sort applied in CLUE – cannot capture the qualitative aspects and determinants of land use change (notably the institutional, the political, and the cultural) which are the most important and critical for future developments especially in the context of developing countries, and (c) the statistical significance/importance of **explanatory** variables does not necessarily assure their theoretical importance (see Achen 1982). Additional problems associated with statistical modes of land use change can be found in the relevant section of this contribution. The statistical analyses which constitute the first step of the CLUE modeling framework may be considered as exploratory steps which should be complemented by thorough analysis using other, mostly qualitative, techniques. Second, the analysis of spatial data in the context of CLUE does not seem to have been performed by means of the appropriate spatial statistical procedures. This can be fixed rather easily, however, given the wide dissemination of the related packages (Levine 1996, LeSage 1999) and expertise as well as the recent integration of spatial analysis techniques and GIS (Fischer and Nijkamp 1993, Longley and Batty 1996, Fischer *et al.* 1996). The most important point, however, which should be stressed is the absence of a rigorous theoretical basis supporting the whole modeling effort. For the moment, the CLUE models yield crude statistical pictures of past and future land use patterns produced mechanistically. The incorporation of at least certain behavioral assumptions and theoretical arguments in the relationships studied will enhance a tool which has already a well-designed structure.

The Cellular Automata Modeling Framework

Another integrated simulation modeling approach draws from the theoretical framework of Social Physics discussed in chapter 3 and more specifically from the theory of fractals to model the structure and evolution of land use patterns. It applies *cellular automata* concepts to model a variety of complex, dynamic, socio-economic and environmental phenomena (see, for example, Tobler 1979, Couclelis 1985, 1988, 1989, Engelen 1988, White and Engelen 1992). The approach – henceforth called cellular automata approach – to be presented below is considered to be "quite general in terms of the situations to which it can be usefully applied" (Engelen *et al.* 1995, 203). It has been shown to apply to both the urban and larger geographical scales for the comprehensive, integrated analysis of land use change.

Before presenting this modeling approach, the concept of the *cellular automaton* is defined and the justification for using this concept in modeling is briefly sketched. "Cellular automata are mathematical objects that have been studied extensively in mathematics, physics, computer science and artificial intelligence (Gutowitz 1991). . . . Tobler (1979) defined them as geographical models but they have only rarely been applied in human geography in the years since he proposed them. . . . A cellular automaton consists of an array of cells in which each cell can assume one of k discrete states at any one time. Time progresses in discrete steps, and all cells change state simultaneously as a function of their own state, together with the state of the cells in their neighborhood, in accordance with a specified set of transition rules. Transition rules can be either quantitative or qualitative or both" (Engelen *et al.* 1995, 207). A *cellular automata model* consists of: "(a) a cellular space, normally two dimensional, (b) a definition of the neighborhood of a cell, (c) a set of possible cell states, and (d) a set of transition rules" (White and Engelen 1994, 240).

Spurred by the need to account for the important role of spatial detail in many real world systems, "in recent years there has been an explosion of interest in what may be referred to collectively as *connectionist* models . . . abstract Boolean algebra, neural networks and cellular automata. Much of the research in this domain is aimed at uncovering general principles for the organization and evolution of dynamical systems" (White and Engelen 1994, 239). The application of cellular automata concepts to the integrated analysis of socio-economic and environmental phenomena seems to fare better than conventional modeling approaches (such as spatial interaction models and GIS-based models) for a variety of reasons. First, they make possible the integration of macro- with micro-scale temporal processes. Similarly, they make possible the integration of macro- and micro- spatial phenomena and the related decisions. In this way, they can make the maximum possible use of available spatial and temporal detail, in contrast to conventional approaches which operate either at the macro- or at the micro- level and cannot integrate both. Lastly, they offer a flexible platform to cope with complex real world systems; i.e. to represent meaningfully a variety of interactions among the various components of a spatial system – social, economic, environmental . This is because cellular automata approaches "can represent the generation of complex patterns by simple rules" (White and Engelen 1994, 238). As the rules can be specified by the users, alternative theoretical assumptions may be tested against reality and their validity assessed in particular socio-economic and environmental contexts. This will be demonstrated in the following presentation.

Drawing on White and Engelen (1994) and Engelen *et al.* (1995), two examples – an urban and a regional level – of the cellular automata approach are offered to present its application to the analysis of land use change in two different contexts and with different degrees of detail. The urban example assumes a cellular city divided into a number of cells each of which can be in any one of four possible hierarchically ordered states (uses of land) – vacant, residential, industrial, and commercial. During the city's evolution, cells are converted from one state (use of land) to another in the order shown above; i.e. only from a lower to a higher state. The hierarchy is imposed to simplify the model and, in fact, it can be dropped easily. In this example, the net number of cells to be converted to each non-vacant state is determined exogenously. The gross number of cells to be converted is larger, however, as some cells will change state and more vacant cells are needed to compensate for these conversions. The neighborhood of each cell has a radius of six units (a unit is one cell width). Each cell in the neighborhood falls into one of 18 discrete distance categories (as the grid is regular). The transition rules are specified in terms of transition potentials for all allowable transformations from a given state to other states. A deterministic rule is as follows:

$$P_{hj} = 1 + \sum_i \sum_k \sum_d m_{kd} * I_{id} \tag{4.98}$$

where,

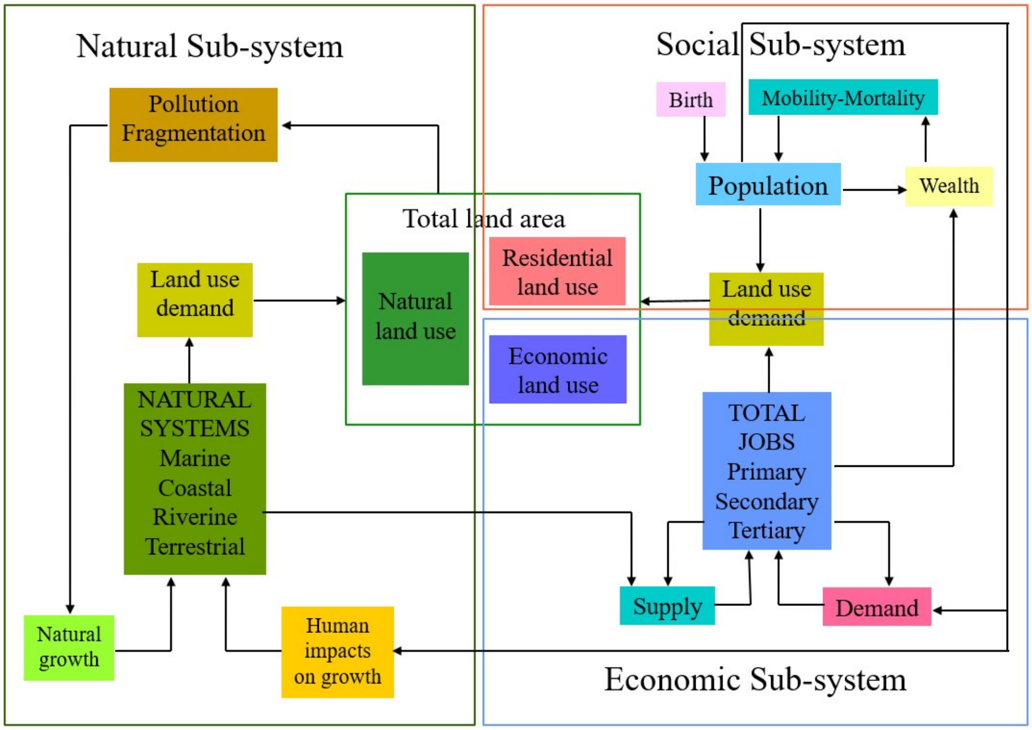
P_{hj}	the transition potential from state h to state j
m_{kd}	the weighting parameter applied to cells with state k in distance zone d
i	the index of cells within a given distance zone
I_{id}	1 if the state of cell $i = k$
I_{id}	0 if the state of cell $i^1 k$

Note that according to this equation, the transition potential has a value greater than one which means that each cell has a non-zero chance of transition.

It is possible to introduce weighting functions that have distance decay properties similar to those of the traditional spatial interaction models but it is also possible to create any other sort of distance relationship which appears meaningful. The deterministic transition potentials calculated by equation (4.98) are multiplied by a stochastic disturbance factor to account for such factors as differences in tastes and values among decision makers in the system as well as imperfect information. At each iteration up to three potentials are calculated for each cell in the array. Starting from the lower state and given the number of cells to be converted to this use (**exogenous**), the cells with the highest potential for this use are converted first. The same procedure is repeated for the other uses. In this example, the number of cells to be converted in each iteration is assumed to grow at a constant rate which represents the urban growth rate. In this way, the land use patterns obtained following these conversion rules are produced and can be observed to change over time at each iteration. This procedure was applied to a large number of cities by White and Engelen (1992) who concluded that despite differences in initial conditions and other stochastic variations, at a deeper level, urban form is quite robust. For example, these authors show that, with four land use types considered, the city has a tendency towards concentric land use zones (White and Engelen 1994).

The regional level example adopts a more comprehensive approach to account for the dynamic mechanisms and geographical features which become important determinants of the organization of higher level spatial systems. Its description reflects its application to the case of a Caribbean island with the purpose of studying the effects of sea level rise caused by climatic change (Engelen *et al.* 1995; White and Engelen 1997; see, also, MODULUS, 1999). The model operates at two spatial levels – an upper and a lower level – which interact with one another as follows: (a) at each time step, the basic geographic data needed by the upper level model are retrieved from the database. These are aggregated to the regions used in the upper level model and passed to it; (b) the upper level model calculates the values of the variables in each region and passes them to the lower level, the cellular model; (c) the cellular model allocates these values on a micro level and in doing that it may use more information from the database; and (d) the results from the previous step are used to update the database and, thus, be used as input at the next iteration as the model returns to the first step (White and Engelen 1994).

The upper or macro-level model integrates the natural, social and the economic subsystems which are linked to each other in a network of mutual, reciprocal influence as shown in Figure 4.2j.



The macro-model in the context of of the cellular automata modeling approach

Source: Adapted from Engelen et al. 1995

Figure 4.2j

The natural subsystem represents the relationships between sea level rise and temperature change with precipitation, storm frequency, suitable land area, and external demands for services and products. In the social subsystem, the demographic conditions of the system are modeled. The economic subsystem is modeled by means of an **input-output model** (of, theoretically, any degree of aggregation) solved at each iteration given exogenous changes in demand (due to exports or to domestic final demand caused by population growth). The economic subsystem is linked to the natural subsystem through climate-induced changes in export demands; to the social subsystem through household demands and to the micro-level model via a *land productivity expression* which translates activity levels to land use demands. This latter expression takes into consideration the scarcity of land, as measured by prices, and land productivity for particular activities.

The lower level model is a cellular automata model which is developed on a cellular array of 500 × 500m cells and calculates land use changes on the basis of transition rules as it was the case with the urban model. The differences from the previous case are that: (a) the neighborhood of each cell is now larger, (b) 13 land use types (states of each cell) are considered, (c) at each iteration cells are converted to the use for which they have the highest potential, and (d) interactions between pairs of land uses (or activities) are modeled in greater detail by means of attraction-versus-distance functions to represent the effects of push and pull factors on each cell and for each activity. The aggregate, distance-weighted push and pull effects of all the cells in the neighborhood together determine the *locational suitability* of the cell for each possible land use type. To determine the cells' potential for transition from one type to another, the cell's *intrinsic suitability* in terms of its own physical, environmental and institutional characteristics is calculated as an aggregate measure from a number of geographical attributes such as soil quality, elevation or land use regulations stored in a geographical database. A cell's suitability can change during a simulation either by the user or due to changes in environmental or other conditions produced by previous iterations (Engelen *et al.* 1995).

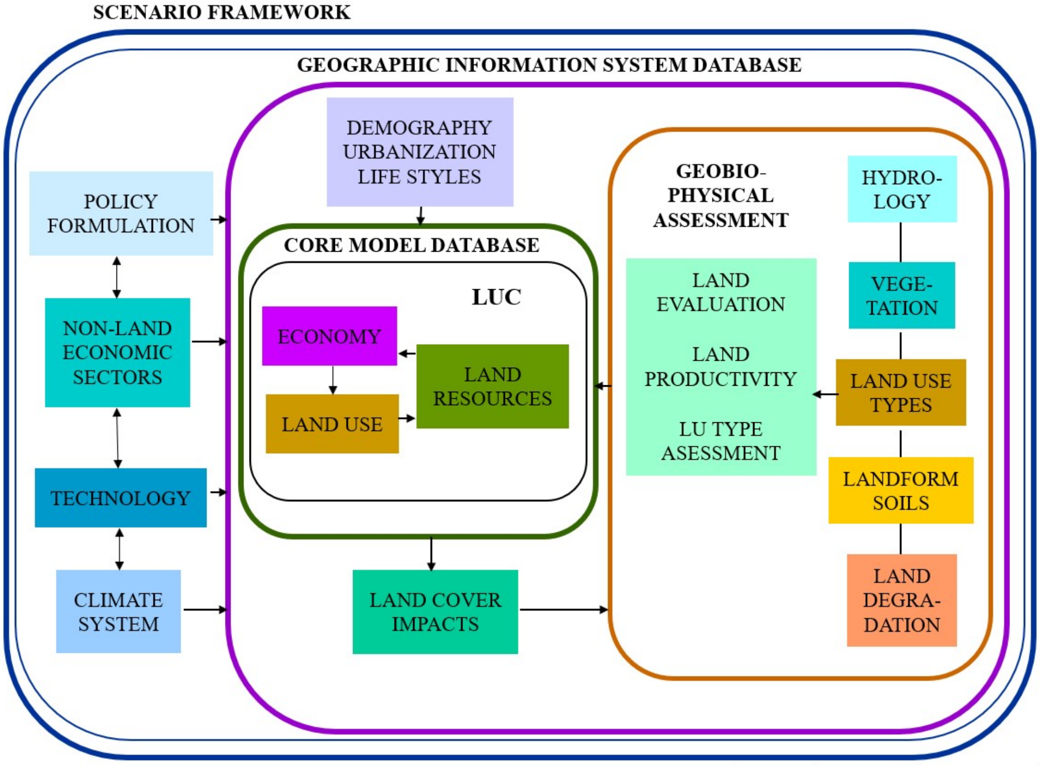
It is interesting to discuss the land allocation process simulated in this model. As said before, cells are converted to the use for which they have the highest potential. The conversion process starts with the cells having the highest potential and proceeds until a sufficient number of cells have been converted to satisfy the demands established by the upper level model. A *land rent* is calculated also for each economic sector based on the existing level of demand for land use by that sector, relative to the quantity and suitability of available land. The rents are returned to the upper level model where they affect the land productivity coefficients translating output into demand for land. Similarly, the suitability factor for all cells actually occupied by a particular activity is monitored and changes in average suitability for the activity are passed back to the upper level and result in further changes in productivity parameters. In this way, the model captures the interactions between the micro-scale geography and the global dynamics directly and continuously (White and Engelen 1994).

The approach described above has been applied to both urban and regional level cases for the analysis of land use change (the island of St. Lucia in Eastern Caribbean and the metropolitan region of St. John's Newfoundland, Canada). Further developments include, among other, the design of an interface between this approach and GIS and its incorporation into broader decision making support tools. In this latter application, cellular automata models are linked to models of the economic, environmental and social subsystems of a spatial system for integrated analysis and decision support. Such a spatial decision support tool is MODULUS developed in the European Union for the integrated analysis of land degradation, desertification and water management in the Northern Mediterranean (MODULUS 1999). For other applications of the cellular automata modeling approach in urban and regional contexts which allow for greater complexity in land use conversion and the resulting patterns to be modeled the reader is referred to Clarke *et al.* (1997), White *et al.* (1997), Wu and Webster (1998).

Before moving to the next integrated simulation model, some comments on the cellular automata approach are in order. First, it is a discrete modeling approach and serves as an additional indication that discrete approaches may be better suited to modeling spatial change phenomena than continuous approaches. The cellular automata approach makes no direct claim to economic theory as it is the case with the discrete choice models referred to in the previous group of urban simulation models. It can accept various specifications of the rules governing the conversion of land uses in the cells of the study area. This means that economic or any other theory can be used to guide the particular rules used. In addition, it has the added flexibility of incorporating environmental and other considerations in the assessment of the potentials for change as well as of being linked to higher level models as well as to GIS for more efficient use and manipulation of input and output spatial information. The concept of the transition rules in cellular automata modeling and the estimation of transition probabilities are similar to the corresponding concepts and estimation in discrete choice modeling and in Markov modeling which will be discussed in the section on other modeling approaches. It is noted that cellular automata modeling does not consider the transportation system explicitly (at least) which may be a shortcoming in view of the important feedbacks between land use and transportation as well as the environmental impacts caused by the development of transportation systems. Finally, as regards its apparent lack of firm theoretical grounding, the cellular automata approach is arguably designed to provide a testing ground for a variety of theoretical propositions as reflected in the specification of the transition rules. The question which arises, however, is whether the spatial subdivision assumed by the model (the cellular array and the magnitude of the cells) is congruent with the actual spatial formations which emerge under the complex interplay of the forces which drive land use change.

IIASA LUC (Land Use Change) Model

The last regional level modeling framework to be discussed is perhaps the most ambitious effort to build one of the most comprehensive, integrated models for the analysis of land use change. The International Institutes for Applied Systems Analysis (IIASA) Land Use Change (LUC) project has developed a modeling framework for "the analysis of spatial and intertemporal interactions among various socio-economic and biogeophysical factors that drive land use and land cover change" (Fischer *et al.* 1996a, 74). The modeling framework is intended for use in various policy and decision making settings where land use change is directly or indirectly implicated. The overall modeling framework is depicted in Figure 4.2k (see, also, the IIASA/LUC web page).



Source: Adapted from Fischer *et al*. 1996a

The IIASA/LUC Modeling Framework

Figure 4.2k

The theoretical and methodological basis of this modeling endeavor is provided by welfare theory and the related analytical methods. As shown in Figure 4.2k, the whole modeling exercise is embedded within a GIS framework which provides both the necessary spatial databases as well as stores and generates the resulting land use maps. LUC has been developed for modeling land use changes and related policy issues in China and Northeast Asia but its structure and methodology is applicable to several other regional contexts. A brief presentation of the main features of the complex LUC modeling framework is given here drawing on Fischer *et al.* (1996a); the reader is referred to related publications for full information (found at the IIASA web-site listed in Appendix 1.B). The conceptual framework of welfare analysis adopted is discussed first and then the treatment of the spatial and temporal aspects of modeling land use and land cover change in LUC is described. The analysis of land resources is outlined with an emphasis on the specification of land-based production sector models (agriculture and forestry).

In welfare analysis a number of commodities are assumed to exist in the study area. These include both goods and factors of production (e.g. food, fiber, energy, labor, capital, services) indexed $k = 1, \ldots K$. Each commodity is exchanged at a price p_k. Demand is generated by a number of consumers indexed $i = 1, \ldots .I$. Supply is provided by a number of producers indexed $j = 1, \ldots .J$. The netproduction of a number of commodities by producer j is denoted by y_{jk}. Producers sell their products (y) at the market at market prices p. Consumers own commodity endowments, w_i, which they offer for exchange and, at given prices p, they demand commodity bundles x_{ik}. An excess demand vector can be formed:

$$z(p) = \sum\nolimits_i x_i(p) - \sum\nolimits_j y_j(p) - \sum\nolimits_i w_i \qquad (4.99)$$

Naturally, for the market to be in equilibrium, prices should adjust so that no commodity is in excess demand; i.e. $z(p)\text{£}0$.

Each producer operates within certain technology options which can be represented by a set of possible production plans Y_i. If a competitive equilibrium situation is assumed, then producers choose production levels y_j that maximize their profits, π_j:

$$\pi_j = \sum\nolimits_k p_k y_{jk} \qquad (4.100)$$

The resulting maximum profit function is:

$$\Pi_j(p) = \max\{[p, y_i]^{1/2} y_j \hat{I} Y_j\} \qquad (4.101)$$

Similarly, consumers consume commodity bundles, x_i, so as to maximize their utility subject to their budget constraint determined by available consumer income h_i which consists of two elements: the proceeds of selling the endowments w_i and the consumer's share in profit Π_j. It is assumed that consumers own a non-negative share θij in firm j and that they receive dividends $\theta_{ij}\Pi_j(p)$. The utility maximization relationship is:

$$\max\ u_i(x_i) \qquad (4.102)$$

subject to:

$$[p, x_i]\text{£}h_i \qquad (4.103)$$

In this context, an optimal welfare program refers to the choice of the levels of commodities to be produced by producers so that the welfare of consumers is maximized subject to commodity balances. The welfare of consumers is assumed to be the sum of their individual utilities properly weighted by socially defined weights, α_i. In mathematical notation this problem is written as:

$$W(\alpha) = \max_{x,y} \sum\nolimits_i \alpha_i u_i(x_i) \qquad (4.104)$$

subject to:

$$\sum_i x_i - \sum_j y_j \le \sum_i w_i \qquad (4.105)$$

The solution to this welfare maximization problem produces **Pareto-optimal solutions** . The above problem can be modified to take into account trade as well as policy measures adopted by the state to correct for market imperfections in the allocation of resources. In LUC, as in several similar applications of this welfare theoretic framework, there are three types of economic agents – consumers, producers and the government – which are represented by means of homogenous groups in each type.

The spatial representation of the economic system as specified above incorporates several other characteristics of the natural and social environment within which the activities of these economic agents and the interactions among them take place. The study region is divided into compartments, i.e. subregions. In each compartment, the economic system is modeled in the way specified above. A compartment may be a collection of farms, a watershed, a zone within a country or a group of provinces. Compartments reflect structured entities – i.e. subsystems of the larger system being modeled. Because they may change over time, the designers of LUC contend that the compartments must avoid being geographically static. Hence, they propose the organization of all relevant spatial data on rectangular grids with compartments being defined as collections of grid cells which can vary possibly over time. Areas where no human intervention takes place – as in wilderness areas – form separate compartments.

A compartment is not necessarily internally homogeneous; in fact, it can be further subdivided into smaller homogeneous land management units to facilitate meaningful biogeophysical evaluation (see, the FAO AEZ procedure mentioned in Chapter 1). Compartments are organized hierarchically so that the particular characteristics and land use driving forces at each level of the hierarchy can be described as well as decision making at various levels of hierarchy can be modeled. All spatial data are stored in and manipulated by a GIS. Each compartment is described in terms of its physical, geographic and environmental characteristics and the characteristics of the endowments of the economic agents it includes. The description refers also to applicable economic and physical balance equations (e.g. budget constraints, commodity demand and supply balances, consistency between resource use and availability) as well as to the identification of "immobile" (e.g. soil, climate) and "mobile" (e.g. labor, capital, water, minerals) resources. In the LUC modeling framework, the economic agents within the compartments interact through commodity trade and financial markets, and flows of mobile resources. They compete for the allocation of limited public resources and they are jointly affected by policies and other constraints. Compartments interact also through human migration, materials transport and flows of pollution.

To model the flows of commodities and resources among compartments at various levels of the spatial hierarchy, certain approaches are adopted to simplify the onerous modeling of several thousands of commodities produced and transported through the compartments of the spatial system. In particular, the trade-pool approach is adopted which assumes a *trade pool* into which all exports flow and from which all imports originate. In addition, commodity balances are constructed which constitute fundamental relationships in general equilibrium models.

Temporally, the LUC model is specified in discrete, five-year, time steps. A distinction is made between **exogenous** and **endogenous** dynamics. Exogenous dynamics is caused by factors which are specified outside of the model and they are built into the model by means of time-dependent functions defined by the user (such as shifts in technology, consumer preferences and life styles, etc.). Endogenous dynamics refers to the allocation decisions of consumers and of producers and they are modeled via a **T-period competitive equilibrium model** which ensures – within its assumptions and other limitations – intertemporal Pareto-efficiency of the allocation produced over time (covering T periods). Population dynamics is modeled also in accordance with the temporal framework mentioned above and taking into account natural increase (births minus deaths) and net migration.

The centerpiece of the LUC model is a welfare program. This program has the form of an optimization problem that maximizes the weighted sum of the utilities of the consumers (see equations 4.104 and 4.105). The program includes four types of constraints: (a) the utility constraint which specifies how the **utility** of a given consumer group depends on its consumption in the current and in the next time period – i.e. it reflects group preferences intertemporally; (b) the transformation constraints which reflect the technology of the economy – i.e. describes net supplies in period t and resources in the next period which are feasible at the given level of resources in the current period; (c) the commodity balance which ensures that demand for commodities does not exceed feasible supplies; (d) the stock consistency constraint which ensures that the level of a resource used in a given period does not exceed the level carried over from the previous period.

The above welfare program and the decentralized competitive equilibrium operating context which is assumed are normative with respect to institutions; i.e. they assume perfect market economies, an assumption which may not be true and realistic for several countries or groups of countries. The LUC research team anticipates input from experts to specify how the basic model structure can be "distorted" to accommodate real world institutional and political systems which do not comply with the general equilibrium welfare model assumed above (Fischer *et al.* 1996a).

Modeling the dynamics of resource stocks in the LUC model takes into account processes of both resources accumulation as well as resource degradation associated with production activities. The production component of the LUC model purports to analyze the spatial and temporal allocation of land and its resources to various regional activities such as crop agriculture, livestock grazing, forestry, energy production, mining, settlements and infrastructure, manufacturing, recreation and natural reserves. Under natural conditions, land cover (not land use) changes can be estimated from vegetation models under various assumptions about biogeochemical and climate conditions. The task of modeling land use change (or, transformation) in systems managed by human agents is much more difficult as these changes are constrained by natural conditions and they are determined by the level of technology, economic conditions and demographic trends. These supply-side factors are taken into account in the LUC model.

The production component of the model assumes capital and environmental stocks which are available at the beginning of the current period as inputs to the production process. Pollution is represented as use of resources. The effects of production processes on human welfare (e.g. health) are taken into account either as arguments in the utility functions or as constraints on production. One of the main tasks in the LUC modeling framework is the specification of *spatial production functions* for land-based sectors which account for the accumulation and degradation of resources used as well as for resource conversion (e.g. land use change from one type to another) and resource migration (e.g. flows of pollutants, capital, labor). Details on the specification of the agricultural supply and demand models can be found in Fischer *et al.* (1996a).

The treatment of land resources and of land use change in the LUC modeling framework is particularly elaborate given that these are among the principal objects of the modeling exercise. The characteristics of land resources are distinguished between those which are intrinsic to land, such as soil type, and those which are related to particular land uses such as fertilizer input. *Site classes* are defined in terms of intrinsic land properties (temperature regime, moisture regime, landform and slope, soil type, phase and texture, land accessibility). Land classification follows established international approaches for land characterization which are based on three main criteria: physiography, terrain components and soil components. To take into account the fact that land characteristics may change over time due to both natural and anthropogenic causes, the LUC modeling framework treats site classes in a dynamic way generating trajectories of the extent of site classes over time. Hence, a tract of land may change site class within a given time period because of: land improvement, land degradation or allocation of a site class to a particular activity, and climate change. Accounting identities are established to keep track of the changes in the extent of site classes as well as of the transfers among site classes over time. The geographic representation of land resources and land uses (see next paragraph) utilizes pixel data on a gridded format.

A hierarchical land use classification system is adopted; the higher level of the land use hierarchy consists of the set: unused/natural, protected, agriculture, grassland, forestry, residence, infrastructure, mining. Within each major land use type, more detailed classification of land uses is established in a nested sequence based on physical and economic characteristics needed for the analysis of the causes and impacts of land use change. For example, for the case of maize production, the following classification emerges: agriculture - irrigated crop production - high input, single-crop maize production. This hierarchical system is used to describe the two major processes of land use change: land conversion (transfer of a tract of land from one major land use type to another) and land modification (transfer of a tract within subdivisions of major land use types).

The land allocation procedure observes certain land balance constraints which are detailed in Fischer *et al.* (1996a). It is important to note that land allocated to different major land use types within a given site class is limited by the availability of land of that quality.

Further discussion of the LUC modeling framework is beyond the scope of this contribution and it is premature as the model is continuously being developed and improved in several respects. Overall, it represents one of the most ambitious efforts to provide for a truly integrated modeling framework which is sensitive to both global and local land use change dynamics. At this point, only two issues are stressed with respect to the general modeling approach it adopts. First, it is firmly based on welfare theory and the associated analytical tools which offer elegant devices for modeling economy-environment interactions and provide the economic rationale for the solutions produced. However, the critique of welfare analysis should be brought in mind (see, for example, Cooke 1983, Daly and Cobb 1989, Galbraith 1975, Sayer 1976, 1979b) both in general and, in particular, as regards its applicability in non-competitive market socio-economic systems which abound around the world. Secondly, several intangible and non-quantifiable aspects of land use change defy treatment by means of conventional techniques of analysis and getting into the details of local particularities both as regards the causes of land use change and the impacts of this change requires application of more qualitative techniques of analysis. This comment applies to all large-scale models in general and concerns the range of their applicability and validity of their results. Necessarily, the patterns and processes observed at higher scales as well as the related decision making issues differ from those operating at lower scales and of concern to local level decision making.

The IMPEL (Integrated Model to Predict European Land Use) model

Another model which is similar in several respects to the LUC model presented above but which is more restricted in scope is the IMPEL model (Rounsevell 1999). The broad aim of the modeling exercise was to develop a formal modeling framework for study of the impact of climate change on the spatial distribution of agricultural land use in Europe. The following presentation of the basic characteristics of IMPEL is based on the final report of the research project (Rounsevell 1999).

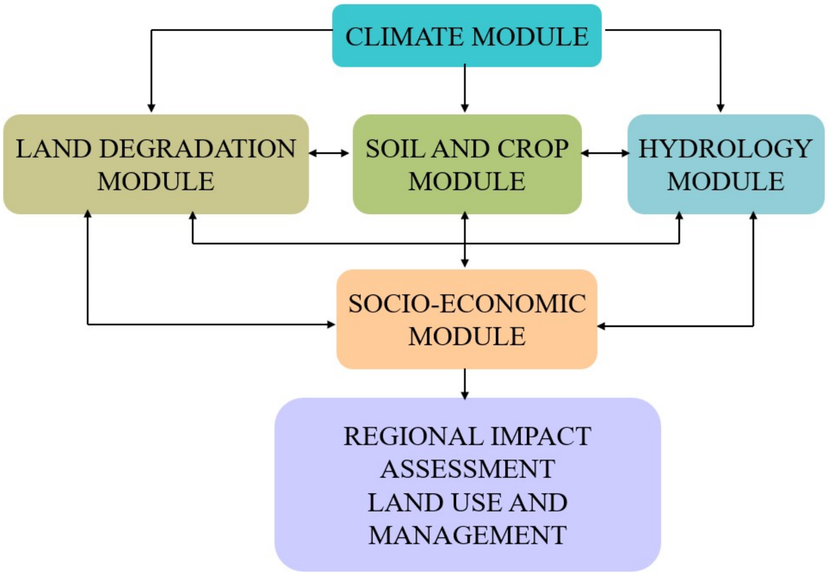
The aim of the IMPEL modeling framework was “to assess the impact of climate change, within the context of plausible socio-economic changes, on the distribution of agricultural land use and the potential for adaptation through land management at the farm and the regional scales.” (Rounsevell 1999, 2). Among the guiding principles adopted for the development of the overall modeling framework, three are especially important:

a. Land use change is caused by the decisions made by individuals based on the opportunities and constraints within the basic spatial units of the land they manage.

b. The assessment of regional land use change should be based on the extrapolation of decision making models at the farm scale to the broader region based on georeferenced, spatially-explicit data sets.

c. Extrapolation of site or farm based models to the regional scale requires knowledge about the technical limitations of the extrapolation process, especially the implications of using imprecise spatial data.

The modeling framework of IMPEL belongs to the category of modular models; i.e. it consists of a set of interlinked modules as shown in Figure 4.2l.



The IMPEL modeling framework

Source: Adapted from Rounsevell 1999

Figure 4.2l

The *climate module* (EuroSCEN) downscales baseline climate data and GCM (General Circulation Model) climate change scenario data sets. The *soil and crop module* (ACCESS) evaluates the soil water balance and crop yields for a wide range of European crops at the scale of the soil map units. The *land degradation module* evaluates the impact of soil erosion and changes in soil quality on crop productivity at the scale of the soil map units. Finally, the *socio-economic module* predicts changed land use and optimal management requirements at the scale of the individual farms. This last module is presented in greater detail below.

The socio-economic module employs linear programming to derive optimum land use patterns at the farm scale for a range of European environments as well as the need for machinery, farm labor and the timing of machine operations. The optimum land use is the cropping towards which land use will tend, with the rate of change depending on the drivers. A major driver considered is the difference between the profits of the existing and the new system which can be influenced, for example, by subsidies to stimulate initial take up and to overcome the start-up penalty of new crops.

The underlying hypothesis of the farm scale model is that farmers are profit maximizers. Differences in the actual crops grown by different farmers are due to soil type, climate, scale of operation, and attitude to risk. The model may indicate the impact of a change in climate on cropping selected by a profit maximizing farmer. A central consideration of this modeling effort was the specification of the function representing the riskiness of the cropping systems. Among the various approaches to including risk in the objective function (utility function) of the farmer examined, the research team decided to utilize a function which combines both risk and profit. More specifically, the utility function, L, to be maximized has the general form:

$$L = E - \psi\sigma \qquad (4.106)$$

where,

E	is the average expected profit
ψ	is a parameter that represents risk aversion

σ is the standard deviation of profit

The detailed mathematical model employed is a multiobjective linear optimization model. It consists of an objective function which is the weighted sum of profit, risk and environmental objectives. It takes into account three main types of constraints: machinery limit, total amount of operation and total amount of activity, and operation and crop sequencing. The **dependent variables**, i.e. the output of the model, include:

- amount of activity (area if crop, number if animals)
- number of machines by type
- amount of product produced or required
- area of crop c following crop i completed in period d
- amount of operation j on activity i on day d, where the amount is an area if the activity is a crop, a number if the activity is livestock and a weight if the activity is a product

The **independent variables** , i.e. the input of the model, include:

- maximum amount of activity
- number of years necessary between crops (taking into account the incidence of diseases)
- the cost of operation j on crop i
- the effect on yield of operation j on crop i
- the change in environmental impact of operation j on crop i
- the change in product due to operation j on crop i
- inflation rate
- hours available for operation type n on day d
- interest rate
- last operation on an activity
- minimum time between operations
- machinery cost
- number of year ends the crop i crosses
- number of machines by type required by an operation
- set of permanent crops
- standard amount of product required or produced by an activity
- time periods d when operation j on activity i can be done
- set of crops with main disease class k
- cost of crop c following crop i
- effect on yield of rotation crop c following crop i
- change in product w due to crop c following crop i
- resale value of machine after T years
- replacement interval of machine
- maximum time between operations
- product w cost or value

- workrate of operation j given sizes of machines
- yield of crop i

The reader is referred to the final report (Rounsevell 1999) for a more detailed description of the mathematical structure of the socio-economic module. Overall, it is an elaborate model which attempts to represent those details of the farm system which make possible the assessment of the (agricultural) land use impacts caused by climate change as well as a series of related impacts closely linked to land use.

4.6.3C Global level simulation models

The last group of integrated simulation models comprises global level models. At higher spatial levels the application of simulation techniques is widespread given the complexities of modeling socio-economic and environmental interactions. The impetus for the development of new or for the use of existing global models for the analysis of land use change in the last 15 years has come from the recognition of its critical role in mediating global environmental change (see, among others, Briassoulis 1992, Meyer and Turner 1994, Turner *et al.* 1995). The purpose of global simulation models is to serve mostly as (land use and environmental) impact assessment tools of such phenomena as climate change, desertification, etc. and to provide decision support on critical issues such as food security and human vulnerability to natural and technological hazards. Given the aggregate level of spatial resolution on which they operate, their results have to be interpreted and used accordingly, however (see, also, Liverman 1989).

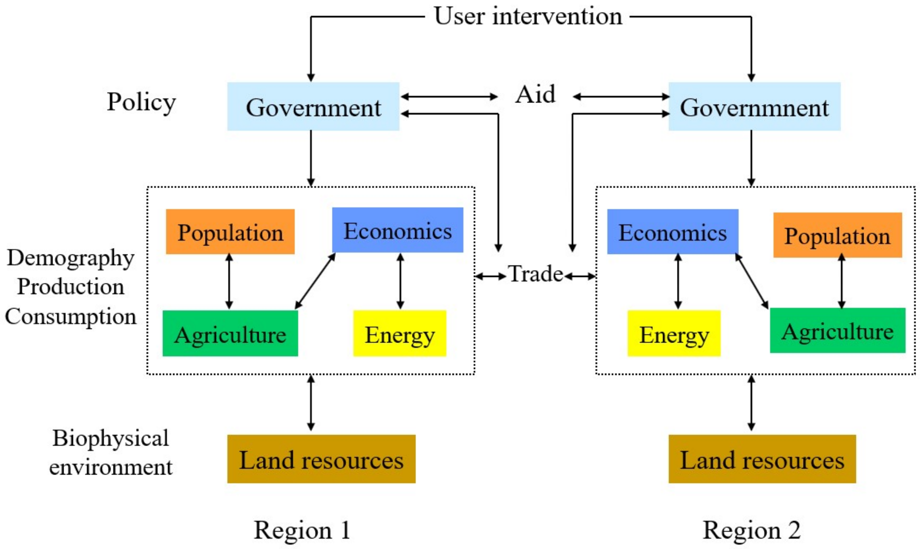
Several of the early global level simulation models were either aspatial – i.e. they assumed only one region, the world – or they employed a very small number of aggregate world regions (Liverman 1989) which impeded seriously their use for the study of land use change. In these models, land use and its change are either not addressed at all or they are addressed at a very high level of spatial resolution. Among them, the well-known WORLD3 model developed at MIT in the 1970s (Meadows *et al.* 1972) simulated the relationships between population, resources, capital, agriculture and pollution at a global level and provided gross estimates of agricultural land requirements in the year 2000. These estimates had to be interpreted, however, within the serious limitations of this modeling endeavor (Liverman 1989). Other global models, some of which included land use explicitly while others did not, were built for other purposes than that of analyzing the land use and environmental impacts of human activities. For example, Liverman (1989) mentions several such models – MOIRA (Model of International Relations in Agriculture), the United Nations World Model, the United States Department of Agriculture GOL (Grains-Oils-Livestock) model, SARUM (Systems Analysis Research Unit Model) – which have been used to analyze the impacts of climate change, trade liberalization policies, food prices, and food aid on agriculture at the national and the global level. Liverman (1989) observes that "many models do not represent environmental changes explicitly and they must be introduced through the **exogenous** forcing of variables like 'yield' or 'land area"' (Liverman 1989, 217). This last point can be taken as an indication of the implicit recognition of the mediating role of land in global environmental change.

Fischer *et al.* (1996a) mention the IIASA global model BLS (Basic Linked System) which was built to model the relationships between agriculture and the rest of the economy. It consists of a number of linked national models based on welfare economics and general equilibrium modeling principles (see the IIASA LUC model described above). The model accounts for population dynamics, socio-economic factors, capital accumulation and market clearing conditions to project demand and supply of agricultural products as well as agricultural land use at the national level. Its recent improvement with elaborate process crop models purported to make the model suitable for assessing the impacts of climate change on world food supplies, demand, trade and risk of hunger. However, the BLS model accounts only for land use changes in agriculture (caused by climate change) and does not assess changes in other land uses.

Two global integrated simulation models in which land use is modeled explicitly are presented briefly below – the IFS model and the IMAGE 2.0. model.

The IFS model

The presentation of the IFS model follows Liverman (1989) and the emphasis is placed on the particular way land use and its change are modeled. According to Liverman (1989), IFS is a version of the World Integrated Model which was sponsored by the Club of Rome and developed by Mesarovic and Pestel (1974 cited in Liverman 1989, 220). IFS simulates trends in regional and global conditions such as population, food production, energy use, trade, and GNP for a set of 10 world regions linked by trade and aid. It is a partial equilibrium model with a one-year time step. Most of its equations are simple mathematical functions whose coefficients are estimated from historical data. Five economic sectors are distinguished in each region – agriculture, raw materials, energy, manufacturing and services. Detailed resource models are used for agriculture and energy. Its basic conceptual structure for two of the 10 regions is shown in Figure 4.2m.



The IFS model

Source: Adapted from Liverman 1989

Figure 4.2m

Population estimates generated by using **cohort-survival analysis** are used as inputs to the demand and supply economic models. Production in all sectors is estimated using **Cobb-Douglas functional forms** as a function of capital investment, capital efficiency, labor, labor efficiency, and GNP per capita. In the agriculture submodel, production is *basic* (long-term) *crop yield* which is multiplied by a saturation coefficient to represent decreasing marginal returns to inputs. The short-term, final yield is calculated from basic yield by taking into account price and weather effects. Total crop production is *final yield* multiplied by land under crops. In IFS, land use change is caused by population growth (i.e., urban development), agricultural investment to bring new land into production, and an **exogenous** depreciation term which can represent land degradation. The agriculture submodel estimates livestock production and feed also. Demand for agricultural products in each region is for livestock feed, industrial production, and food. It depends on livestock herd size, manufacturing sector gross production and population expenditure on food in relation to price. Finally, trade in agricultural products depends on the ratio between world and regional prices, moving averages of production, demand, balance of payments and stocks.

The results of the standard runs of the model is a reflection of the model's assumptions, a critical issue to which Liverman (1989) draws attention and provides a very careful and instructive analysis. The first assumption relates to the degree of spatial aggregation the model adopts, an issue of critical importance especially in the context of global models. IFS's 10 regions are assumed to be environmentally homogenous on environmental and food systems grounds. However, this assumption may not hold even for these dimensions as also for the economic dimension. Economic groupings of countries like "OPEC" or "Rest of the World" conceal significant differences in many other dimensions – environmental, socio-economic, political, cultural, etc. The coarse degree of aggregation makes it necessary for the user to perform exogenous estimates of the impacts of environmental and other kinds of change and find ways to weight them and integrate them into the model. One way around the problems created by high levels of aggregation is to model environmental issues on a national or, even better, on a subnational basis. But this has a high cost in terms of (appropriate) data needed, money and time resources, etc.

Sectoral aggregation in IFS creates problems also. In the case of yield estimates figures concerning a variety of agricultural products are lumped together into a gross figure which conceals the many variations in their production, input requirements, resource use, environmental impacts, etc. The same applies to aggregating all agricultural inputs into one capital investment function. This kind of aggregation makes it extremely difficult and problematic to perform a variety of impact analyses of alternative food, price, regulatory and other kinds of measures. Liverman (1989) stresses the critical assumptions related to relative price changes as prices are the assumed signals to both consumers and producers and the basic market clearing mechanism which determine the equilibrium between supply and demand. Finally, she discusses the problems created by trying to operationalize such difficult-to-define variables as "starvation" the result being that "starvation" in IFS bears little resemblance to any real measure of the concept.

Another important aspect, common to several similar modeling situations, is the model's use for simulating environmental and other (e.g. policy) changes. "Yields" are used as surrogate measures for providing information about the weather during the decade and "land area" is used as a measure of land use policy (Liverman 1989). However, these turn out to be imperfect proxies which cannot explain the model's results. The user has to further explore the results to see whether they are plausible and supported by other pieces of evidence as well as to provide justification for over- and/or under-estimates in the model's values of dependent variables.

The IMAGE2.0 model

The second model to be presented is IMAGE 2.0, a model built for the analysis of the various impacts of climate change under the direction of Joseph Alcamo (Alcamo 1994; see, also, Issue No. 1-2, Volume 76 of *Water, Air and Soil Pollution*, July 1994 dedicated to the presentation of this model). The development of this model was funded by the Dutch Ministry of Housing, Physical Planning and the Environment and the Dutch National Research Programme on Global Air Pollution and Climate Change (NOP). The terrestrial environment research of the IMAGE model is an Activity of the Core Project "Global Change and Terrestrial Ecosystems" (GCTE) of the International Geosphere-Biosphere Programme (IGBP).

The development of the IMAGE 2.0 model was preceded by the development of IMAGE 1.0 (Rotmans 1990, Rotmans *et al.* 1990) a model which was more aggregate spatially and temporally and did not contain several components like emissions from energy and land use which were incorporated in IMAGE 2.0. IMAGE 2.0 has a higher degree of spatial resolution, the models it contains are more process-oriented, and contains fewer **global parameterizations** than previous models which enhance the scientific credibility of its results (Alcamo *et al.* 1994a). The following description of the model borrows heavily on Alcamo *et al.* (1994a).

IMAGE 2.0 has a number of scientific and policy objectives. The former include: (a) providing insights into the linkages in the society-biosphere-climate system, (b) investigating feedbacks in this system, (c) estimating sources of uncertainty in such a linked system, (d) identifying gaps in knowledge to help set the agenda for climate research. The latter include: (a) linking scientific and policy aspects of global climate change in a geographically explicit manner to support decision making, (b) providing a dynamic, long-term perspective about the consequences of climate change, (c) providing insight into the cross-linkages in the system and the side effects of various policy measures, (d) examining the influence of economic trends and technological development on climate change and its impacts, (e) providing a quantitative basis for the analysis of the costs and benefits of various measures to address climate change.

IMAGE 2.0 assumes a subdivision of the world into 13 world regions (consisting of contiguous countries) and its time horizon extends to the year 2100. The time step used differs from one submodel to another but they usually range between one day and five years. The intended spatial resolution of the model is a grid of 0.5° latitude by 0.5° longitude as: (a) all potential impacts of climate change exhibit a strong spatial variability, (b) land use-related greenhouse gas emissions depend on "local" environmental conditions and human activity, (c) policy makers are interested in regional/national policies to address climate change (most policies are location-specific), and (d) grid-scale information makes model calculations more testable against observations. The model could not at the time of Alcamo's (1994) writing provide grid scale calculation for several components of climate change as it was not possible to specify the needed factors and their relationships on a country or subcountry scale for the whole world for such a long time horizon.

IMAGE 2.0 consists of three fully interlinked subsystems of models: (a) the Energy-Industry System, (b) the Terrestrial Environment System, and (c) the Atmosphere-Ocean System as shown in Figure 4.2n (adapted from Alcamo *et al.* 1994a).

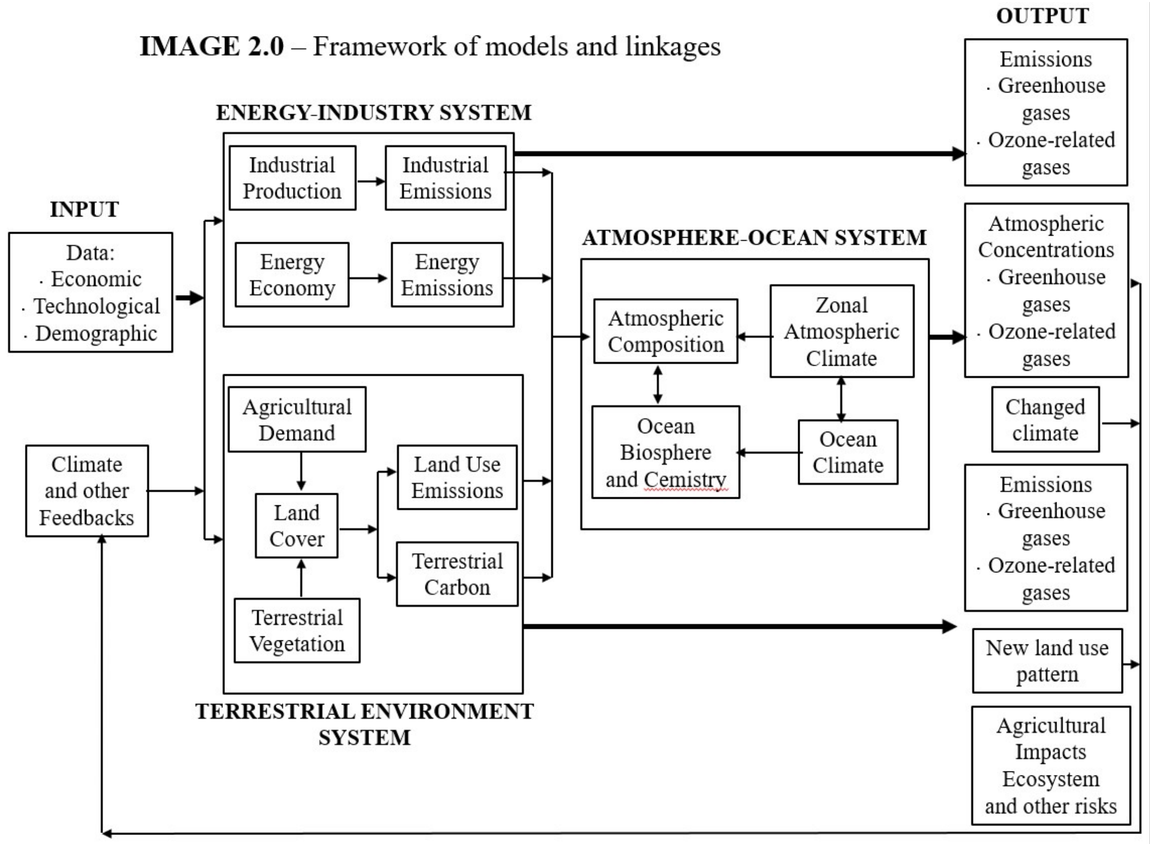


IMAGE 2.0 – Framework of models and linkages

Source: Adapted from Alcamo *et al.* (1994a)

Figure 4.2n

The *Energy-Industry* models estimate the emissions of greenhouse gases in 13 world regions as a function of energy consumption and industrial production. End use energy consumption is estimated from various economic driving forces. It includes the following submodels: energy economy, energy emissions, industrial production, and industrial emissions. The *Terrestrial Environment* models simulate changes in land cover on a grid scale as a function of climate and economic factors. These land cover changes are then used to compute the flux of CO_2 and other greenhouse gases from the biosphere to the atmosphere. It includes the following submodels: agricultural demand, terrestrial vegetation, land cover, terrestrial carbon and land use emissions. The *Atmosphere-Ocean* models estimate the buildup of greenhouse gases in the atmosphere and the resulting zonal-average temperature and precipitation patterns. It includes the following submodels: atmospheric composition, zonal atmospheric climate, oceanic climate, and oceanic/biosphere chemistry.

Alcamo *et al.* (1994a) make an important note on the modeling approach emphasizing the fact that IMAGE 2.0 is based on large global data sets and poorly understood global change processes. It is, hence, unavoidable that many model parameters are ill-defined and have many degrees of freedom, a fact that led the research team to propose submodels with comparable levels of process detail and to adjust a limited number of model parameters with the greatest degree of freedom to obtain model calculations in reasonable agreement with 1970-1990 available data. This procedure does not ensure that the adjusted parameters will be correct for future scenario analysis but it indicates the adequacy of the model to reproduce the 1970-1990 global changes in energy-related emissions, deforestation rate, terrestrial carbon fluxes, and the buildup of various greenhouse gases in the atmosphere.

A very brief description of IMAGE 2.0's submodels is offered below taking a closer look at the land use models employed. The *energy-economy model* divides the energy economy of each world region into five energy sectors and computes the demand for end use "heat" and "electricity" in each sector. These are estimated from elasticity functions that relate activity levels of each sector with end use energy consumption taking into account energy conservation measures. The computed end use electricity in each sector is converted to required power plant capacity. The final step is to compute primary energy consumption for each region. The *energy emissions model* multiplies the energy consumption estimates of the previous model by sector-specific emission coefficients to compute the amounts of CO_2, CH_4 (methane), N_2O (nitrogen oxides) and other greenhouse gases released from each region. The *industrial production model* and the *industrial emissions model* are used to compute emissions of greenhouse gases or their precursors that are not directly associated with energy production. The industrial production model uses a simple indexing method to compute future industrial output in each region to be used by the industrial emissions model. The outputs of these models are fed into various other submodels of IMAGE 2.0. Emissions calculated are fed into the Atmospheric Composition model. Estimated demand for fuelwood and biofuels are used in the Land Cover model and the Terrestrial Carbon model. No feedback of global change on energy use is accounted for in the model, however.

The *agricultural demand model* (see, Zuidema *et al.* 1994) estimates societal demands for agricultural products that lead to significant land use demands assuming two main driving factors: population change and GNP. It starts by estimating the per capita human consumption for different crop and meat products using an assumed elasticity relationship between consumption and per capita income. Total human (as opposed to animal) demands are then calculated for a given income and population scenario. The same procedure is used to calculate total demand for meat in each region which is converted to a required number of livestock and feed requirements for animals. The latter are distinguished into "concentrates" and "roughage". The amount of "concentrates" from crops and crop residues is added to the demand for crops from the human population. The demand for roughage is used to estimate the required area for rangeland and pastures. Thus, the total demand for cropland and rangeland is assessed taking into account also imports and exports. The 1994 version of IMAGE 2.0 did not include world timber production and trade. Moreover, world food trade was **exogenous** to the model.

The *terrestrial vegetation model* consists of two submodels which account for changes in land cover as a function of demand for land, potential vegetation, and potential crop productivity for a given climate and soil (see, Leemans and van den Born 1994). A modified version of the BIOME model (Prentice *et al.* 1992 cited in Alcamo *et al.* 1994a, 10) is used to compute potential vegetation. This model distinguishes plant functional types each having definable environmental characteristics. Different plant types are aggregated into the land cover categories of IMAGE 2.0 which are described below. The FAO Crop Suitability model (FAO 1978 cited in Alcamo *et al.* 1994a, 10) is used to compute potential productivity of eight crop classes on a global grid based exclusively on local climatic conditions. The climate-related yields are then adjusted for grid-specific soil conditions by a "soil factor" which takes into account four soil quality indicators (nutrient retention and availability, levels of salinity, alkalinization and toxicity, and rooting conditions for plants).

The *land cover model* simulates land cover transformations on a global grid as a function of regional demands for land use and local "potential" for land (Zuidema *et al.* 1994). Inputs to the model come from: (a) the agricultural demand model – regional demands for cropland and rangeland, (b) the energy economy model – fuelwood demand, and (c) the terrestrial vegetation model – local potential for land. To compute land cover changes, the land cover model takes into account the following: (a) factors for land use demand – demand for eight classes of crops, demand for four classes of livestock, demand for fuelwood, land for biofuels and plantations, (b) factors for land cover potential – climate-limited potential productivity of eight classes of crops, reduction in crop productivity due to local soil conditions, land requirement per unit of livestock, climate-limited potential vegetation types (other than crops).

The land cover model assumes an aggregation of 51 land cover categories into 17 types on a global 0.5° by 0.5° grid. These 17 categories are: agricultural land, ice, cool (semi)desert, hot desert, tundra, cool grass/shrub, warm grass/shrub, **xerophylic** woods/shrub, taiga, cool conifer forest, cool mixed forest, temperate deciduous forest, brown leafed/warm mixed forest, tropical dry/savanna, tropical seasonal forest, tropical rain forest, and wetlands.

The land cover model changes gridded land cover within a world region until the total demand of all regions are satisfied by assuming that this can happen by increasing agricultural production anywhere in the world. This is an unsatisfactory but unavoidable assumption as data limitations did not permit a more detailed modeling of the real spatial distributions and relationships. The model accounts for several types of conversion such as tropical deforestation and reforestation of abandoned agricultural land. Because the full understanding of the driving forces of land conversion is poor, the model uses transparent rules to match land demand with potential which are tested against historical data. The model includes a "management factor" which takes into account the effect of technology on yield per hectare which is used to adjust the computed coverage of agricultural land in each region to FAO estimates (FAO 1992 cited in Alcamo *et al.* 1994a, 11).

The *terrestrial carbon model* (Klein Goldewijk *et al.* 1994) estimates the sources, sinks, and reservoirs of carbon in the terrestrial biosphere resulting from natural processes and human disturbances. The energy emissions model estimates the sources of CO_2 from fossil fuel combustion and the ocean/biosphere chemistry model estimates its net geochemical sink in the ocean. The model estimates the CO_2 flux of the biosphere by computing Net Ecosystem Productivity (NPP) which is pre-defined for each land cover category but scaled to temperature and moisture availability to account for changes in productivity if local climate changes. When land conversion occurs, the balance between carbon stored in terrestrial ecosystems and the atmosphere is disturbed. To account for these human disturbances, this model makes a number of consistent assumptions concerning the fate of biomass under each type of conversion. The model also takes into account various feedbacks to the biosphere.

The *land use emissions model* (Kreileman and Bouwman 1994) estimates emissions of CO_2, CH_4 (methane), N_2O, NO_x (nitrogen oxides) and VOC (volatile organic compounds) stemming from different types of land use/cover (shown in Table 2 in Alcamo *et al.* 1994a, 8). The flux of CO_2 from the terrestrial environment is computed from the terrestrial carbon model above. The land use emissions model receives as input the land cover patterns and transformations computed from the land cover model and multiplies them by emissions coefficients by land use category.

The linkages of the models within the Terrestrial Environment Subsystem as well as of this subsystem with other models in IMAGE 2.0 are discussed further in Alcamo *et al.* (1994a). Finally, the group of models constituting the Atmosphere-Ocean Subsystem are used to compute the buildup of greenhouse gases in the atmosphere and the resulting changes in global temperature and precipitation patterns (as opposed to most General Circulation Models – GCMs – which account for CO_2 only). However, compared to GCMs, IMAGE 2.0 has a lower degree of scientific realism, includes many **parameterizations** , and requires a GCM to scale down zonal average temperature and precipitation patterns to the grid level. Several climate-related feedbacks exist within the Atmosphere-Ocean Subsystem as well as with other models of IMAGE 2.0.

The basic IMAGE 2.0 model described above has been used to analyze four future development scenarios: a conventional wisdom scenario, a Biofuels Crops scenario, a no Biofuels scenario, and an Ocean Re-alignment scenario (Alcamo *et al.* 1994b). It has been linked also with WORLD SCAN, a model of the global economy, to integrate long-term economic and energy developments with climate change (Timmer *et al.* 1995; Gerlagh *et al.* 1996, Bollen *et al.* 1996b). Further development of the submodels of IMAGE 2.0 and their linkages are built into a new version IMAGE 2.1. In particular, the agricultural demand model – a critical component of the economic subsystem at the world scale – has been improved to include more detail and sensitivity to issues of soil quality and land management as well as to provide for consistent linkages with aggregate figures of production and trade of agricultural commodities produced by WORLD SCAN.

There is no doubt that IMAGE 2.0 as well as its newer versions is another ambitious global level modeling endeavor which attempts to provide meaningful representations of the society-environment-economy interactions at a global level while acknowledging the serious constraints and difficulties of this task. In the perspective of the present contribution, it represents an important model where land use change plays a pivotal role in the assessment of the economic and environmental consequences of climate change. Moreover, land use is modeled in a careful and sensitive way given the global nature of IMAGE 2.0. It is interesting to note the recognition by IMAGE's modelers of the lack of a theory of the society-environment-economy (and land use) interactions which could potentially provide more guidance to model building. However, it seems that, at such a level of aggregation, the lack of theory is reasonably expected. In any case, global models of any kind (economic, environmental, social) are meaningful only at that scale and their downscaling to lower levels requires "translator models" customized to particular geo-political contexts. This is a modeling task yet to be undertaken in the future.

4.6.4. Input-Output-Based Integrated Models

The broad framework of **Input-Output (I-O) Analysis** as been used for the analysis of the economy-environment interactions in several instances, a short account of which will be given shortly. In the particular case of the analysis of the land use change, the literature contains contributions utilizing input-output models although not with the frequency with which other analytical frameworks are being used. Two general directions in the use of I-O analysis for the study of the economy-environment-land use relationships can be distinguished. The first involves the integration within the structure of an I-O table and model of environmental and land use considerations; this is the case of building a *compact model* and it is explained briefly below. The second involves the linking of an I-O model of an economy with other models describing its environment and land use system; this is the case of a *modular model.* These are detailed below.

4.6.4A Compact Input-Output Models

The earlier attempts to use the I-O model beyond the narrow confines of economic analysis are found in the models proposed by Cumberland (1966), Daly (1968), Leontief (1970), Isard (1972) and Victor (1972). The common thread of thought in all these attempts is to augment the standard economic I-O table with rows and columns which represent somehow the inputs and outputs of elements of the environmental system to and from the economic system. In the following, only a few of these attempts are discussed. The reader may refer to Lonergan and Cocklin (1985) and Bolton (1989) for additional analyses of these and other similar efforts. Leontief (1970) proposed an adaptation of the basic I-O model to accommodate the "environmental repercussions of the economic structure". The interindustry matrix of the basic I-O table is augmented with extra rows and columns, the rows representing the generation of pollutants by the economic sectors and columns representing anti-pollution economic sectors established to remove the pollutants generated by the economic system. This augmented table is suitable for the analysis of pollution caused by economic activities. The analysis of land use change, however, is not addressed by this framework. In fact, changes in land requirements are estimated **exogenously** based on the results of the augmented I-O table. An application of this approach by Leontief *et al.* (1977) is briefly described below.

The United Nations World Model

Leontief *et al.* (1977) designed and applied the United Nations World Model (mentioned previously) in a global modeling exercise commissioned by the United Nations for the study of the interactions of the world economy with the environment. All countries of the world were grouped into 15 regions. In each region, 48 producing and consuming sectors were distinguished connected with each other and with the economies of the other regions by means of I-O relationships. A multi-regional Input-Output system was set up consisting of 2626 equations that describe the interrelations between production and consumption of various goods and services within each region as well as interregional relationships (imports and exports). On the basis of various assumptions as regards basic macroeconomic magnitudes, the model projected the output of the economic sectors for a range of alternative future development scenarios to the year 2000.

Consumption coefficients measure the amounts of specific agricultural products, among others, consumed per unit dollar of additional total expenditure. The specific agricultural products considered are animal and milk products, cereals, high-protein crops and root crops. These were measured in physical units. Their consumption was estimated and projected from region-specific consumption functions published by FAO which take into account the income elasticity of demand for these products. All other agricultural products were labelled “residual agriculture” and their output is measures in value units. The following equation (4.107) was used to assess the cultivated land requirements for the projected levels of agricultural output.

$$SLAND = K * AGS + K * AGR \qquad (4.107)$$

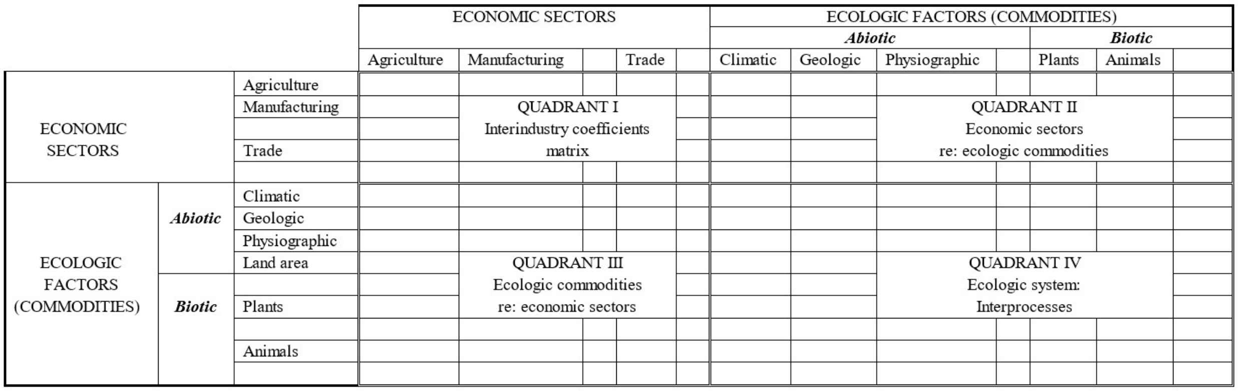
where,

$SLAND$	cultivated land area
AGS	selected agricultural products
AGR	residual agriculture
K	capital coefficients

Capital coefficients reflects each year’s investment in equipment, land, plant, and irrigation. In the case of agriculture, the levels of investment in land development and irrigation are set exogenously. Land-input coefficients (the inverse of yield ratios) were held at the 1970 levels given the difficulties to project agricultural yields satisfactorily for the different regions of the world. In this respect, Leontief *et al.* (1977, 21) note that the projections offered can be “viewed as showing the combination of yield improvements and/or increases in cultivated area needed to realize the projected levels of agricultural output.” The agricultural output and the associated food consumption projections were made on the assumption that the extent of self-sufficiency of each country will not change from its 1970 level. Based on these projections, a land/yield index, an arable land index and a land productivity index were estimated. The *land/yield index* measures the changes in land under cultivation, as compared with the base year 1970, required to achieve the predicted levels of agricultural output assuming that the productivity of land is at the 1970 levels. This index is essentially an index of agricultural production weighted by land per unit of output. Combining this index with **exogenous** estimates of new land brought into cultivation in the individual regions, the *arable land index* was calculated. This measures total arable land in 2000 as compared to 1970. Finally, the *land productivity index* gauges the increases in production that must be sought by means of technological change, and the use of high-yield crop varieties, pesticides and fertilizers.

Economic-Ecologic Models

Walter Isard (1972) offered a more complete adaptation of the I-O framework for the economic- ecological analysis of a region as shown in Figure 4.2o.



			ECONOMIC SECTORS					ECOLOGIC FACTORS (COMMODITIES)						
								Abiotic				***Biotic***		
			Agriculture	Manufacturing		Trade		Climatic	Geologic	Physiographic		Plants	Animals	
ECONOMIC SECTORS		Agriculture												
		Manufacturing		QUADRANT I Interindustry coefficients matrix						QUADRANT II Economic sectors re: ecologic commodities				
		Trade												
ECOLOGIC FACTORS (COMMODITIES)	***Abiotic***	Climatic												
		Geologic												
		Physiographic												
		Land area		QUADRANT III Ecologic commodities re: economic sectors						QUADRANT IV Ecologic system: Interprocesses				
	Biotic													
		Plants												
		Animals												

Isard’s Economic-Ecologic Model

Source: Adapted from Isard (1972)

Figure 4.2o

Isard's proposal is conceptually similar to the models proposed by Cumberland (1966) and Daly (1968). The extended I-O table has four quadrants which represent four two-way types of relationships between economic sectors and ecological processes. Vertically, the conventional economic sectors are identified in the first block of columns. The second block of columns is devoted to ecological processes classified broadly as biotic and abiotic. Biotic processes are further classified into fauna and flora-related while abiotic processes are further classified into climatic, geologic, physiographic, hydrologic, and soils. Horizontally, the first block of rows represents again the conventional economic sectors while the second block of rows represents ecological commodities which are classified broadly into biotic and abiotic. Biotic commodities are further distinguished into plant and animal life-related while abiotic commodities are further distinguished as the corresponding abiotic ecological processes. Observe that "land area" (and "water area") is introduced as one row of the extended I-O table. The first quadrant of the extended table is the typical matrix of interindustry coefficients of a conventional, economic I-O table. The second quadrant, designated as "economic sectors re: ecologic commodities" (i.e. economic sectors related to ecologic commodities), represents the production of pollutants by the economic sectors and forced on the environment. The third quadrant, designated as "ecologic processes re: economic sectors" (i.e. ecologic processes related to economic sectors), refers to economic commodities which are produced and used by ecological processes (this quadrant contains very few entries). The fourth quadrant, designated as "ecologic system: interprocesses", refers to the inputs and outputs exchanged during ecologic processes in the environment.

The Isard extended I-O table is an idealized representation of the economy-environment system characteristic of the early-1970s efforts to model holistically the interplay between the economy and the environment. It presents both conceptual as well as practical problems whose discussion is beyond the present purposes. Suffice to mention that the fourth quadrant is the most problematic of all as it contains the whole set of still unknown environmental processes which do not necessarily have an I-O (linear) representation. In addition, the treatment of the constituents of the environment in ways similar to the treatment of the material inputs and outputs of the economic system poses deep conceptual questions as well as methodological and practical problems of handling, measuring and *interpreting* the resulting coefficients. From the point of view of the analysis of land use, land area may be included in this framework but its mechanistic and linear treatment – as it is the case with all economic and ecological commodities and processes in I-O analysis – leaves much to be desired from the perspective of a comprehensive and meaningful analysis of land use and its change.

An extended I-O framework for the study of the economy-environment interactions similar to that proposed by Isard above was suggested and used by Victor (1972). The differences between Victor's and Isard's schemes are: (a) Victor uses the commodity-by-industry version of the economic I-O table instead of the industry-by-industry version, (b) the interpretation of the second quadrant is that the entries represent the amounts of ecological quantities used to satisfy interindustry and final demand, (c) similarly, the interpretation of the third quadrant is that the entries represent the amounts of ecologic commodities which are the outputs of interindustry and final demand activities, and (d) the fourth quadrant (Figure 4.2o.) is blank in Victor's scheme(!).

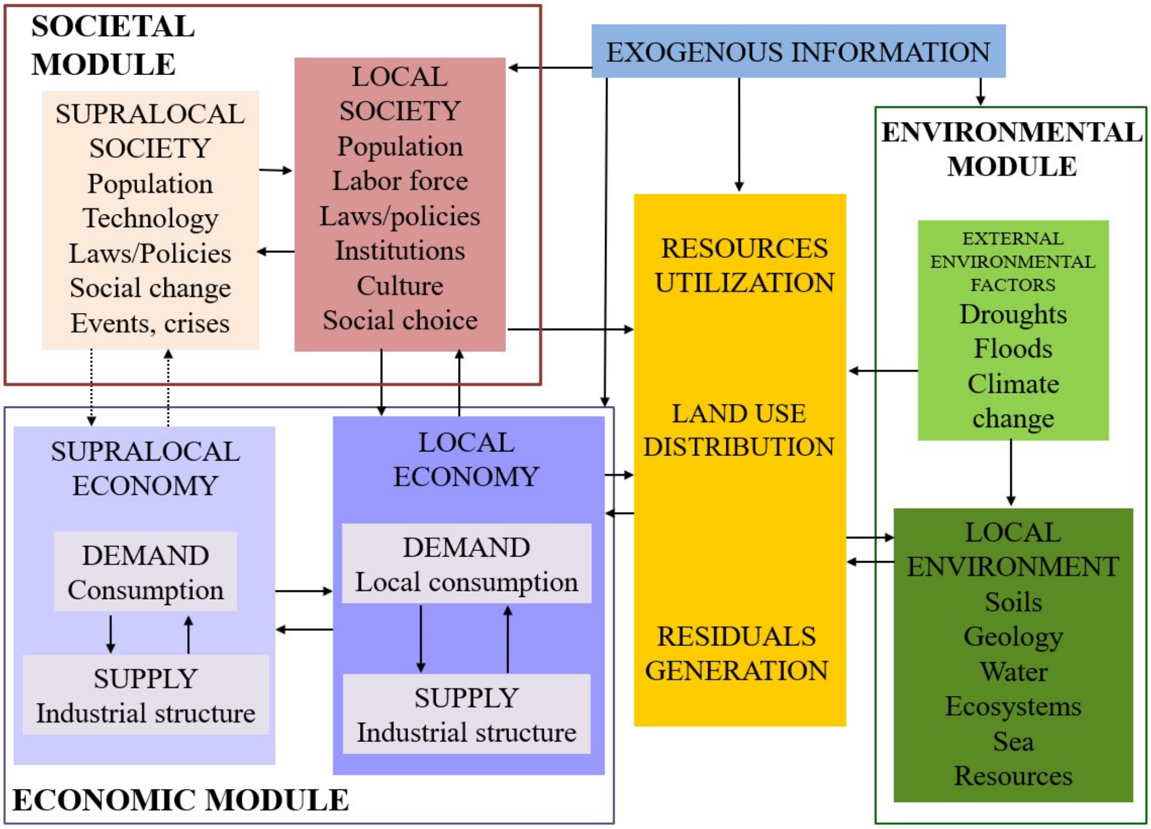
Victor defines as ecologic commodities all material inputs from the environment on their first introduction to the economy and classifies them according to the main environmental compartments of land, air and water. Similarly, the waste products of the economic system which are returned to the environment are also ecologic commodities. The "land" compartment accounts for material (land area included) and ecosystem inputs to the economic system as well as for the material and ecosystem outputs of the economic system (i.e. the environmental modifications effected by economic activities). Another characteristic of Victor's use of the I-O framework is that he defines a number of accounting identities which must hold for both the economic and the ecologic commodities to ensure that the economic-ecologic system is in equilibrium. The identities concerning the ecologic commodities are considered material balance identities following from the law of the conservation of mass (the **First Law of Thermodynamics**).

The models referred to above are *compact* models which attempt to force the spirit of the I-O accounting framework on the economy-environment interactions. From the perspective of the analysis of land use and its change, several observations should be made. First, there does not seem to exist any real world application of this modeling approach to the analysis of the land use impacts of economic activity. Most of the applications refer to pollutants (i.e. flows) generated by the economic system and abated by the anti-pollution sectors of the same system. Even in this case, the compact I-O modeling framework is not capable of handling a host of other environmental impacts either because they are intangible or because the restrictions of the I-O model (mostly the linearity and stability of the technical coefficients) do not provide for a realistic representation of the ecological processes as well as for the economic-environmental interactions over space and time.

Second, there are particular conceptual problems with handling land use and its change in the compact I-O model in addition to those associated with its handling of economic-environmental relationships in general. Land use conceptualized as area of land occupied by an economic activity is a stock concept, a form of capital, which can be considered as a "primary input" in the I-O model – i.e. it does not enter the interindustry matrix. If, however, the resources (or the services, products, qualities or other attributes) associated with a given land use are considered as flows, they can be incorporated in an interindustry matrix and treated like the economic interindustry coefficients. Still, there has to be a reasonable interpretation of these "flow" items to use the extended I-O meaningfully for the analysis of land use change which results from changes in the economic structure. Finally, it has to be kept in mind that I-O analysis in general is predicated on a demand-driven model of economic development which does not account for supply side factors, a particularly sensitive and critical issue when it comes to the constraints imposed by land use and the environment.

4.6.4B Modular Models with an Input-Output Component

Another direction in the use of I-O analysis for building integrated economy-environment models in which land use and its change are included is the design of *modular* models in which the economic system is represented by an I-O model. Several modular models for the study of the economy-environment interactions have been proposed since the mid-1970s (see, for example, Bolton 1989, Braat and van Lierop 1987, Briassoulis 1986, Hafkamp 1983, Lakshmanan and Bolton 1986, Lonergan and Prudham 1994). A schematic structure of such a model is shown in Figure 4.2p for a single-region case.



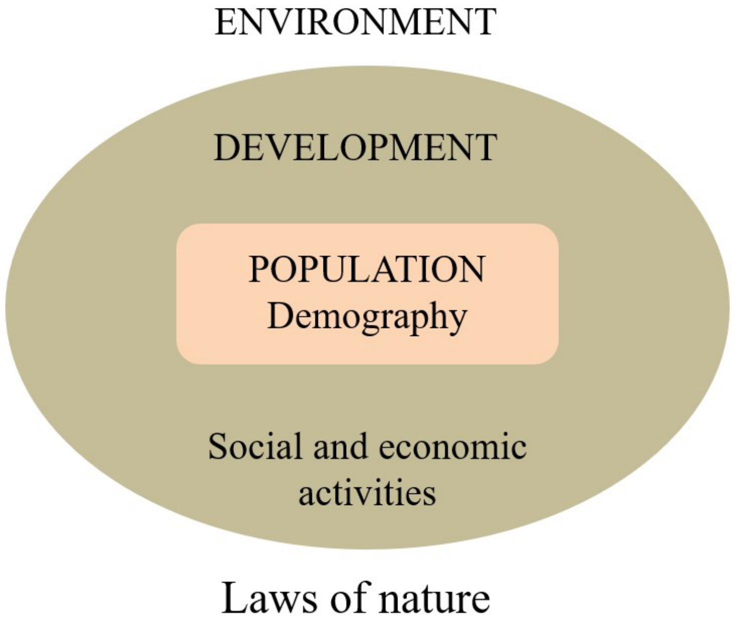
A prototype modular economic-ecologic model

Source: Author

Figure 4.2p

The economic system in these models can be specified by means of several alternative functional forms one of which is an I-O model which provides for a complete picture of the interindustry relations. One such modular model has been already mentioned previously in the context of the application of the cellular automata modeling approach (Engelen *et al.* 1995). This model is rather simple compared to more elaborate modular integrated models. Another integrated model where the I-O model is used for modeling the regional economy and it is linked to other models representing the environmental system – including land use change models – is presented next.

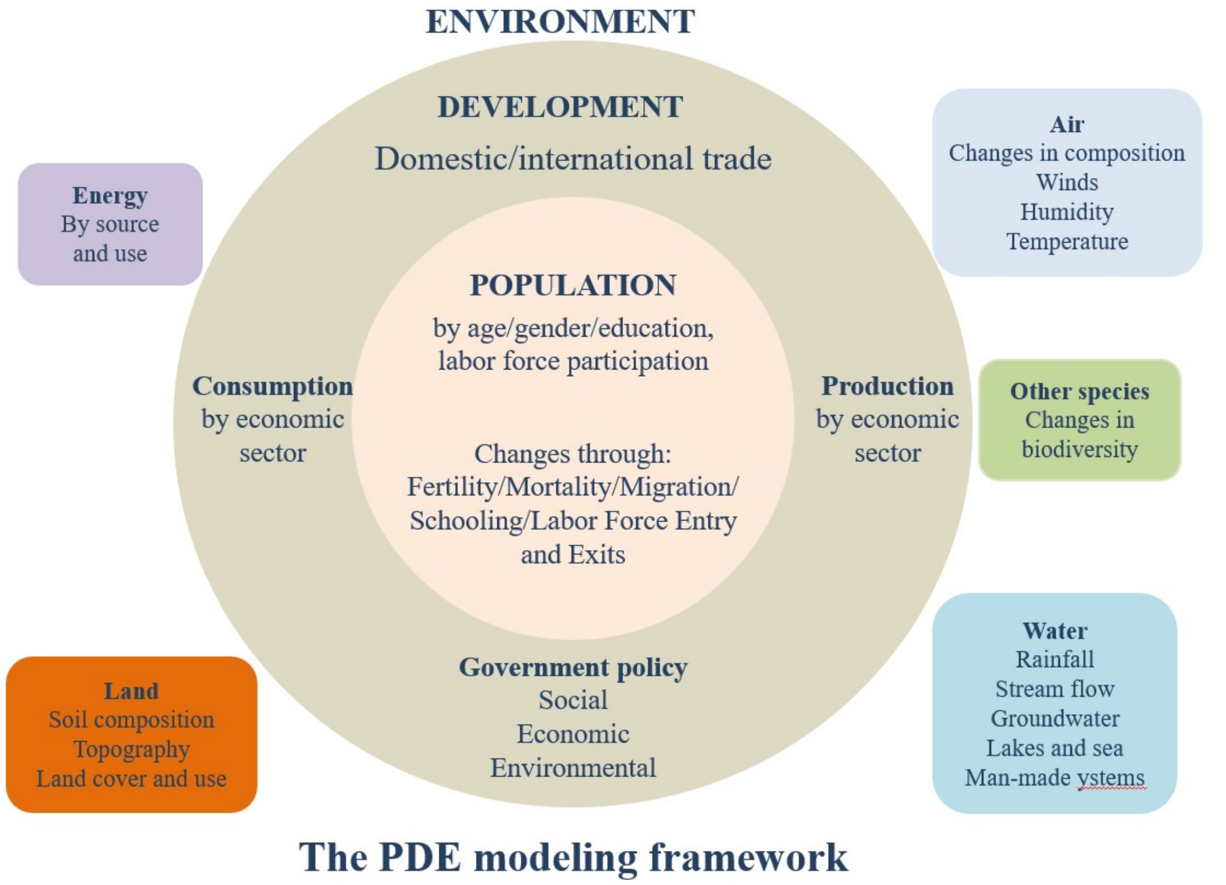
The model built for Mauritius was designed at IIASA (International Institute for Applied Systems Analysis) by a research team led by W. Lutz (Lutz 1994a). The underlying philosophy of the model is termed the "PDE approach" (which stands for Population, Development, and Environment). The purpose of this modeling approach is to facilitate, through modeling, the study of the interactions between population change, socio-economic development and the environment. The sequence Population, Development, Environment is not arbitrary. According to Lutz (1994b) "Population is taken as the point of departure as one of the basic driving forces that – together with many other factors – has an impact on development within environmental constraints.. Rather than viewing population-environment linkages in terms of a linear causal chain, it should be visualized as a series of concentric rings where the sphere of development . . . .. is intermediate between the demographic aspects of the human population and the natural environment" (Lutz 1994b , 210-211). This philosophy is depicted in Figure 4.2q. Drawing on Lutz (1994a) the broad modeling framework which has been designed to express the above philosophy is presented in the following. Its structure is modular, the three constituent modules being the population, the economy (or development) and the environment modules (Figure 4.2r.). These are described briefly next.



The basic philosophy of the PDE approach

Source: Adapted from Lutz (1994a)

Figure 4.2q



The PDE modeling framework

Source: Adapted from Lutz (1994a)

Figure 4.2r

The *population module* (Lutz and Prinz 1994) is perhaps the most elaborate of all three given the importance attributed to the quantitative and the qualitative aspects of the demographic structure of an area within the PDE approach. The core of the module is a multi-state population model – an elaboration of the multi-regional demographic model transferred to the study of many population groups defined along any criterion of interest. In the present case, population groups were distinguished by education and labor force participation status. Population dynamics is studied along four main dimensions: age, sex, education and labor force participation which are considered as the most important in the study of the interactions between population and the environment. A distinction is drawn between determinants and characteristics of population change. The basic demographic determinants of population change are fertility, mortality and migration, their effects being not always immediate but working through birth and death age-specific rates. However, the parameters of the population system are significantly affected by local and supra-local physical, economic, social, cultural, and political conditions and, in their turn, may affect some of these conditions. The characteristics of population change – which are the outputs of the population module – include: total population size, growth rate, density, age distribution (mean age and dependency ratios), sex ratio, and regional population distribution. These impact on the economic and the environmental systems variously. Usually, population change affects the environment via the economy although in several instances the population-environment relationship is direct as it is the case with the use of land for housing or the use of water by private households.

The *economic module* (Wils 1994) is an input-output (I-O) model for a small, open economy. The economy mediates the relationship between population and the environment as the economic activities of the population use the resources and sink functions and services of the environment. Especially with respect to the uses of land, the economic structure is a critical determinant of the allocation of land to various activities which, in their turn, impact on environmental resources and receptors. The (I-O) model is demand driven. The final demand for the output of the economic sectors determines the total production of each sector according to the basic I-O identity:

$$X = (I - A)^{-1}Y \qquad (4.108)$$

where,

X	is a $n \times 1$ vector of the output of the n economic sectors
Y	is the $n \times 1$ vector of final demand for the output of each sector
A	is an $n \times n$ matrix of inter-industry technical coefficients and
$(I - A)^{-1}$	is the $n \times n$ Leontief inverse matrix of sectoral multipliers

For an exposition of I-O analysis the reader is referred to Hewings (1985), Miller and Blair (1985), and Schaffer (1999). For each sector, labor and environmental coefficients are specified; e.g. number of workers per unit value of output by sector, area of land per unit value output by sector, volume of water demanded per unit value of output by sector, and so on. In the complete model, these coefficients are frequently adjusted to produce consistent projections of population, economic activity and environmental conditions.

In the particular application in Mauritius, where a very open (and small) economy is to be modeled, prices are assumed to be fixed. The **exogenous** information provided to the I-O model includes:

a. export demand (for sugar)
b. population – provided by the population module
c. per capita government expenditure
d. labor coefficients – calculated on the basis of the labor force (by education group) projections of the population module and influenced by technological change which is exogenously determined
e. per capita income (by income group) and the distribution of per capita consumption – which determine the magnitude of private consumption together with the size of the population,
f. land and water needed per unit of sectoral output as well as pollution emissions per unit of output – these are determined by the land and water models of the integrated model
g. value-added (capital productivity) coefficients
h. the exogenous part of investment demand – net borrowing from abroad, and
i. the tax rate.

The I-O model is a series of single-period models which operates under the assumption that all goods produced are sold within the same year. The model outputs are: (a) total production by sector with **endogenous** investment and (b) total production by sector with endogenous investment and private consumption. More details on the treatment of consumption as well as of other population characteristics in the economic module are provided in Wils (1994).

The *land use model* (Holm 1994) – a component of the environmental module of the Mauritius model – assesses the distribution of land to various land use categories as a function of the demands made by the economy, competition among land uses (basically, competition among the economic activities using land), and environmental constraints on the availability of land which is suitable for specific purposes. Land is assumed to be a form of capital a certain amount of which is necessary to produce a unit of sectoral output. Because the I-O model used employs linear production functions without returns to scale, no substitution between inputs is permitted. Hence, the land use requirements of a sector s (within a certain time period t), LD_{st}, are found by simply multiplying the sectoral output estimated by the I-O model (within a certain time period t), G_{st}, by the inverse *land productivity coefficient*, l_{st} (monetary value of output per square kilometer) as follows:

$$LD_{st} = (1/1_{st})G_{st} \qquad (4.109)$$

As it was the case with the economic model, the land use model accepts **exogenous** input for land productivity which may be changed between time-periods. It, then, produces the land use distribution which is constrained by the amount of land available and the amount of water available for irrigation. In the case of a land or water conflict (over-prediction of demand for land or water basically), a solution is found by iteration. In other words, if there is a land shortage, the model changes final demand **endogenously** until a production mix is achieved which satisfies the land constraints. This procedure is detailed below.

The land use model distinguishes four aggregate types of land use: sugar cane land (the main economic good produced), other agricultural land, urban land, and beaches. Certain rules for land conversion from one land use type to another are established to guide the land allocation process. These rules draw from the experience of historical land transformation in the island as well as from logically derived sequences of possible transformations. Hence, sugar cane land and other agricultural land can be traded and transformed into urban land. Beach land cannot be transformed. The model is not spatially explicit; hence, transitions from one type to another are not specified by location. Although this lack of spatial specificity in the case of Mauritius did not create problems, it is generally preferable to have spatially-explicit (or, geo-referenced) models which produce more reliable land use changes as they reflect the actual spatial variability of various constraints on land transformations.

The assessment of the area of the four types of land use distinguished above is done separately for each type taking into account its particularities and applicable constraints. For example, in the case of agricultural land which is distinguished between sugar cane and other, demand for land is estimated initially by equation (4.109). However, if there is a water shortage, land productivity decreases. The impact of water shortage is reflected in a user-specified elasticity measure which shows how much land productivity will decline in the case of water shortage. The estimate of the new land productivity coefficient is used to adjust the demand for land by the particular sector (which is impacted by water shortage).

Urban land is considered an absorbing state; i.e. once agricultural land is converted to urban land the reverse change is not possible. The only source for new urban land is agricultural land (which was historically the case). Urban land is distinguished into residential and commercial. The demand for commercial land is directly estimated by equation (4.90). For residential land, the demand is estimated as a function of household consumption and land price as follows:

$$LD_{st} = [h_1 P_t + (h_2 C_t / h_3)]10^{-6} \qquad (4.110)$$

where,

s	is the residential sector only
h_1	is the minimum residential space per person (by default 10 m^2)
P	is total population
h_2	is the share of private consumption spent on housing (by default 9%)
C	is private consumption
h_3	is unit price of residential land

All parameters are user specified and the per capita income elasticity of housing demand is assumed to be 1.

As regards beaches, these are assumed to be the key resource for tourism on the island. Therefore, all economic activity in the hotel and restaurant sectors are directly related to the length of the beaches (although these may not be located necessarily along the beach). Beaches are distinguished into two classes. The "strip" is currently used and it is considered the best; hence it is not changed at all in the model. What does change as a response to increased demand is the *density of use* of these beaches. There is another class of secondary beaches which can be converted to beach use for tourism. Finally, the "other land" type contains natural features and is used to assist the model user to redefine the amounts of available agricultural or urban land by transferring some land to and from the "other land" category.

Because of differences in land profitability among uses, the actual allocation of land to alternative uses is governed by economic factors, by now a common knowledge based on experience and urban land market theory (see Chapter 3 and the utility maximization models). The land use model of Mauritius employs a market mechanism for resolving land use conflicts which mimics a market bidding process (as in Alonso's model). However, in addition to a market-based conflict resolution mechanism, the model accepts the possibility of public intervention in settling conflicts which involve the public interest. Because the model does not include market demand and supply for land and the corresponding prices (the rent profile) to employ an Alonso-like bidding process, it uses the production per unit of land as a substitute for the relative worth of the different types of land use, as profit per unit of land is almost proportional to production in this model. Based on value-added figures for the different economic sectors, the land use types are ranked from higher to lower priority for conversion and this ranking is assumed to remain constant over time. Hence, following Holm (1994), the decision rules adopted are: (a) in case of conflict, urban land demand wins over agricultural land demand unless a policy to preserve agricultural land is stipulated; (b) if no policy is specified, and if the land available for sugar and other agriculture is less than demanded when the urban land demand is satisfied, then the output of both agricultural sectors decrease proportionally. The decrease in demand for sugar land is initiated by decreasing export demand for sugar proportional to the land shortage. Decrease in other agricultural land demand is initiated by proportional decreases in export demands and in domestic household demand for food. This decrease is exactly compensated by an increase in import demand from households. Urban land is not allowed to decrease, regardless of the development of land demand. Consequently, agricultural land cannot increase but it can remain constant.

The land use model is used to simulate the land use and economic impacts of various types of plausible policies such as a "sugar policy" and an "agricultural policy". Finally, the model calculates the changes in population and in the total size of urban areas on the island as a function of specific scenario assumptions regarding population change, economy, land use, and the environment. On the basis of user-supplied assumptions, the spatial distribution of the population is projected. Two main assumptions are considered: (a) distribution proportional to the initial number of inhabitants, an assumption without enough empirical and theoretical support and (b) distribution proportional to population change in 1985-1990. For information on modeling the water systems in Mauritius in the context of the integrated model the reader is referred to Toth (1994).

The integrated model presented above presents another alternative way of modeling land use change in an integrated context. It may lack the sophistication of several other models reviewed before although here is nothing in the model structure to prevent more sophisticated treatment of model components. It seems that in the case of Mauritius – a relatively simple spatial system compared to complex urban or global systems – the level of sophistication employed was adequate for the problem at hand. The PDE modeling approach is distinct for its elaborate treatment of the population component whose detailed analysis provides the basis for a better representation of the socio-economic and environmental dynamics. The model adopts a coarse land classification system and it is not spatially explicit but again there does not seem to be any conceptual problem for its incorporating more spatial and land use detail. The land allocation module attempts to simulate a realistic land conversion, rule-based, process by taking into account environmental constraints. A similar procedure was used also by Engelen *et al.* (1995) in the context of their cellular automata modeling approach.

4.7. Other Modeling Approaches

The four main categories of models presented in the previous sections cover more or less the majority of models of land use and land use change. However, there are several other approaches which, on the one hand, do not fit easily into these categories and, on the other, cannot constitute a separate category by themselves as their application is either specialized or sparse, or very recent. In this section, certain of these other approaches are brought together and discussed. These are loosely grouped into: (a) natural-sciences-oriented approaches, (b) Markov modeling of land use change and (c) GIS-based approaches.

4.7.1. *Natural-Sciences-Oriented Modeling Approaches*

Modeling of land use change has been undertaken primarily in the disciplines of geography, regional science, and urban and regional economics. Planning and related fields have mostly borrowed from these principal disciplines although exceptions do exist especially in contemporary times when disciplinary boundaries become blurred and fuzzy. Modeling of land use change, however, has been historically and is currently the subject of other disciplines such as ecology, landscape ecology, forest science, soil science, and environmental science, in general. The models developed in these disciplines have a common characteristic; namely, they are natural sciences-based placing a heavy emphasis on the bio-physical aspects (determinants and impacts) of land use change and, at times, almost ignoring the socio-economic, institutional, political, and other determinants. They cover a variety of levels on the spatial and the temporal scales. Frequently, they are called land cover change or land use/cover change (and not land use change) models as, at higher spatial levels especially, land cover dominates which may or may not be associated with land use (as it is the case with natural vegetation). A brief indicative overview of these models is offered below, drawing on several reviews of the literature, to show the range and variety of the modeling studies available.

Landscape ecology models is a general category which includes models used to analyze landscape patterns, associated characteristics and processes, and change. Depending on the particular component of a natural ecosystem being studied (e.g. a plant or animal species, a particular ecosystem, a watershed) there is a wide variety of these models (see, for example, Baker 1989, Turner and Gardner 1991a). Two notable, interrelated characteristics of all approaches to the analysis of landscape change are mentioned. First, is their emphasis on the level of the spatial and temporal scale at which the analysis is performed as it has a determining influence on the patterns and processes of change identified and analyzed (Turner and Gardner 1991b). A variety of data analysis techniques have been developed and utilized in landscape models to address the issue of scale appropriately (Turner et *al.* 1991, Quattrochi and Pelletier 1991, Dunn *et al.* 1991, Milne 1991). The second characteristic is the spatial explicitness of landscape models which has been greatly improved with the advent of remote sensing techniques and GIS.

Sklar and Constanza (1991) distinguish two major categories of landscape models: stochastic and process-oriented. *Stochastic landscape models* employ Markov or semi-Markov processes to the study of changes in a study area which is subdivided into cells. Transitions in the state of each cell (e.g. the state of vegetation) are modeled by estimating transition probabilities which account for interactions between neighboring cells. The impact of climatic and other environmental factors can be incorporated also in estimating these transitions for a more realistic representation of the dynamics of landscape change. *Process-oriented landscape models* simulate spatial structure by compartmentalizing the landscape into a number of geometric areas and, then, describing abiotic and biotic flows between compartments according to certain location-specific algorithms. Various processes can be analyzed such as habitat succession, land use change, etc.

Although the majority of landscape models analyze change in terms of environmental determinants, the introduction of the human dimension in these models has been attempted also. Parks (1991) distinguished three groups of models of forested and agricultural landscapes which take into account the influence of socio-economic factors is the analysis of landscape change: (a) inventory/descriptive models, (b) engineering/optimization models, and (c) statistical/econometric models. These models can take into account various socio-economic factors such as returns per acre, net economic benefits, prices of inputs and outputs (products) associated with land use conversion (Parks 1991, Pfaff 1999). However, they are not based explicitly always on economic theory as it was the case with the discrete statistical models reviewed in section 4.3.1. (Bockstael 1996, Bockstael and Bell 1997, Irwin and Bockstael 1999).

A variety of solution techniques are employed in landscape models of land use/cover change. Most common among them are techniques which require the subdivision of the study area into cells (called also patches in landscape models) and estimate transition probabilities among different states of land use in each cell. The use of Markov and semi-Markov chain models is widespread especially when the data analyzed are obtained from remote sensing and related sources. GIS-based models are employed also for the same reasons. These two types of models are presented in the following sections. The main point with respect to these techniques is that they lack explanatory power as the causal relationships underlying the transitions studies are left unexplored. Transition probabilities are estimated as proportions of cells which have changed state from one point in time to another. This appears to remain the most handy way to estimate these probabilities despite the development of procedures for estimating transition probabilities on the basis of more complex, scientific considerations (Baker 1989). Other techniques used include statistical, regression models (Parks 1991, Pfaff 1999) as well as fractal models (Milne 1991). The latter provide appropriate tools for modeling the heterogeneity and complexity of landscape structure and processes of change. Fractal models belong to the same modeling tradition as the cellular automata models of urban spatial structure which were discussed in section 4.6.3B before. These models are also poor in explanatory power and grounding in economic, sociological or some other type of theory.

Turner *et al.* (1995) cite ecological modeling approaches that have been applied to model vegetation cover and soil organic matter dynamics in managed (and unmanaged) grassland ecosystems. These include the CENTURY model (Parton *et al.* 1987, 1993) as well as SAVANNA (Coughenour 1993 cited in Turner *et al.* 1995, 42), a process-oriented model of pastoral ecosystems. Similarly, livestock models and the underlying vegetation dynamics models of those linked explicitly to rangeland management contribute to studying land use change in specific ecosystem types. Global vegetation models employed for the study of biophysical relationships of plant canopies and global natural vegetation models employed for the study of natural vegetation as a function of climate (Meyer and Turner 1994, 74) are, in one way or another, related to the analysis of land use change from the particular disciplinary perspective of the life sciences.

Forest models are employed also to analyze land use changes, especially as regards the impacts of human colonization and deforestation in forest areas. Related studies include Brondizio *et al.* (1994), Pfaff (1999), and cited in Turner *et al.* (1995, 42) include Grainger (1990), Dale *et al.* (1993), Southworth *et al.* (1991) and Lambin (1994); the latter reviews modeling approaches applicable to deforestation processes.

Soil erosion and desertification represent important processes which effect land use changes in the course of time. Various physical models exist which account for these processes as well as for their close and critical interactions with other environmental factors – e.g. vegetation, water resources, climate. At times, interactions with socio-economic factors are also taken into account. These models contribute to the analysis of land use change especially in agricultural, rangeland, and sensitive (erosion-prone) areas (see, for example, Thornes and Brandt 1996). A number of recent research projects produce models developed in this direction such as MEDALUS I, II, III (see, Thornes and Brandt 1996 and the MEDALUS website in Appendix 1.B) and IMPEL (Rounsevell 1999).

Models have been used to study the impacts of climate change on the location and extent of natural ecosystems and agro-ecosystems. Related studies cited in Turner *et al.* (1995, 41) include Bultot *et al.* (1992), Emanuel *et al.* (1985), Parry *et al.* (1988a, 1988b). Climate change models – starting with IMAGE 1.0 (Rotmans 1990; see, also, Alcamo 1994) and developing into the ESCAPE framework (CRU and ERL 1992 cited in Turner *et al.* 1995, 41) have been linked to several impact models such as sea-level rise, agriculture and ecosystems which relate to the analysis of land use change in particular environments (usually the tropics and sensitive ecosystems).

The above brief account of natural-sciences-based modeling approaches to the analysis of land use change is simply indicative of the broad spectrum which needs to be covered for a comprehensive account of the related phenomena. These modeling efforts – as several others described in the preceding sections – have their own particularities and are suited to the study of special aspects of more general phenomena and processes. Further discussion of these models and additional references are found in various sources (see, for example, Turner and Meyer 1990, Meyer and Turner 1994, Turner *et al.* 1995). Their value lies in that they clarify particular aspects of the natural world dynamics and, hence, they make possible their integration, or the knowledge they provide, into more sensitive integrated models of land use change at various spatial and temporal scales.

4.7.2. *Markov Chain Modeling of Land Use Change*

Markov chain modeling (henceforth called Markov modeling, or Markov analysis, for brevity) is basically a simulation technique which has been applied to the analysis of land use change but it is not as widespread as other simulation techniques for reasons which will be discussed shortly. Its use in landscape models of land use change has been mentioned already in the previous section. It is worth noting, however, that the application of Markov analysis for the prediction of long-term land use changes is included among the proposals of the LUCC Implementation Plan (LUCC 1999). For preliminary applications see, also, Geoghegan *et al.* (1998).

The application of Markov analysis to the study of land use change was proposed in the geographic literature as early as 1965 for the study of the movement of central city rental housing areas (Clark 1965). Subsequent applications concerned mainly the study of land conversion processes mostly in urban contexts such as suburbanization, neighborhood housing turnover, land use change (Drewett 1969, Gilbert 1972, Bell 1974, 1975, Bell and Hinojosa 1977) and more special theoretical issues such as the process of land use succession (Bourne 1971). Other applications concerned the use of Markov chain analysis in the context of land use impact assessment of large public investments such as dams (Vandeveer and Drummond 1978) and of analyzing the historical dynamics of urbanization in agricultural areas (Muller and Middleton 1994). More recently, Markov analysis has been applied to problems of assessing the impacts of land use/cover changes on local climate (Lein 1989) and of projecting changes in organic carbon stores caused by land use changes (Howard *et al.* 1995). Finally, Markov analysis of land use change has been combined with GIS to create a tool for visualizing and projecting the probabilities of land use change (the transition probabilities) among categories of land use (Logsdon *et al.* 1996). The following discussion presents briefly the basics of Markov chain analysis as applied to issues of land use change and comments on issues related to its applicability.

Markov chain analysis belongs to the analytical methods of **stochastic processes** . A Markov process is a stochastic process with particular characteristics which distinguish it from other stochastic processes. For a system of interest, say a parcel of land, there is a set of discrete states (or classes) – $S_1, S_2, \ldots S_n$ (say, different types of land use). The process can be in one and only one of these states at a given time. It moves successively from one state to the other with some probability which depends only on the current state and not on the previous states. This is a characteristic assumption of Markov processes (or, otherwise stated, this is *a process without memory*; see, Bell and Hinojosa 1977). The probability of moving from one state i to another state j is called a *transition probability*, P_{ij}, and it is given for every ordered set of states. These probabilities can be represented in the form of a *transition matrix*, P, as shown below:

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \qquad (4.111)$$

“Since the elements of the matrix are non-negative, and the sum of the elements in each row are equal to 1, each element of the matrix is called a probability vector and the matrix P is a stochastic or probability matrix” (Judge and Swanson cited in Clark 1965, 352).

This idea is easily transferred to the case of an area subdivided into a number of cells each of which can be occupied by a given type of land use at a given time. Transition probabilities are then computed on the basis of observed data between time periods which show the probability that a cell will change (or, move) from one land use type to another within the same period in the future. This probability depends only on the state in which a cell is at any given point in time - i.e. its current land use type – and not on the land use types by which it was occupied in the past. Obviously, the plausibility and acceptability of this assumption depends on the time span considered. For example, this may be true for long time spans (e.g. for more than 50 years although, in general, the longer the time span the more plausible this assumption becomes). Given the matrix P of transition probabilities, its use to project future changes in land use is as follows. A vector, l_0, depicting the distribution of land uses among the different types at the beginning of the period is required. The vector, l_t, showing the distribution of land use types at the end of the projection period is found by the following formula:

$$l_t = l_0 P \qquad (4.112)$$

The distribution of land use types after k time periods (of a given length) is found by powering matrix P:

$$l_t^k = l_0 P^k \qquad (4.113)$$

If a Markov chain is *regular* (i.e. the entries of each row are non-negative and sum to one), then it can be used also to compute the equilibrium vector of land use distribution – i.e. this land use pattern in which *net* movements from one land use type to another are zero (Vandeveer and Drummond 1978). The resulting matrix has identical rows, each row representing the equilibrium distribution of land use types in the area. This equilibrium matrix is found either by raising matrix P to successive powers until the rows do not change or by following a more efficient procedure proposed by Judge and Swanson (1961 cited in Vandeveer and Drummond 1978).

Markov chains are classified variously depending on their properties. One such important property for its application in the analysis of land use change is the property of *stationarity.* A Markov chain is called *temporally homogenous* if the transition probabilities are identical for two time periods of elapsed time of the same duration occurring at different points in time. The concept of stationarity is closely related to the concept of temporal homogeneity and they are sometimes used synonymously. "A temporally homogeneous process is stationary when the (unconditional) probabilities of the system being in the different states at future points in time are constant" (Bell and Hinojosa 1977). A non-stationary Markov process is one in which the condition of stationarity does not hold – i.e. the transition probabilities are not constant at different time periods. Most of the applications of Markov analysis to the study of land use change assume that the process is stationary although this is not easy to prove in practice, the most important reason being the lack of data to test if the process is stationary.

Most of the applications of Markov analysis of land use change pursue a procedure more or less similar to the one described above. However, Markov analysis is a rather involved statistical method of analysis and its use requires thorough understanding of the mathematics and statistics involved as well as rigorous tests of the basic assumptions made; namely, that the observed processes are Markov processes and, in particular, stationary Markov processes. One of the reasons these basic assumptions are difficult to test is the lack of sufficient time series data on changes of land use between time periods to set up the transition probability matrices and then test the stability of the transition coefficients over time. Most applications admit to the presence of this difficulty and caution the reader against the limitation of the analysis in the case this test cannot be undertaken (Clark 1965, Bell 1977, Sklar and Constanza 1991). Therefore, a valid application of Markov analysis for the projection of land use changes requires a prior rigorous test of these basic assumptions. Once these tests are done and show that the assumptions are met in the particular case being studied, the procedure described above (and several versions of it found in the literature) can be applied. It is noted that the recent availability of remote sensing images as well as of GIS makes easier the testing and application of this type of analysis. An interesting application by Logsdon *et al.* (1996) proposes the procedure of "probability mapping" with the use of GIS to facilitate the visualization of the process of past change in space (the mapping of the transition probabilities) as well as its projection into the future (see, also, Geoghegan *et al.* 1998).

Markov analysis of land use change is an aggregate, macroscopic modeling approach as it does not account for any of the drivers of land use change; instead, it assumes that all forces that worked to produce the observed patterns and governed their transition probabilities will continue to do so into the future. Of course, advanced applications of Markov analysis relax the assumption of stationarity and make possible the exploration of alternative futures produced by changing appropriately the original transition probabilities to simulate different probabilities of transition among land use types. However, these applications presuppose high competency in the related mathematics and statistics. If the assumption of stationarity can be assumed to be valid – something which is time- and place-specific – then Markov analysis can be used in three different ways: (a) for *ex-post* impact assessment of land use (and associated environmental) changes of projects or policies in the spirit of Vadeveer and Drummond's (1978) application; (b) for projecting the equilibrium land use vector as well as for approximating the time horizon at which it may be obtained; and (c) projecting land use changes at any time in the future given an initial transition probability matrix as it is commonly done in most applications. It has to be noted, however, that, in addition to the assumptions mentioned above, the type of Markov analysis presented here does not incorporate constraints on possible transitions or other types of constraints (e.g. availability of land and other resources). Future research may attempt to relax this and other constraints and provide versions of this simulation technique which can accommodate more plausible and defensible assumptions about reality.

4.7.3. *GIS-Based Modeling Approaches*

A last group of modeling approaches is currently under development and the related applications to the study of land use change are still to be evaluated compared to the more established modeling techniques discussed so far. These are termed here *GIS-based modeling approaches*, a term that will be qualified shortly. The development of GIS in the last 20 years has opened new horizons for the management and manipulation of spatial data sets. However, as Fotheringham and Rogerson (1994) observe: "the field of GIS had too long ignored the potential contribution to be made by integrating some of the achievements of theoretical and quantitative geographers with the emergent technological developments in hardware and software.... While developments often focused upon the storage, retrieval and display of spatial information, few advances were made in providing (GIS) with the capability for spatial statistical analysis and modeling... (In another sense) ... GIS technology could play a role in the development of new techniques for spatial analysis or, promulgate the use of existing exploratory and data-driven techniques" (Fotheringham and Rogerson 1994, 175). To explore the types of GIS-based modeling approaches for the analysis of land use change, it is necessary to take a brief look at the issues of spatial data, the functions of GIS for the analysis of these data, and the broad field of spatial analysis.

Spatial data sets have two distinctive traits. First, they describe the locations of objects in space (and their topological relationships) – called *topological* and *positional* data. Second, they describe non-spatial attributes of the objects recorded – called *attribute* or *thematic* data (Fischer *et al.* 1996).

GIS have four main functions related to spatial data:

a. Data input,

b. Data storage, retrieval, and database management,

c. Data analysis (data manipulation, exploration, and confirmation), and

d. Output (display and product generation) (Fischer *et al.* 1996).

Spatial analysis has evolved considerably over the last 40 years offering a multitude and diversity of procedures for the analysis of spatial phenomena. Two main directions can be distinguished broadly:

a. *Statistical spatial data analysis* – which makes possible the appropriate analysis of spatial data, and

b. *Spatial modeling* – which provides a variety of models for the study of spatial phenomena (process, policy, location-allocation, spatial interaction, regional economic, spatial choice models) (Fischer *et al.* 1996).

The analysis of land use change, based on available sets of geo-referenced (spatial) data, in a GIS environment involves the coupling (or, interfacing) of spatial analytic models with a GIS. This coupling may take two forms, in general: (a) *tight coupling* or (b) *loose coupling* (Goodchild 1992, Batty and Longley 1996, Fischer *et al.* 1996, Nyerges (1993) cited in Jankowski 1995, 264).

Tight coupling may be either *full* or *close.* Full coupling has not been achieved yet as it involves complete integration of spatial analytic models and techniques within the GIS or vice versa. Close coupling appears more realistic as it involves exchange of various types of information between spatial analytic models and GIS. However, several issues related to the interfacing of these tools are yet to be resolved. Finally, loose coupling is the current, widespread practice at present. Spatially-explicit models are linked to a GIS either to retrieve input spatial data and/or to display graphically the model results in map form. Several of the models presented before, especially those which are rule-based such as the cellular automata approach, the CLUE models, the USTED models, IIASA's LUC model, and Markov modeling, among others, have already developed or are developing linkages with GIS.

However, if a separate group of modeling approaches to the analysis of land use change is to be distinguished – the *GIS-based modeling approaches* referred to in the beginning of the section – then these should refer to the tight coupling of spatial analytic models and GIS. This means that a spatial analysis and modeling technique is fully integrated with a GIS which performs the required analytical procedures and operations as part of its overall structure in addition to spatial data manipulation and map generation. At this point, a natural question that arises concerns the types of modeling approaches which are capable of being incorporated into GIS. Aspinall (1994) distinguishes four types:

a. rule-based

b. knowledge-based

c. inductive-spatial, and

d. geographic.

Rule-based approaches employ rules to weight data sets in the geographic database. *Knowledge-based approaches* employ equations/relationships – developed outside the GIS – to data sets in the geographic database. *Inductive-spatial approaches* employ spatial analytical techniques (spatial statistics) to identify relationships between data sets in the geographic database (see, for example, LeSage 1999). Finally, *geographic approaches* are spatial statistical descriptive approaches which describe patterns in data sets in the geographic database in terms of location. All four approaches are relevant to the analysis of land use change although a strict reading of the term "location" would exclude the fourth group (see the extensive arguments offered in the beginning of this chapter on considering location theory and the related models as land use theory and models proper).

Of the four approaches, rule-based modeling is perhaps the most widely used GIS-based approach in the form of *map overlay analysis* which has many applications in planning contexts. Data pertaining to several attributes of a study area (elevation, slope, climate, hydrology, land uses) are stored in *layers* in a GIS. Different layers are overlain to generate maps showing "unique conditions" in McHarg's (1969) tradition. Overlay analysis is used also to predict a new map as a function of the distribution of observed attributes (Unwin 1996). However, the caveats of the map overlay technique which Hopkins (1977) has so succinctly analyzed should be borne in mind irrespective of whether this is applied on a luminescent table or in a GIS. As Batty and Longley (1996) note: "(The layer model) . . . is a product of the notion that data can be separated in a clear spatial way, and although this may be possible, there is no guarantee that data should be put back together in the same way though simply adding layers. . . No one would pretend that the world works through such simplistic merging. Moreover, the notion that the addition of layers is the central modeling capability of GIS simply illustrates that GIS is based not upon the definition and representation of processes but simply upon static structures." (Batty and Longley 1996, 349-350).

Applied to the analysis of land use change, rule-based approaches can, in principle, contribute to three of the four major purposes of analysis: description, prediction (and conditional prediction), and evaluation. Whether explanation is feasible in this context is an open question. Description of land use change can be performed by overlaying land use maps from different time periods to identify the location and assess the magnitude of change. The accuracy of the description provided depends on the detail of the land cover classification employed which at the time of this writing is not sufficient to match the needs of actual decision making on land use issues (see, for example, the contributions in Liverman *et al.* 1998). Prediction of land use change – at least, particular types such as degradation, desertification, abandonment, urbanization, suburbanization – can be performed by combining various characteristics which are assumed to determine these kinds of changes (such as soil conditions, slope, climatic conditions, migration, economic stagnation). Utilizing scenarios to define future values of particular characteristics or different weightings of these characteristics, conditional predictions of such changes can be obtained (see, for example, Despotakis 1991, Despotakis *et al.* 1993). Finally, evaluation of proposed or expected future patterns of land use change is a function which can be undertaken in the context of a GIS also but it is a subject beyond the scope of this contribution (see, for example, Jankowski 1995, Pereira and Duckstein 1993).

Within the general trend to integrate GIS with spatial analysis and modeling techniques (see, for example, the contributions in Issue No.3, Vol.1 of the journal *Geographical Systems*), knowledge-based approaches have a great potential to contribute to the design of meaningful integrated systems for spatial analysis and decision making (see also, Fischer and Nijkamp 1993). Several of the land use models – especially those which are spatially explicit such as the spatial interaction, the linear programming and many more models – which have been presented in this chapter may be suitable pools of knowledge which can be used to guide the manipulation and analysis of the related spatial data. This is a future research area whose outcomes are difficult to envision and much more difficult to evaluate at present. What is visible, however, is that spatial decision support systems (SDSS) are going to proliferate in the near future given the enabling functions of technological developments, their rapid diffusion, and the various facilities they offer to interested users – researchers and modelers included (see, for example, Densham 1991). It remains to be seen whether these SDSS will be simply technical aids devoid of theoretical content and meaning or whether they will develop into multifaceted and sophisticated platforms for carrying out integrated analyses of land use change grounded on rigorous theories of how land use interacts with its socio-economic and bio-physical determinants in space and time.

4.8. A Summary Evaluation of Models of Land Use Change

The models reviewed in this chapter may not represent the whole universe of models which have been built and/or are actually used for the analysis of land use change. Several models have never been published in books or scientific journals. Others are built and never used however valuable they might have been if adopted. With these observations in mind, this chapter closes with a broad assessment of the models presented in the previous section. This is not an easy task as they exhibit a considerable diversity ranging from comparatively simple and single-sector or single-activity models to integrated models of complex environmental and socio-economic systems. Models are built for a variety of purposes, with differing available human, technical and financial resources, and at historic times when required basic knowledge may not be well developed across all aspects of a model's structure. Hence, it is not possible to judge whether a model is "good" or "bad" – except for extreme cases of technical inefficiencies and caveats – as everything depends on the constellation of circumstances leading to model building and use. From a practical point of view, an elementary test of a model's "worth" may be its adoption and sustained use. But even in this case, one should look for the particular circumstances accounting for this fact to get to meaningful explanation. And, naturally, practical "worth" does not imply theoretical and methodological rigor.

For the above reasons, this section offers a summary account of the main model characteristics along the principal (interrelated) aspects of the models which were covered before: (a) model purpose and object of study, (b) level of aggregation – spatial, sectoral/land use, temporal, (c) dynamics, (d) underlying theory, (e) functional specification – mostly, solution techniques and spatial explicitness, (g) data issues, (f) real world applications. The very important issue of the use of models for policy support is left for discussion in the last chapter.

A. Model purpose and object of study

A major distinction among models can be drawn on the basis of their purpose and the object of their study, two aspects which are closely related. As regards model purpose, models are frequently distinguished broadly into positive and normative. The former concern mostly descriptive, predictive (or forecasting) and impact assessment models. The second refer to prescriptive models which are favored in planning contexts. Early models of land use and its change were basically descriptive or prescriptive (like the very early model of von Thunen). Very soon, however, forecasting models of land use became popular as, together with prescriptive models, they played important functions in planning. In the post-1970s period, impact assessment models became widespread as they facilitated the assessment of land use impacts (usually associated with plan and/or program implementation) and, consequently, the environmental impacts associated with land use change. Explanatory models are the least frequent as explanation is most difficult to ensure in its deep, theoretical sense and not in the narrow, superficial sense of statistical explanation. However, several models claim explanatory status like the spatial interaction models and the economic theory-based models. These are deductive models which postulate an explanatory schema – mostly narrow and accounting for only a few economic determinants of land use change – and then use data to verify the model's theoretical statement. In a sense, they force reality to fit into the model as critiques of urban modeling have so forcefully and cogently demonstrated (D. Lee 1973, Sayer 1979a, 1979b, Cooke 1983).

As regards their object of study, the models reviewed here refer to the analysis of land use change in general but even within this broad area models are distinguished by the particular nature of the spatial entity of reference – urban areas, rural areas, large regions, nations, groups of regions or nations, the world as a whole. A very large number of models, especially those built in the early decades of model building – the 1950s and the 1960s – refer to urban or to large metropolitan areas. Progressively, they have moved from partial to general or integrated approaches (Batty 1976), their post-1970s versions being the integrated land use/transportation models given the close relationships between both individual and collective land use and transportation decisions at least in urbanized settings. Land use models for other types of spatial entities were until recently less frequent and it is surprising that the bulk of modeling in geography and economics did not pay enough attention to the land use modeling needs of other types of areas such as agricultural regions, forest and mixed regions and so on. As Turner *et al.* (1995) note, at these larger scales, "what pass for land use models are typically models of economic sectors predicting changes in production at the country level . . . ... They need to be better linked to outputs of locationally specific land use and land cover" (p. 28). The recent developments in land use change modeling (e.g. IIASA's integrated modeling studies, the CLUE group's models, etc.) tend to meet this last requirement but there is still a long way ahead to producing fully integrated models at various spatial scales and for the whole variety of socio-economic and environmental spatial settings.

B. Level of aggregation – spatial and functional

Early land use models already employed a system of zones to represent the distribution of land use types in the study area. This is perhaps the distinguishing characteristic of these models as a spatial system of reference is essential for modeling land use and its change which has characteristic spatial variability following the variability of its drivers. It is important to emphasize the determining role the particular zonal system exerts on the results of the analysis; namely, the number of zones, the shape of zones and the (implicit, at least) assumption of the homogenous distribution of modeled characteristics within zones. The level of detail of the spatial system of reference is not unrelated to other model characteristics and to the theoretical framework adopted. Different levels of spatial detail are suitable for modeling land use change at different spatial levels and relating this change to its determinants at the particular spatial level. Veldkamp and Fresco (1996b), among others, have specifically explored the effects of spatial scale on modeling land use change. The exploration of the effect of scale on the analysis of land use change is a central concern also in landscape ecology models (see, for example, the contributions in Turner and Gardner 1991).

Recently, there is a growing tendency towards spatially-explicit models in several scientific fields such as geography, urban and regional economics, ecological economics, landscape ecology. These models use the individual land parcel, the farm, or very small patches of landscape as units of analysis. Focusing on the individual land parcel – which in most cases is the decision making unit in the context of land use change, makes possible the use of micro-economic theory as well as micro-level theories from the environmental sciences to support modeling of land use change. Although the desirability of these detailed models is unquestionable, the important issue of spatial aggregation has to be thoroughly explored. The point is that several of the factors which impinge on the individual level of decision making operate at higher levels (see Blaikie and Brookfield 1987, LUCC 1999) and they are assessed by means of models operating at these higher scales. The results of these models have to be downscaled to lower levels which raises the issue of validity of the resulting estimates. The same is true with aggregating individual level model results to higher levels of the spatial and temporal scale.

Functional aggregation refers here to the particular sectors represented as well as to the associated land uses. In this sense, the level of functional aggregation in models of land use change is relatively low as it depends on the land using sectors being modeled, technical (solution) considerations, and, most critically perhaps, on the availability of appropriate, disaggregate sectoral data. The same applies to the level of land use detail employed. As regards the first point, models of a particular use of land – e.g. residential, commercial, agricultural – usually represent only the land use and the related sector of interest as well as those uses of land most closely associated with them. This is the case, for example, in residential land use models where residential and employment areas are targeted, the latter being modeled in differing degrees of detail. Large-scale models employ coarser land use and sectoral classification schemes and the same is true for several simulation models. Progress in GIS, computing equipment, and data dissemination systems may facilitate the use of more disaggregate information. Two points should be born in mind, however. Increasing the level of functional and spatial aggregation in models of land use change may improve the representation of the underlying processes but at the expense of computational efficiency and, from the user's point of view, of the ability to interpret, comprehend and use effectively the models' results. Hence, a trade-off is almost unavoidable between level of disaggregation and ease of use of model results. In addition, improving the level of functional and spatial aggregation should raise the question of whether the adopted theoretical framework and model specification are appropriate to modeling phenomena at other levels of detail than those for which they are fit as well as the issue of cross-scale interactions.

C. Dynamics

Naturally, the study of land use change dictates the explicit treatment of time – the temporal relationships among land use and its various determinants – in the respective models. The models presented in this contribution, however, are static or quasi-static although issues of dynamics have been discussed at times. The design of dynamic models encounters considerable difficulties in several respects: conceptual/theoretical, computational, availability of data. This is not to say that no attempts have been and are being made at building dynamic models. Dynamic versions of spatial interaction models – interpreted as entropy models, of the Lowry model, and EMPIRIC, among others, have been proposed (Batty 1976, Wilson 1974, Batten and Boyce 1986, Bennett and Hordijk 1986). Moreover, several other types of dynamic models of spatial systems have been proposed (Andersson and Kuenne 1986, Miyao 1986, Fischer *et al.* 1996). Integrated land use-transportation models attempt to introduce the feedbacks from changes in transportation network characteristics on land use patterns. However, taking into account even the most essential feedbacks and two-way relationships between land use and its bio-physical and socio-economic determinants represents a significantly complex modeling task. In all cases, a trade-off between model tractability and realism has to be made eventually. A (relatively) simple, analytically tractable model reduces the real world variety to the point that the model may lose its utility as a decision support tool. On the other hand, adding complexity into a dynamic model increases both the computational burden and the ability to comprehend model results.

A compromise between static and dynamic are the quasi-static models which simulate the passage of time usually through the choice of suitable (lagged) variables, functional forms, pooling cross-sectional and time series data, and solution procedures. A common practice is to solve a static model sequentially using a time step of, say one- or two-year time interval, over the specified time horizon. It is, thus, possible to observe the changes which occur over time and to make adjustments (**exogenously** specified or **endogenously** provided) to certain model variables to reflect the changes which occur from one time step to another. It is also common to provide for user-intervention during the sequential solution of a model; the user can change model parameters to simulate changes in particular conditions, foreseeable "surprises", or the implementation of policy measures which cannot be accommodated in the model's structure. An even more advanced form of user intervention is offered by interactive models of land use change which are suited specifically for use in planning and policy making contexts; the user continuously interacts with the model – through appropriate model-user interfaces – modifying parameters, providing requisite information (e.g. on preferences, priorities, etc.) and choosing among model solutions those which most closely match the problem under study.

D. Underlying theory

The issue of theory is perhaps one of the two most important considerations in model building in general, the other one being availability of proper data sets. Although the use of theory (about the system being modeled) in model building seems indispensable, several model builders – especially of integrated economic-environmental models – acknowledge the lack of theory which would assist them in making important choices during model specification. Looking at the several theories of land use change which were presented in Chapter 3, it is surprising that a relatively small number of them have been used to support and guide operational model building. Some theories and models have been conceived simultaneously; hence, the use of the terms "theory" and "model" either interchangeably or to denote a set of conceptual and operational statements about reality (e.g. the urban land market theory and model). But the majority of theories are still without modeling (not necessarily mathematical) counterparts and the reverse is also true. Several models are devoid of theoretical foundations. The reasons for this gap are explored later in this section.

Models of land use change can be distinguished broadly into these which are based on a theory of some kind and those which are not. The first group includes economic theory-based models as well as spatial interaction/entropy models especially when derived from economic principles. In fact, the dominant theoretical frameworks employed are those of (mostly neoclassical) economic theory. The other group comprises all other models which either make no claim to any theory or that adopt an instrumental approach to theory (Sayer 1979a); i.e. they justify the choice of spatial, temporal and functional specification on the basis of certain theoretical statements and assumptions. In fact, there is a gray area between the two extremes of models based on theory and those which do not with models employing some form of theoretical assumptions and considerations to justify various choices related to model specification as well as to interpret model results. At this point, it is important to note that the role of theory is critical not only during model specification but also during interpretation of model results. In this respect, even economic theory is not adequate as land use change is not governed exclusively by economic considerations. At one extreme, that of individual decision making, many other personal and idiosyncratic factors will intervene and shape the final decision about the use of land . At the other extreme, that of global land use change, environmental factors seem to dominate the global patterns of change (although human roles in causing climatic change may prove to be very important in the future).

In all cases, the theoretical underpinnings and the related assumptions of a model bear importantly on its performance and the results it yields. Several of the models presented in this chapter have been criticized for their assumptions which do not always hold as they abstract heavily from the real world. Examples are von Thunen's and Alonso's land rent theories and models with their assumption of a monocentric plane with uniform properties and characteristics in all directions. Linear regression and linear programming models are based on a fundamental assumption of linear relationships between land use change and its determinants, an assumption which frequently is violated in reality. The same is true for the Input-Output models where the production relationships used are linear (as well as constant and inelastic to changes in output, technology and so on). Various modeling efforts have had and are having as their point of departure extant models with the purpose of relaxing some of their restrictive assumptions and, thus, making them more responsive to reality and more useful in applications. Two main concerns about a model's assumptions are emphasized here. The first has to do with interpreting a model's results in the context of its assumptions and the second with the linkage between spatial scale and model assumptions.

With respect to the first issue, the influence of a model's assumptions on the model's output is not always examined. This is particularly obvious in the "new generation" models which exhibit an strong tendency to produce practical modeling tools without questioning some fundamental assumptions made to produce results (e.g. the overlay technique in GIS-based models). From the point of view of a model's use, interpreting a model's results in the context of its assumptions and other limitations (e.g. available data, level of aggregation, etc.) makes the model more reliable and trustworthy than it is the case otherwise as it shows the range of its applicability and makes possible further improvements. With respect to the second issue, a model's assumptions refer, explicitly or implicitly, to a given spatial level (and, more broadly, to particular socio-spatial structures). It is reasonable to posit that, once these assumptions are made, the model's results refer to the respective spatial level. Therefore, when transferring models from one scale to the other (space and time), several of their assumptions may not hold. This may be one reason for invalid model results. For example, the theory of consumer utility maximization makes assumptions about individual consumers who, more or less, act at the lowest level, the individual, of decision making. At this level, the socio-economic determinants of land use relate to micro-behavioral factors and the bio-physical determinants relate similarly to micro-climatic and local environmental factors. These assumptions may be valid at this particular level (although critiques of "rational economic man" contend to the opposite). Applying these same assumptions to macro-models of land use change (e.g. at the urban and regional or even the global level) necessitates aggregation of consumer preferences along assumptions about individual behavior as well as aggregation of several other land use determinants from the micro to macro levels. The question which arises is whether model results obtained in this way are valid when the validity of their assumptions at a different scale than the one to which they are fit is questionable. Veldkamp and Fresco (1996b), among others, have explored this issue which bears importantly on a model's essential usefulness in practical decision making. Needless to say that what has been said about the particular issue of assumptions in relation to spatial scale applies to several other model assumptions whose discussion is beyond the scope of this contribution.

Finally, the gap in the relationship between theories and models is discussed briefly. Of the several explanations for this discrepancy, two are mentioned here. The first, most important perhaps, reason is that the **epistemological** bases of several theories are not congruent with the idea of mathematical, symbolic modeling. More generally, theory and model builders adopt differing epistemological positions. Usually models move in the **positivist epistemological** tradition while theories cover a much broader spectrum of epistemologies. A sharp reflection of these differences is the way land is usually being conceptualized in theory and in models. A related reason is that reality is so complex; land use change comes about under the influence of many macro and micro factors, acting and interacting within varying time frames. Land use change problems are essentially **metaproblems** . Therefore, the reduction and simplification of this real world diversity to serve the purposes of model building is extremely difficult. The result may be either a very crude representation of reality or, on the contrary, a very complicated model structure that is impossible to handle within the bounds of reasonable time and other resources available to answer practical questions. A second reason is that many theories are cast in abstract terms which make their operationalization difficult. Abstract theories are, in part, a reflection of real world complexity and of inability, on the part of the theoretician, to disentangle the complex world and discover order behind the apparent chaos.

E. Functional specification

The models reviewed exhibit a considerable variability in terms of functional forms but some of them are more widely used than others basically because of their relative simplicity and ease of application. Hence, statistical models as well as linear programming models are more common compared to other functionally more sophisticated and involved model forms (e.g. nonlinear statistical and programming models). The most recent trend in land use modeling is the use of **heuristic** modeling techniques linked to GIS for easier manipulation and visual presentation of model input and output. In addition, it seems that, gradually, integrated models of various types and levels of integration are gaining ground as the demand for realism in modeling land use change cannot be met by single-sector or mono-dimensional, in general, models.

Another characteristic of the functional specification of land use change models, from the early to their most recent versions, is their spatial explicitness. All models employ a zonal system – a subdivision of the study area into smaller spatial units – however simple this may be. The advent of GIS and improvements in data processing technology facilitate the design of complete spatially explicit models. In this case, spatial detail may refer even to the level of the individual land parcel. In several countries (e.g. the United States, England, Canada) building block and parcel-level data are increasingly becoming available in GIS format which make possible the very detailed analysis of land use change. However, these developments point to the need for parallel developments in the techniques of spatial data analysis and their application to the particular issue of land use modeling. Spatial statistics and other techniques of spatial analysis have experienced a considerable growth in the last two decades but their widespread application remains to be seen. In the present context, several models of land use change analyze spatial data with conventional statistical techniques which apply to aspatial data; i.e. they do not account for the particular characteristics of spatial data such as spatial autocorrelation. The need for the application of spatial statistical techniques in the context of the analysis of land use change is emphasized, among others in the 1999 LUCC Implementation Plan (LUCC 1999). What is needed, however, is research on the adaptation of many more modeling techniques to the analysis of geo-referenced data.

F. Data issues

The second most important consideration in model building, together with the issue of the underlying theory, is the availability of proper data sets. Of course, the term "proper" needs qualification in each particular situation. The issue of data has been always the "headache" of modelers and it continues to be despite improvements in data collection and dissemination. The reason is that models are now called to meet more demanding tasks in terms of detail and integration. In general, data sets for meaningful analysis of land use change are presently considered those which are geo-referenced. The issues which relate to the availability of proper geo-referenced data to meet the needs of land use change modeling have been the theme of special initiatives on the part of organizations active in the analysis of land use change. In particular, LUCC, a core project/research programme jointly sponsored by IGBP and IHDP, has included among its activities an integrating activity concerning data and classification and intends to integrate the data collection efforts of the IGBP and IHDP DIS (Data Information Systems Offices). DAPLARCH (DAta Plan for LAnd use and land cover change ResearCH) was the main initiative within the LUCC programme whose aim was to define the data needs and convey them to the responsible agencies (in the 1996-1999 period). It organized four workshops to complete the first actions in the direction of addressing the main issues of data needs for LUCC studies. Other related activities were undertaken by research projects funded by the European Union. For information the reader is referred to CLAUDE (1997), LUCC (1997), LUCC (1998) and to the LUCC website (listed in Appendix 1.B).

The main data issues surrounding the comprehensive analysis of land use change are summarized below while for more information the reader is referred to LUCC (1997) and Briassoulis (1997), among others. Four groups of issues can be distinguished along four main data dimensions: spatial dimension, temporal dimension, definitions, and data collection. Chief concerns in all four groups are: data consistency, compatibility, reliability, availability, ease and cost of data collection/finding, and data transferability among spatial levels.

With respect to the *spatial dimension*, the spatial systems of reference used for collecting land use, economic, environmental, and other data frequently suffer from lack of compatibility and consistency in terms of level of spatial resolution, coverage and spatial definition. The spatial units usually follow administrative boundaries which, although appropriate for policy implementation, may not be meaningful for all types of data (e.g. the environmental). For certain variables, the spatial system of reference may not be standard and explicit at all. Moreover, spatial systems of reference change over time, a fact that may account for variations in the value of a variable over time. Making assumptions to aggregate or disaggregate different types of data (i.e. transferring data among spatial scales) in order to use them at the required spatial system of reference may generate inconsistencies among data sets. Compatible and consistent data sets are usually available relatively easily and at reasonable cost for larger scales mostly and for selected (but not all) variables of interest. Geo-referenced (and longitudinal) data exist for recent time periods only. All data problems become more acute when comparing different jurisdictions or when multi-jurisdictional areas are analyzed.

With respect to the *temporal dimension*, the temporal systems of reference (unit of temporal aggregation, spacing, timing and number of observations, etc.) which are appropriate for various types of variables are not always compatible and consistent and, consequently, reliable. Temporal systems of reference may change over time also, a fact seriously affecting their compatibility and consistency especially when aggregating or disaggregating such data. The greater the length of the time period analyzed, the greater the difficulty of ensuring the temporal compatibility, consistency and availability of the required data. This is especially critical for land use data which are collected from various sources such as past records, historical records, past maps, aerial photographs, and satellite data. These issues are more serious for policy data for which the exact timing and length of the policy intervention is critical in the analysis. Availability and cost of obtaining proper longitudinal data depends on the lack of: (a) agency coordination responsible for collecting different categories of data; (b) users of data and/or feedback from users of data; (c) organizational continuity in the data collecting agencies; (d) funds; (e) systematic data collection procedures and rules. In the case of different jurisdictions or study areas composed of segments of different jurisdictions all previous problems are compounded.

With respect to (operational) *definitions* of the concepts employed in models, the compatibility of the definitions of land use types, economic sectors, social variables, etc. are critical aspects of the validity and reliability of the whole analytical effort. Usually, definitions differ among jurisdictions and time periods especially at lower levels of aggregation. Aggregate definitions are impossible to disaggregate for particular spatial entities and time periods. Moreover, definitions change over time giving rise to problems of compatibility and consistency of the data collected. These problems are more serious with historical data. Usually, for aggregately defined variables data are available easily and at reasonable cost.

Finally, *data collection and management* procedures and rules are not always compatible and consistent among agencies in the same or in different countries as well as over time with the exception of internationally standardized data (e.g. population). Lack of systematic data collection procedures affects significantly the *precision* of measurements taken. Incorrect and imprecise collection and recording of field observations, intentional or unintentional omission or concealing of true data, untrained personnel, etc. generate unreliable data and makes their transfer among spatial and temporal scales problematic. Historical data, specifically, should be closely scrutinized. Moreover, the lower the spatial level, the fuzzier and less reliable the available information becomes. Data collected systematically, regularly and with the use of standardized techniques are usually more easily available and less costly than it is the case otherwise.

G. Real world applications

Several of the models presented in this chapter have been used in real world applications which are mentioned in the relevant references. The information available, however, refers mostly to industrialized countries and there is not enough information about model applications in other countries with the exception of models commissioned and/or used by international organizations. Shortage of adequate information makes difficult the assessment of the frequency of model applications over time. It is conjectured, however, that two periods of intense modeling and land use change model use activity can be discerned. The first coincides with the "highs"' of the quantitative revolution and the explosion of modeling activity in the 1960s to 1970s. The second started in the late 1980s and continues to the present. This latter resurgence of modeling activity and use is spurred by changes in perceptions and needs of important environmental and economic problems which are associated, in one way or another, with changes in land use.

Closing this summary account of land use change models, the last issue addressed is: what makes a model of land use change "successful"? Setting aside the philosophical analysis of the meaning of "success", a model's success operationally relates to its acceptance (not necessarily its adoption) as a guide to thinking and acting in real world decision and problem settings. In this perspective, it is suggested that a successful model is one that matches satisfactorily purpose, theory, specification, available data and other resources (such as know-how, expertise, money, time, effort). Frequently, there is a mismatch between any two or more of these factors and models are found unsatisfactory and in need of improvement. The spatial and socio-cultural variety of land use contexts and of the corresponding decision making entities are such that it seems that not many "successful" models exist to date. This is reflected in the research agenda on (regional and global mostly) models proposed in the 1999 LUCC Implementation Plan (LUCC 1999) whose main points include: (a) coping with heterogeneity and scales in regional models, (b) improving the environment-economy linkage, (c) dealing with technological change, (d) representing the regulatory contexts in regional models of land use/cover change (policies and institutions). Hence, the agenda for land use change models is full and awaiting for modelers to respond to the challenge!

Summary and Future Research Directions

5.1. Theories and Models of Land Use Change: The Main Issues

Land is used to meet a multiplicity and variety of human needs and to serve numerous, diverse purposes. When the users of land *decide* to employ its resources towards different purposes, land use change occurs producing both desirable and undesirable impacts. The analysis of land use change is essentially the analysis of the relationship between people and land. Why, when, how, and where does land use change happen? To provide answers to these closely interrelated questions, theories have been advanced and models have been built in the last 200 years. This contribution attempted to provide a panorama of theoretical and modeling approaches to the study of land use change as well as to examine broadly how well they reflect the drivers, processes and implications of this change. This section first summarizes the main issues which pertain to the theories and the models presented in chapters 3 and 4 and, then, focuses on a number of selected broader issues; namely, the importance of scale in the analysis of land use change, the relationship between theories and models, and the use of models in making land use decisions. The whole discussion is set within the context of the broader quest for theories and models of land use change which can offer meaningful and essential guidance in understanding land use change and making decisions for future sustainable uses of land in a variety of real world settings.

5.1.1. Summary of the main issues pertaining to theories and models of land use change

The presentation of theories of land use change made clear one basic point – that each theory focuses on particular aspects of the subject. Each **theorization tradition** specializes more or less on a given spatial and temporal level which determines, to a considerable extent, the nature of and the emphasis placed on the components of the system studied. At lower levels, theorizing is usually more concrete and gives (or aspires to give) more realistic accounts of the agents, context and mechanisms of change. At higher levels, theorizing is more abstract and getting from theory to the real world is not always simple and straightforward. Similarly, each theorization tradition conceptualizes land and land use change differently; some conceptualizations are more realistic while others are abstract and "space-neutral". Some theories specify the land use patterns that result in the process of change while some others give only vague indications. The former are associated usually with a state of equilibrium while the latter make no such assumption considering land use change as a continuous, rarely equilibrating process.

The role of the **theorization tradition** is critical with respect to the identification of the drivers of land use change. Some theories emphasize the economic, some others the socio-political, while some others the environmental determinants of land use change. The recent trend is towards more integrated theoretical schemata although the influence of the "mother discipline" remains strong in most cases. Explanation of land use change and direct reference to the mechanisms of change varies also considerably among theories depending on their **epistemological** basis. This is one of the reasons why, in their present form, very few theories have filtered down to models of land use change.

Lastly, the desirability and possibility of a general theory of land use change is basically an open question. The diversity of real world situations casts doubt on whether a general theory of land use change will be able to provide, besides broad explanatory driving factors, patterns and processes of change, those details which may be critical in explaining land use change in particular contexts and circumstances. At present, it seems that a sensible approach to formulating a general theoretical framework for land use change is to attempt a synthesis of extant theories employing each at the spatio-temporal level of detail for which it is mostly fit.

The models of land use change presented in Chapter 4 constitute a diverse universe in terms of purpose and object of study, level of aggregation, dynamics, underlying theory, functional specification, data requirements, and real world applications. Descriptive, predictive, prescriptive, and impact assessment models of land use change have been built for urban/metropolitan areas, regions, nations, as well as for groups of regions and nations and the globe as a whole. The level of functional and spatial aggregation of the models varies with their purpose and object of study mainly. Models which account for a few (two or three) uses of land have been the norm until now. The level of spatial representation ranges from a few, coarse zones to a great number of detailed zones. Spatially explicit models at fine levels of spatial resolution -- the individual parcel level -- are increasingly being developed as the required computational and technological infrastructure improves continuously and as data at this level are becoming available. The improvement in the functional detail of types and drivers of land use will hopefully follow suit soon.

Although land use change automatically implies the concept of time, dynamic models are rare at a level of spatial and functional resolution which is relevant in most practical situations. The difficulties of building truly dynamic models are not only technical but theoretical as well. Specifying and interpreting the results of a dynamic model requires a corresponding theory of change. But models differ in important respects, in terms of underlying theory. Broadly, there are models which are based on some kind of theory and those which are not. Models based on an explicit theory do not necessarily provide acceptable accounts of change, however. The same is true for models which adopt an **instrumental approach** utilizing simple theoretical statements to justify their assumptions and functional form.

Despite the diversity of model functional forms, the majority of models adopt simple functional forms – statistical or linear programming models – or rely on **heuristic techniques** (simulation). The recent emphasis – which runs in parallel with the progress made in GIS – is towards spatially explicit models which make possible the explicit treatment of the spatial incidence of the causes and the resulting changes of the uses of land. However, a major impediment to the full realization of such models – in addition to the lack of appropriate theories – is the availability of data of a given quality and specifications; more specifically, the demand is for compatible, consistent, reliable, timely, updated, transferable, and low-cost data sets.

Lastly, of the variety of models of land use change presented in this contribution, several have remained at the level of the proposal, some have been calibrated with data from various real world settings, while some others have been used in the context of policy analysis. Whether and to what extent the use of models has improved decision making on land use issues is a question which cannot be answered satisfactorily as important information on the "politics" of model use is not usually reported.

5.1.2. Scale issues in the analysis of land use change

The importance of scale – spatial, temporal, institutional, etc. – in the analysis of land use change has been mentioned on several occasions in this contribution. In fact, the issue of scale is a cross-cutting theme for both theories and models and for all disciplines which study spatial phenomena (at least). This section brings together and summarizes the main issues related to scale in this context starting with a definition of the term.

The usage of the term "scale" as well as its connotations are not uniform among scientists and among disciplines. Gibson *et al.* (1998), in a concise treatment of scaling issues in the Social Sciences, provide a definition of scale as "the spatial, temporal, quantitative or analytical dimensions used by scientists to measure and study objects and processes" (Gibson *et al.* 1998, 8; the definition first appeared in Turner *et al.* 1989; see also, Turner and Gardner 1991, 7). Related to this conceptualization of scale, are the terms level, extent, resolution, grain, hierarchy, absolute and relative scale (Definitions of these terms are given in Appendix 5.A). The literature does not comply always with this definition using it frequently interchangeably with the term "level" although this latter term denotes a subdivision on a scale (Gibson *et al.* 1998).

Based on the above definition, several types of scale can be distinguished. The spatial and the temporal scales are the most widely known and used. However, various other scales are being used, sometimes unknowingly or without properly acknowledging their usage. Buttimer (1998) provides a useful categorization of these scales. "*Administratively-defined* scales, from local through national to global, through which various social and political functions are normally processed; these are spatially circumscribed and representable as a nested hierarchy of domains . . . . Secondly, there are *functionally-defined* scales, such as those within which industrial systems, urban fields of influence and service networks radiate their influences. These are nodally-organized spaces and their dimensions reflect the varying strength of particular functions, production or service-based sectors of the economy. . . . *Perceptually-defined* scales of reach vary among people and places, reflecting culturally-diverse traditions and aspirations" (Buttimer 1998, 18-19). "Reach" denotes access to (and responsibility for) resources, information, and decision making (Buttimer 1998).

The above discussion implies that scale, irrespective of type, is not given always in an absolute sense but it is socio-culturally produced and modified and varies with the phenomenon being studied. The distinction between absolute and relative scale underlines this fact. In the discussion of the *theory of uneven development*, it was mentioned that the capitalist **mode of production** produces different scales as a way of coping with its need for a spatial fix to its internal contradictions. The famous problem of the **ecological fallacy** in the Social Sciences as well as of the more general **modifiable areal unit problem** (MAUP) in geography are among the most salient manifestations of the significance of (spatial) scale. In landscape ecology models, scale is the fist and foremost concern in analyzing land use change. In the present context, the issue of scale is crucial because of its important implications for the analysis of land use change. These are discussed in the following under the headings of: (a) definition and classification of land use types, (b) measurement/assessment of land use change, (c) explanation of land use change, (d) assessment and evaluation of the impacts of land use change, and (e) decision making in the context of land management and land use planning.

Land use classification systems are tied usually to particular spatial scales but they reflect also functionally-defined scales such as the scale of agricultural or industrial organization. At the world level, the FAO distinguishes four or five major land use types. At the level of nations, the number of land use types increases to around ten. At this level, other scales enter the classification system to differentiate further the land use typology – agricultural land is further subdivided according to the type of product (annual, perennial), pastures are distinguished according to ownership status into public or private, etc. At the level of a parcel of land, land use classification becomes very detailed capturing local environmental, socio-cultural, demographic, economic and other details. In general, at lower levels of the spatial scale, land use types are defined along additional scales which reflect modes of economic, social, and institutional organization. The analysis of land use change is essentially performed at the level of detail of the land use classification system adopted which, in its turn, reflects a certain combination of scales. It is, thus, important to examine the extent of agreement between the intended level of analysis and the actual level at which the analysis is eventually performed to provide consistent interpretations of the results obtained.

The first step in any study of land use change concerns the measurement and assessment of land use change involved. This is influenced significantly again by the level of scale at which the measurement is conducted – spatial and temporal scale primarily but also social, economic, institutional and cultural scale. For short time intervals at the level of the globe, no land use change may be discernible while at the level of a field measurable change may be recorded. Longer time intervals reveal significant changes in the uses of land. The case may be, however, that, depending on the socio-political and geographic context, very long time intervals may conceal the true "history" of land use change. Similar observations apply to the level of the spatial scale used. For a given time interval, land use change may not be discernible at higher spatial levels while at lower levels – e.g. at the level of a settlement – very large changes may be measured. The role of the land use classification system is critical in this context also as the measurement of change involves the land use types which this system includes. Hence, regardless of the intended level of analysis, the results obtained and the ensuing description of land use change refer to land use change at the level of the spatial, temporal and socio-economic scale to which the land use classification system refers. Prediction of land use change, similarly, refers to the scale of the land use classification system used.

Explanation of land use change – answering the question of "why" of the "what" measured – is inextricably related to the scale at which the analysis is pitched. Meaningful explanation of land use change (and of its impacts) at a given level of any scale, requires that the relevant explanatory factors are identified at the levels of the particular (and of other relevant, perhaps) scale at which they operate in reality. The critical point is that "the relevant explanatory factors" – with the exception of the bio-physical determinants – are associated with particular individual and collective actors – agents involved directly or indirectly in the process of land use change. Essential explanation focuses on these agents, their differing resource endowments to influence land use change, and their actions through which land use change is effected. For example, to explain land use change and its impacts at the farm or the parcel level, relevant explanatory factors may include soil type, slope, water availability, local climate, and the characteristics of the household or of the head of the family; in a few words, factors which operate at the same level of the spatial and perhaps of the temporal scale. However, other relevant factors which influence land use change at the farm or the parcel level operate at other – higher and/or lower – levels of the spatial and temporal as well as of economic, organizational, and institutional scales such as financial assistance, agricultural policies, product prices, climate change, past types of land use, past policies, etc. Hence, the need to employ a *nested set of scales* for a comprehensive explanation of land use change in concrete settings (Blaikie and Brookfield 1987, Veldkamp and Fresco 1996b). In other words, the drivers of land use change as well as the determinants of the resulting impacts have to be sought at a variety of scales and levels of these scales.

Focusing on just one scale and on a particular level of that scale, leads to biased explanation as either the full set of factors is left unaccounted or a wrong or irrelevant set of determinants is taken into account. Turner *et al.* (1995) discuss this issue in the context of global *vs.* local level studies of environmental change in general. At higher spatial levels, the PAT variables – Population, Affluence, Technology – are found to have important statistical associations with environmental change implying that these may be the underlying drivers of change. However, local level studies do not reveal such associations; on the contrary, the most important associations relate to such factors as institutions, policy, social organization. A related problem arises when the assumptions made for the purposes of analysis at a particular level of a scale are transferred to another level at which they are most probable not to be valid and produce biased explanation. For example, the assumption of homogeneous household preferences (by group) may be valid at the regional level but may be inappropriate and misleading at lower spatial level or in the longer run.

In a similar vein, the impacts of land use change and the degree of severity attached to them are influenced by the scale of the analysis. Land use change at the level of a settlement may have a number of local, direct, short-term impacts – environmental (e.g. air pollution), economic (e.g. changes in land values, tax base), social (e.g. disruption of social cohesion). However, these same changes may produce supralocal, indirect and longer term impacts; i.e. impacts at different levels of the spatial, temporal and social scale. These may include negative environmental impacts on agricultural production in neighboring areas, increased demand for exurban space (caused by increases in urban land values), population and jobs migration. At the regional level, land use changes impact not only on regional climate, economy and social structure in the short run but also on individual land owners (e.g. farmers), or on the larger national level both in the short and in the longer run. Deforestation due to over-exploitation of forest resources or other natural and/or anthropogenic causes impacts on the hydrologic balance, soil quality, regional income, population migration. But it also impacts on local lives; households face a different environment within which they have to make a living, the family structure changes (fewer and perhaps older members, lower reproduction), household income and quality of life changes. The impacts of deforestation may show up also on higher spatial levels as changes in productivity, changes in the balance of trade, regional imbalances. The indirect impacts set in motion by deforestation may also show up in the longer term as further population migration, further land use change, institution of state policies to assist declining regional economies. The list is endless. What is important is that all these impacts are not confined to only one scale or to one level of the spatial, temporal or organizational scales but they diffuse to higher and lower levels and to different scales.

Less visible but of no lesser importance is the buildup of small impacts at lower levels of the spatial and temporal scales to generate impacts on higher levels of these scales; this is the case of *cumulative* impacts which are caused by incremental impacts at the individual level and are felt usually after some period of time at the regional or even the national level. Water abstraction by a single farm may not disturb the water table but a dramatic drop may be caused if all farmers follow this practice. Temporally, cumulative impacts appear as lagged effects of land use change. **Salinization**, **acidification**, **desertification** are caused usually by the buildup of smaller, short run changes in the use of land. Lastly, another class of impacts are the *distant* impacts; those caused in a place by land use changes in another place (or places). The development of exurban space results from changes of land use, among others, in urban areas. Water shortages in a region may be due to excessive water abstraction to serve a fast growing tourist area. The issue of scale is implicated in all these and similar instances and makes imperative the use of "scale-sensitive" analytical approaches.

The evaluation of impacts caused by land use change is influenced also by the scale of analysis. Land use change may have important impacts (beneficial or detrimental in an economic, social or any other sense) at the farm level but it may be of no importance at the level of the rural settlement or the larger region. Moreover, the same change may be important in the short run but it may loose its importance in the longer run. The myriads of land use changes which occur continuously on the earth's surface are evaluated differently at different scales. This is not surprising as evaluation implies an "evaluator". Different interests are involved at each scale with different criteria and priorities attaching, consequently, different importance to the various impacts of land use change. The importance of scale in the evaluation of impacts is closely related to the last, and perhaps the most important, consideration to be discussed, the role of scale in decision making in the context of land management and land use planning.

Land use change results from direct or indirect decisions to alter the current uses of land at the level of an individual land owner, of a regional or national authority, of an international body, or of any other land-related interest. Whatever the form these decisions take, the important point is that they involve decision making units and decision making processes at particular levels of one or more scales. In other words, the analysis of land use change necessarily asks “who decides to change the use of land, where, when, and why”. The factors which are taken into account in the analysis relate to the particular decision making units and processes as well as to those influences which impinge on the range of choices open to the decision making units (see, Blaikie and Brookfield 1987 for a discussion of this topic in the context of land degradation). The assessment of land use change, the assessment and evaluation of the resulting impacts as well as the decision to act are all related to the pertinent decision making units and processes. Land management and land use planning in response to land use change or with the purpose of effecting desirable land use change are tied to decision making units at various scales. The meaningful and useful analysis of land use change in support of these functions should, therefore, pay due attention to the different scales involved and to their relationships.

5.1.3. The relationship between theories and models of land use change

The linkages between theories and models of land use change have not been strong over time in general. Early theories and models tended to be interrelated (e.g. von Thunen’s and Alonso’s theories and models) but the level of abstraction on which they operated and the limited number of real world situations which they could successfully approximate did not lead to any widely known useful operational tools. Urban economic theory has guided model building and has provided theoretical support (the **instrumental approach to theory**) to modeling efforts but the scope of this theory is limited judged in the light of the socio-culturally and geographically variegated nature of land use change. At several instances, theories and models developed independently; hence, neither theories led to models nor models were based on theories. Most frequently, however, especially in contemporary practice, models fall in the gray area mentioned to in Chapter 4; in other words, they attempt to include in their design determinants of land use change revealed by theory – this is the case, for example, of several (although not all) statistical models of land use change which choose the independent (explanatory) variables on the basis of broad theoretical considerations as well as of simulation models which attempt to approximate the working of the urban or regional system being modeled.

Risking a rough comparison of theories and operational models of land use change, it seems that, overall, the latter are more developed than the former. Although this is not the place to delve into the reasons for this gap in development between theories and models, two broad groups of reasons are suggested for further elaboration: substantive and practical. *Substantive reasons* pertain to the difficulties associated with building theories for such complex phenomena as land use change and with trying to disentangle the interactions among their diverse determinants. Important (and socio-politically sensitive) among those difficulties are those associated with identifying the role and contribution of institutional and cultural factors especially at micro-spatial levels where they may be more influential and decisive of the direction and quality of land use change. Moreover, an elaborate and detailed theory will, most of the time, result in a rather involved and contrived model whose use will be questionable. Hence, it is comparatively easier to evade these difficulties by adopting an **instrumental approach to theory**, simplifying the observed relationships, and reducing them to manageable quantitative (or, simple qualitative) mathematical expressions which can be easily understood and manipulated.

Practical reasons which may account for the priority given to models over theory include both the availability of resources of various kinds (money, time, personnel, know-how, effort, administrative support) as well as the demands of the decision making “clientele”. The former are critical and they are usually directed to activities which will bring “visible” and “operational” results within reasonable time; i.e. to activities with high value-for-money. Theories compared to models may have lower value-for-money, at least in western societies. The decision making “clientele”, on the other hand, irrespective of their attitude towards theories, may be placing higher priority to operational and easy-to-use tools in decision making where decisions may have to be made in relatively short time, controversial issues are to be avoided, and the results have to be easily translated into concrete actions. Theories may be rating low in this respect too although one should keep in mind the controversial nature of several models also. However, models seem to sell better than theories as they "say it with numbers" and, thus, appeal to a much broader and diverse decision making "clientele". The modern trend to produce visual versions of model results with the use of GIS are even more appealing as they use "the seductive power of the visual medium " (Longley and Batty 1996, 9) to enhance the market potential of models. Naturally, these are very sketchy explanations of the gap between theories and models and further analysis is needed to give them more concrete form and substance. Whatever, the outcomes of this analysis may be, however, the true explanation should always lie in the synthesis of substantive and practical reasons.

It must be admitted that the linkage between theories and models is not an easy one to achieve. Theory is indispensable in meaningful model building as "the role of theory is to explain experimental findings and to predict new results" (LUCC, 199, 89). But one of the reasons why satisfactory models of land use change have not appeared yet is "the lack of a comprehensive and integrative theory of human-environment relationships. Land use/cover change research is embedded within human-environment relationships. To date, these relationships have proven difficult to conceptualize in a meta-theoretical framework (Blaikie and Brookfield 1987; Turner 1997)" (p.89). However, what is important for the development of models appropriate for concrete spatio-temporal contexts and decision settings is the synthesis of elements from the variety of available theories to help explain the dynamics and interactions between land use and the drivers of its change in the particular situation being studied. LUCC (1999) considers the "thorough understanding and modeling of these complex interactions ... a prerequisite to generate realistic projections of land cover changes ... into the future" (LUCC 1999, 89).

Another difficulty surrounding the linkage between theory and models is that theories usually place heavy demands for operationalization especially when important land use change drivers are qualitative and there is no consensus on how best to express and measure them. Scale considerations complicate the operationalization issue further. Models at the micro-level of the parcel require a theory of how individual and higher level factors combine to produce the land use changes observed as well as how to aggregate micro-level changes into higher level changes in land use patterns. Models which attempt to provide for more realism in the representation of the modeled socio-economic and physical entity may become burdensome and, ultimately, unusable. Hence, trade-offs between theoretical rigor and practical usefulness are inevitable. The nature of the linkage between theories and models is a matter of the trade-offs chosen in particular applications.

The issue of communication between theory and model builders should not be discounted. Disciplinary fragmentation and compartmentalization frequently impede the smooth communication between those developing theories of land use change and those building models. Frequently, these individuals reside in different scientific compartments which make the mutual exchange of ideas, knowledge and tools problematic. True interdisciplinary research, a basic prerequisite for the development of theoretically informed and sound models of land use change, is rarely practiced. In the absence of information about the availability of the variety of theories which deal with the multiple dimensions of land use change, then, model builders rely inevitably on the most widely publicized and easy to access theoretical frameworks. This is the case with economic theory and its wide use in supporting models of land use change at all spatial scales.

5.1.4. The use of theories and models in land use decision making

The above discussion leads to a more essential aspect of the whole enterprise which concerns the contribution of theories and models of land use change to improved, informed, and rational decision making on land use issues. The question is whether and how all this available stock of knowledge and analytical capability can assist in making decisions that improve the quality of human life by averting undesirable and promoting desirable forms of land use change; i.e. that lead to sustainable land use. The issue of theory and model use is particularly important nowadays also as there is a proliferation of spatial decision support systems (SDSS) in many disciplinary quarters spurred by developments in computer technology and GIS. Their stated purpose is to offer support and improve the quality of decisions – on land use issues in the present case. The following discussion examines the use of theories and models in land use decision making focusing on the central concern of the issue – the *users* of theories and models. Two questions are addressed in this respect. First, who are the actual users i.e. who are the people *interested in using* theories and models of land use change when making land use decisions. Second, what kinds of users theories, models, and SDSS assume; i.e.

what is the underlying stereotype of users they purport to serve.

The first question of the actual users of theories and models does not have a unique answer. Interest in using theories and models in making land use decisions, and effective demand thereof for them, depends, among others, on the socio-economic, cultural and institutional context as well as on the decision making tradition on land use issues at particular spatial levels and over time. In other words, it is a matter of whether a "culture" of using science, in general, in decision making in the public or in the private domain exists. The literature on this issue is not very rich but it seems that demand for decision support tools is higher in the developed compared with the rest of the world. Most of the applications of the models examined concern western countries; the applications in other countries reported are usually led by professionals educated in western institutions. In a great number of countries, however, land use decision making follows different patterns and logic which do without the use of *formal* theories and models.

Even in those cases where real world applications are reported, however, the critical question is *why* theories and models are used; i.e. for what purpose. Is there a genuine purpose of improving the quality of decisions, as theory and model developers usually assume? Are they used for merely symbolic reasons? Are they used to justify decisions already made? All answers are possible! The politics of theory and model use in decision and policy making, in general, has received considerable attention in the related literature but its discussion is beyond the scope of this contribution (see, for example, Weiss 1972, D. Lee 1973, Greenberger *et al.* 1976, House and McLeod 1977, Rothenberg-Pack 1978, Walker 1978a, 1978b, 1981, Wildavsky 1979, Mann 1981, Szanton 1981).

Assuming that theory and model users have a genuine interest in getting assistance in making land use decisions, the critical question arises whether they are *capable of using* the suggestions of theories and the results of models. At this point, Machiavelli's advice to the Prince is worth remembering: "A prince not himself wise cannot be well advised" (cited in Szanton 1981). However elaborate, sensitive, carefully designed, and technically perfect theories and models may be, their ultimate contribution to informed decision making depends on how "wise" their users are. "Wisdom" in this case has to be construed in the particular sense of users comprehending the theories and models used, being aware of the range of their applicability, and being able to judge whether they are appropriate for the problem at hand. This means that sensible and correct use of theories and models requires that users are aware of and understand the assumptions underlying theories or models, recognize their possibilities and limitations, and use them for the uses for which they are designed and not as hammers which make everything look like a nail, a panacea for addressing all land use ills. The question that arises, then, is whether theory and model users satisfy these requirements.

The theories and models presented in this work leave no doubt that a certain level of education, not to say of specialized education in several cases, is needed in order to comprehend most of them and, consequently, to use them sensibly and appropriately. The higher the level of sophistication of a theory or model, the greater the demand for scientific (broadly conceived) competence on the part of the user. This is particularly true for the contemporary generation of models which utilize diverse visual and other devices to present their results but provide very little guidance or indications of the limits of the validity of these results. A user unaware of a model's assumptions and caveats is prone to succumb to the seduction of the mode of presentation and rely on the results offered regardless of whether they make sense for the problem at hand. The crucial implication of this discussion is the inevitable fact that the wealth of knowledge and information provided by theories and models of land use change is essentially accessible to an *elite* of educated users. Matters of proprietary information or information withholding aside, the greatest barrier to using any theory or model is general and special education. But is it possible that all interested users of theories and models possess the requisite education? Probably not, especially in the present information age when the production and dissemination of information move at unprecedented speed and a whole set of issues arise with respect to the social and economic consequences of the so-called information technologies (see, for example, Castells 1998). At this conjunction, the question of ethics is unavoidable. Given all the constraints surrounding the proper use of theories and models, the elite who possess the requisite education and skills has an ethical obligation to guide the users of theories and models, i.e. the actual decision makers, to making wise use of them in the sense already discussed previously. It rests, therefore, with those individuals who "control" the available information to assure its sensible and appropriate use.

Turning now to the stereotype of the user underlying theories, models, and the fashionable spatial decision support systems (SDSS), it seems that, in most cases, their developers have evaded addressing the tough question of the real model users and their needs. What they assume, instead, implicitly at least, are various types of users such as "intelligent individuals", "educated specialists", and the like. Or, they rely frequently on a vague and abstract notion of a "policy maker" or "decision maker" who usually asks questions the theory or the model is designed to answer! Overall, the underlying stereotype of the user agrees, not unjustifiably of course, with the *elite* of educated users referenced above. The various SDSS being developed recently include in their stated purposes the intent to provide easy access and "user friendliness" to a variety of users. However, several reservations can be expressed in this respect which have nothing to do with the good intentions of their developers.

The term SDSS is used rather vaguely in most cases and without adequate explanation of its content. In fact, this is a term which means different things to different people in different contexts. It is noted that of the variety of available SDSS, the present discussion refers to those related to land use decision support (as opposed to those designed for facility location or network design support). The question is basically what is the meaning of the terms "spatial", "decision", and "support" in the context of a given SDSS, for what kinds of users and related needs it is designed, and how it is used. Any SDSS will necessarily be designed to answer certain types of questions and to serve certain purposes (e.g. description, prediction, prescription, scenario and impact analysis). It will refer to a certain range of spatial and temporal resolution. It will adopt some kind of theory about reality; i.e. particular views of land, land use, land use change, the users of the land, the drivers and the impacts of land use change. It will utilize some kind of modeling device – either a formal or a **heuristic** model – to provide answers to questions. It will utilize particular types of data (of varying degrees of quality and accuracy) as input to the calculations it performs. It may also require input from the user if it is used in an interactive mode – a common trend recently to render SDSS more sensitive to the actual decision environment (e.g. preferences, priorities, constraints). It will utilize some types of presentation aides to communicate the answers to the questions asked. These are critical aspects which should be made clear to users to help them decide whether the SDSS can address adequately and consistently their particular decision support needs. Evidently, intelligent use of a SDSS is not a matter of easy, low-cost access and user friendliness but of the real ability of the user to comprehend it. The availability of high-tech decision support aides makes even more timely the demand for "wise princes".

5.2. Future Research Directions: Theoretical, Methodological and Practical Needs

Future research needs on the subject of theories and models of land use change have been mentioned or indicated on several occasions in the previous chapters. This last section outlines more general, "higher level" research needs which address a central research requirement; that of *integrating* the various pieces of knowledge and producing coherent theories and methodologies to guide future land use change towards sustainable paths. Integration is needed at the theoretical, the methodological, and the practical levels. At the theoretical level, despite efforts to bring together the diverse and interacting drivers of land use change, there is still a long way ahead in terms of true integration of theoretical analyses at various spatial levels and within particular time frames. At the regional and higher levels, theory has not addressed adequately yet the close relationships between the dynamics of urban and regional development and the demands placed on ex-urban space as well as the uses of land within and between regions. For example, land use change (and its environmental and socio-economic implications) in rural areas cannot be explained solely by looking at these areas in isolation but by embedding them in the broader framework of urban-rural or regional, in general, dynamics. Demand for agricultural, industrial, recreation and other types of land use depends on the food, mobility, recreation and other needs of urban populations but also, and perhaps more critically, on the demands of capital (production activities). An important need for integration arises exactly at the interface between theories of production and theories of consumption in all three **theorization traditions** . More specifically, theories which concentrate on the patterns and dynamics of the location of firms need to be tightly coupled to theories which study the land use patterns of residential, commercial, recreational and other extensive land using activities. At lower levels, where the actual land users reside, make decisions and implement them, theory needs to integrate the psychological, socio-economic (e.g. land tenure and ownership, income, family structure), and other aspects of individual decision making with the institutional, cultural (value systems), economic and other higher level forces framing and directing individual as well as collective land use decision making.

At the methodological level, similar developments are expected. The trend is definitely towards integrated modeling but integration is insufficient in several respects. The urban and the exurban dimensions have not merged yet well in modeling. Regional and higher level models mostly ignore the representation of the workings of the urban components of a region. The same applies to urban models which operate as if the surrounding territory in uniform, undifferentiated and unrelated with what goes on within the urban region. It is important to note that integrated models with essential explanatory power are contingent upon the development of proper theoretical structures. Another significant development in modeling land use change is the more realistic representation of land use types, a trend already begun but in need of wider adoption and application. IIASA's modeling projects integrating FAO's land evaluation methodology (the AEZ methodology) with land use analysis is an indication of a more general research direction towards integration. Progress in remote sensing technology is expected also to assist in injecting more detail in the frequently used coarse land use representations (e.g. developed/undeveloped) which will make them more useful to a broader array of land use decisions.

At the practical level, the main issue which future research should continue to address is perhaps the availability of appropriate data sets for integrated analysis of land use change. Data are provided at various levels and degrees of spatial and temporal resolution and from various sources partly reflecting the traditions and needs of particular disciplines (e.g. environmental sciences, demography, economics) and partly reflecting technical, technological and organizational constraints. Standardization of the various dimensions of data is a much needed development which will contribute to the consistent analysis of land use change across space and over time. Another, equally important, practical research theme is the monitoring and analysis of model adoption and use. Although applications and use of several models in actual decision contexts have been reported, for the majority of models not enough is known as regards the level and quality of their utilization except for isolated cases of particular models and specific issues. This research direction is not meant to satisfy academic curiosity but to analyze experience with model use and employ it to the design of models and perhaps to the education of the rich diversity of model users.

APPENDICES

APPENDIX 1.A

ALTERNATIVE LAND USE-COVER CLASSIFICATION SYSTEMS

A. AN INITIAL APPROACH TO AN INTERNATIONAL FRAMEWORK FOR CLASIFICATION OF LAND USES

LEVEL I Degree of modification of the ecosystem	**LEVEL II** Functional land use	**LEVEL III** Biophysical land use
Uses based on natural ecosystem	Not used	
	Conservation • Total conservation • Partial conservation	
	Collection	Plant products Animal products Plant and animal products
Uses based on mixed natural and managed ecosystems	Agrosilvopastoralism	Forest products, cropping, livestock, and aquaculture on the same holding
Uses based on managed ecosystems	Production forestry	Management of natural forests Management of planted forests
	Livestock production	Nomadic grazing Extensive grazing Intensive livestock production Confined livestock production
	Arable cropping	Shifting cultivation Sedentary cultivation, temporary cropping Sedentary cultivation, permanent cropping Wetland cultivation Covered crop production
	Mixed livestock and crop production	
	Fisheries production	Fishing Aquaculture
Settlement and related uses	Recreation	
	Mineral extraction	Mining Quarrying
	Settlement	Residential Commercial Industrial Infrastructure
	Uses restricted by security	

Source: FAO (1995)

B. GEOLOGICAL SURVEY LAND USE AND LAND COVER CLASSIFICATION SYSTEM FOR USE WITH REMOTE SENSOR DATA

	LEVEL I	LEVEL II
1	Urban or built up land	Residential Commercial and services Transportation, communications, and utilities Industrial and commercial complexes Mixed urban or built-up land Other urban or built-up land
2	Agricultural land	Cropland and pasture Orchards, groves, vineyards, nurseries, and ornamental horticultural areas Confined feeding operations Other agricultural land
3	Rangeland	Herbaceous rangeland Shrub-Bushland rangeland Mixed rangeland
4	Forest land	Deciduous forest land Evergreen forest land Mixed forest land
5	Water	Streams and canals Lakes Reservoirs Bays and estuaries
6	Wetland	Forest wetland Nonforested wetlands
7	Barren land	Dry salt flats Beaches Sandy areas other than beaches Bare exposed rock Strip mines, quarries, and gravel pits Transitional areas Mixed barren land
8	Tundra	Shrub and bush tundra Herbaceous tundra Bare ground tundra Wet tundra Mixed tundra
9	Perennial snow and ice	Perennial snowfields Glaciers

Source: Kleckner (1981)

C. CLASSIFICATION FOR LAND USE STATISTICS: EUROSTAT REMOTE SENSING PROGRAMME (VERSION 1.1)

LEVEL I		LEVEL II		LEVEL III		LEVEL IV	
A	MAN-MADE AREAS	A1	RESIDENTIAL AREAS PUBLIC SERVICES	A11	RESIDENTIAL AREAS	A111	Continuous and dense residential areas
						A112	Continuous residential areas of moderate density
						A113	Discontinuous residential areas of moderate density
						A114	Isolated residential areas
						A115	Collective residential areas
				A12	PUBLIC SERVICES, LOCAL AUTHORITIES	A120	Public services, local authorities
		A2	INDUSTRIAL OR COMMERCIAL ACTIVITIES	A20	INDUSTRIAL OR COMMERCIAL ACTIVITIES	A201	Heavy industry
						A202	Manufacturing industrial activities
						A203	Commercial and financial activities and services
						A204	Agricultural holdings
		A3	TECHNICAL AND TRANSPORT INFRASTRUCTURES	A31	TECHNICAL INFRASTRUCTURES	A311	Technical networks, protective structures
						A312	Water and waste treatment
				A32	TRANSPORT	A321	Road transport
						A322	Rail networks
						A323	Airports and aerodromes
						A324	River and maritime transport
		A4	EXTRACTIVE INDUSTRIES, BUILDING SITES TIPS AND WASTELAND	A41	EXTRACTIVE INDUSTRIES,	A410	Extractive industries
				A42	BUILDING SITES TIPS AND WASTELAND	A421	Building sites
						A422	Tips
						A423	Wasteland
		A5	LAND DEVELOPED FOR RECREATIONAL PURPOSES	A50	LAND DEVELOPED FOR RECREATIONAL PURPOSES	A501	Cultural sites
						A502	Sport facilities
						A503	Green or leisure areas
B	UTILIZED AGRICULTURAL AREAS	B1	TILLED AND FALLOW LAND	B11	CEREALS	B110	Cereals
				B12	ROOT AND INDUSTRIAL CROPS	B121	Root crops
						B122	Non-permanent industrial crops
				B13	VEGETABLES AND FLOWERS	B131	Dry pulses
						B132	Fresh vegetables
						B133	Floriculture
				B14	FALLOW LAND incl. GREEN MANURE	B140	Fallow land including green manure

(CONTINUED)

LEVEL I		LEVEL II		LEVEL III		LEVEL IV	
		B2	AREAS UNDER GRASS USED FOR AGRICULTURAL PURPOSES	B21	TEMPORARY AND ARTIFICIAL GRAZING	B210	Temporary and artificial grazing
				B22	PERMANENT PASTURES AND GRAZING	B220	Permanent pastures and grazing
				B23	ROUGH GRAZING	B230	Rough grazings
		B3	PERMANENT CROPS	B31	FRUIT TREES AND BERRIES	B310	Fruit trees and berries
				B32	CITRUS FRUITS	B320	Citrus fruits
				B33	OLIVE TREES	B330	Olive trees
				B34	VINES	B340	VINES
				B35	NURSERIES	B350	Nurseries
				B36	PERMANENT INDUSTRIAL CROPS	B360	Permanent industrial crops
C	FORESTS	C1	WOODED FOREST AREAS	C11	DECIDUOUS TREES	C110	Deciduous trees
				C12	SCLEROPHYLLOUS TREES	C120	Scerophyllous trees
				C13	CONIFERS	C130	Conifers
				C14	INTENSIVELY MANAGED PLANTATIONS	C140	Intensively managed plantations
		C2	NON-WOODED FOREST AREAS	C21	CLEAR-CUT ZONES	C210	Clear-cut zones
				C22	OTHER UNPRODUCTIVE FORESTRY AREAS	C220	Other unproductive forestry areas
D	BUSH OR HERBACEOUS AREAS	D1	BUSHES	D10	BUSHES	D101	Bushy areas in temperate, mountainous and arctic regions
						D102	Xerophyte bushes
				D20	HERBACEOUS VEGETATION	D201	Grassland in temperate, mountainous and arctic regions
						D202	Steppes and dry meadows

(CONTINUED)

LEVEL I		LEVEL II		LEVEL III		LEVEL IV	
E	SURFACES WITH LITTLE OR NO VEGETATION	E0	SURFACES WITH LITTLE OR NO VEGETATION	E01	BARE SOILS	E011	Rocks and scree
						E012	Dunes and beaches
				E02	GLACIERS AND ETERNAL SNOW	E020	Glaciers and eternal snow
				E03	BURNT AREAS	E30	Burnt areas
F	WET SURFACES AND SURFACES UNDER WATER	F1	WET SURFACES	F10	WET SURFACES	F101	Bogs and marshes
						F102	Moors
						F103	Other wet areas
		F2	INLAND WATERS	F20	INLAND WATERS	F201	Inland water courses and bodies of water
						F202	Ponds for fish
		F3	COASTAL WATERS	F30	COASTAL WATERS	F301	Estuaries, lagoons
						F302	Bodies of water with fish or shellfish

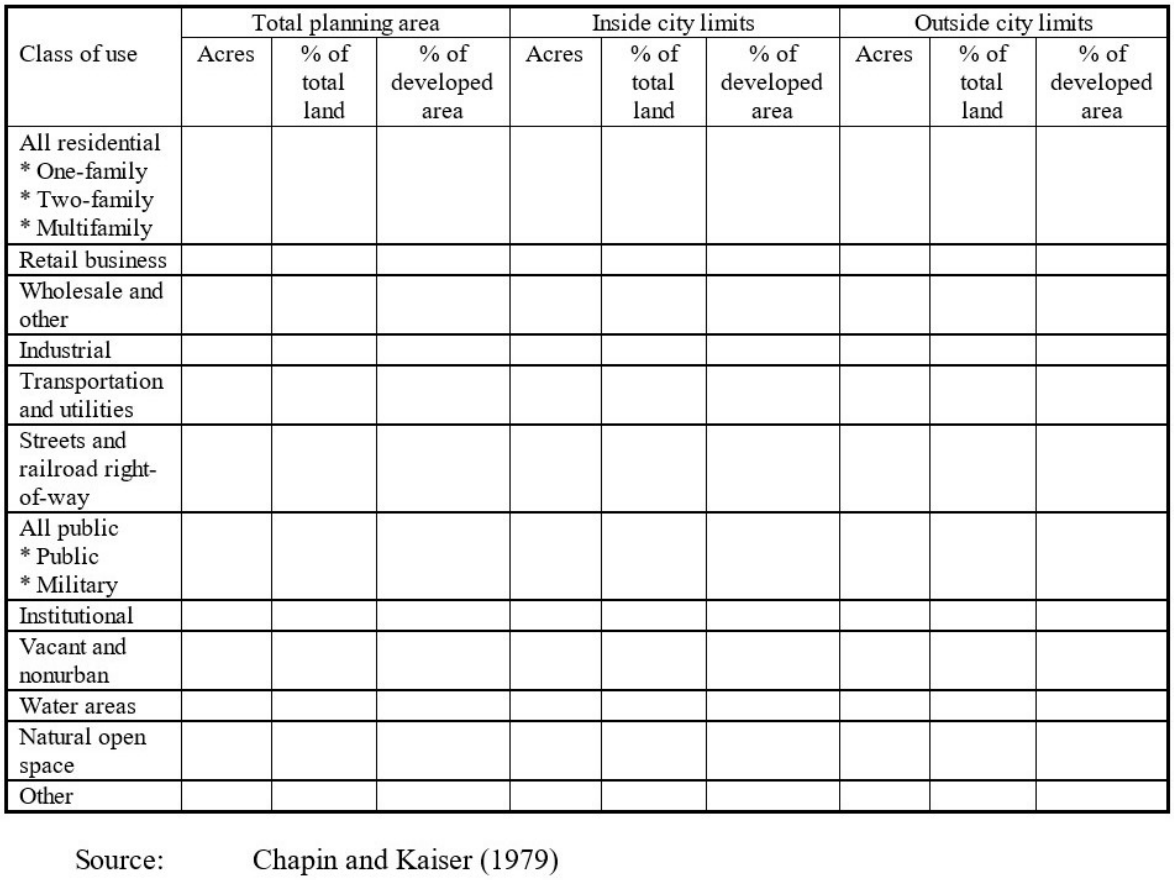
Source: Beale (1997)

D. ILLUSTRATIVE MAJOR URBAN LAND USE CATEGORIES FOR GENERALIZED AND DETAILED LAND USE MAP PRESENTATIONS

Generalized presentation by ground areas	
Residence	
• Low density	yellow
• Medium density	orange
• High density	brown
Retail business	red
Transportation, utilities, communication –	ultramarine
Industrial and related uses	indigo blue
Wholesale and related uses	purple
Public buildings and open spaces	green
Institutional buildings and areas	grey
Vacant or nonurban use	uncolored
Detailed presentations by building space use and open air use	
Residence	
• Low density	yellow
• Medium density	orange
• High density	brown
Retail business	red
• Local business uses	red
• Central business uses	red
• Regional shopping centers	red
• Highway service uses	red
Transportation, utilities, communications –	ultramarine
Industrial and related uses	indigo blue
• Extensive	indigo blue
• Intermediate	indigo blue
• Intensive	indigo blue
Wholesale and related uses	purple
Public buildings and open spaces	green
Institutional buildings and areas	grey
Vacant or nonurban use	uncolored

Source: Chapin and Kaiser (1979)

E. ILLUSTRATIVE SUMMARY OF LAND USES FOR AN URBAN AREA OF 100,000



Class of use	Total planning area			Inside city limits			Outside city limits		
	Acres	% of total land	% of developed area	Acres	% of total land	% of developed area	Acres	% of total land	% of developed area
All residential * One-family * Two-family * Multifamily									
Retail business									
Wholesale and other									
Industrial									
Transportation and utilities									
Streets and railroad right-of-way									
All public * Public * Military									
Institutional									
Vacant and nonurban									
Water areas									
Natural open space									
Other									

Source: Chapin and Kaiser (1979)

Source: Chapin and Kaiser (1979)

F. ILLUSTRATIVE SUMMARY FOR LAND USE IN SELECTED ACTIVITIES AND SUBCATEGORIES FOR A METROPOLITAN REGION

	Region as a whole		Central city		Suburban City A, Etc.		Sector A		Suburban City B, Etc.	
Activity and subcategory	Acres	% of developed area	Acres	% of developed area	Acres	% of developed area	Acres	% of developed area	Acres	% of developed area
Extraction										
Processing										
* Industry group A										
* Industry group B										
etc.										
Transportation										
* Railroads										
* Highways and streets										
* Electric, gas, sanitation										
etc.										
Distribution										
* wholesale										
* retail										
Services										
* Firm headqus										
* Finance, insurance, real estate										
* Amusements, hotels, etc.										
* Personal										
etc.										
Human development										
* Education										
* Cultural facilit.										
* Recreation										
* Protective and misc. gov't services										
* Welfare organiz.										
etc.										
Residential										
* Density Group A										
* Density Group B										
etc.										
No activity										
* Open space										
* Other										

Source: Chapin and Kaiser (1979)

Source: Chapin and Kaiser (1979)

APPENDIX 1.B (websites)

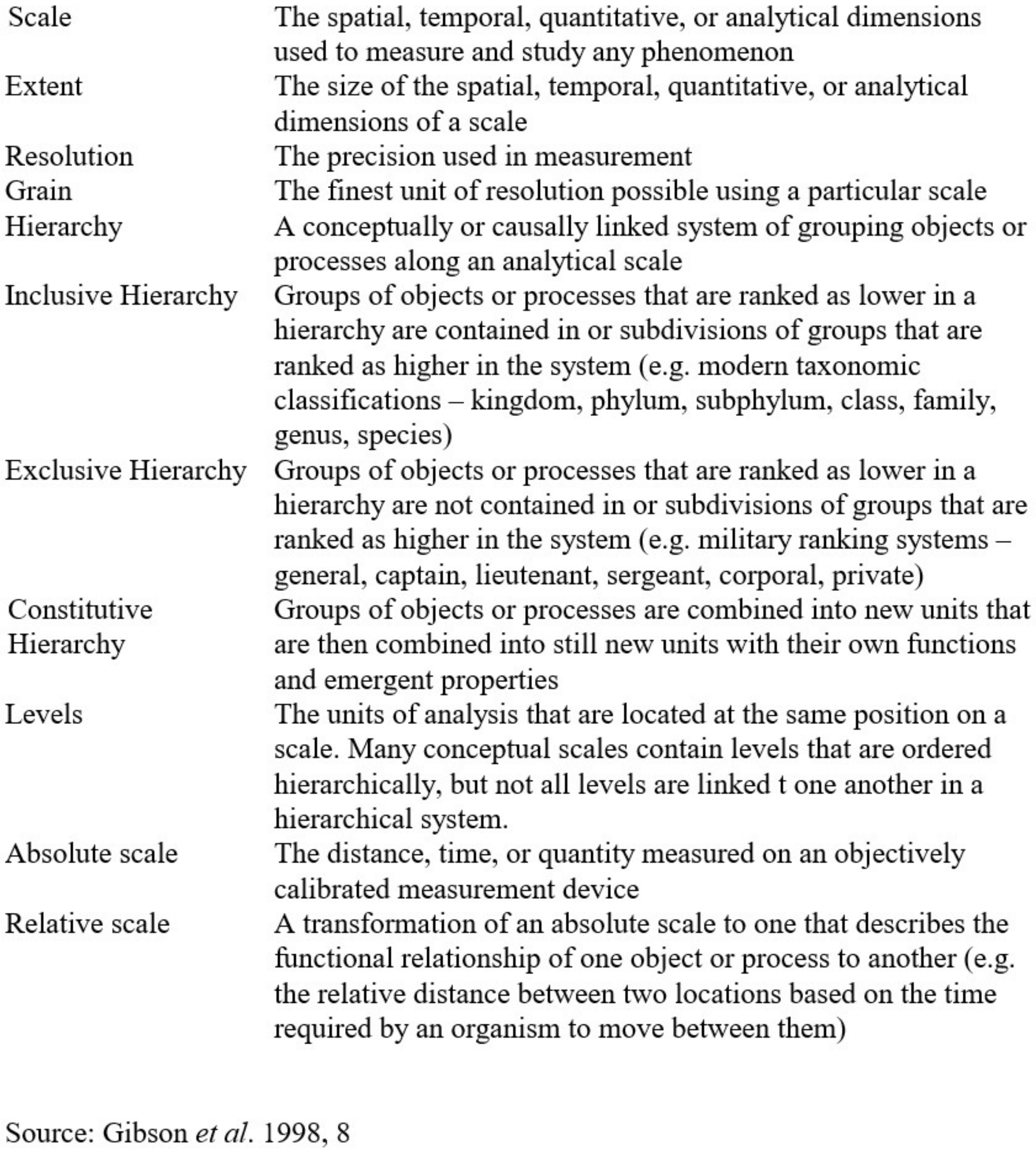
WEBSITES OF ORGANIZATIONS, RESEARCH INITIATIVES,

DATA AND INFORMATION CENTERS RELATED TO THE ANALYSIS OF LAND USE CHANGE AND LAND USE

A. INTERNATIONAL LEVEL BODIES	
FAO	http:/www.fao.org
FAOSTAT	http://www.fao.org/statistics/en/
GRID	https://www.unenvironment.org/about-un-environment/why-does-un-environment-matter/global-resource-information-database-grid
IIASA	www.iiasa.ac.at
ISRIC	https://www.isric.org/
IUCN	http://www.iucn.org/
LUCC	http://www.ihdp.unu.edu/organizations/?id=88
UN-ECE	http://www.unece.org/welcome.html
UNEP	http://www.unep.org/
B. NATIONAL LEVEL BODIES	
BLM	http://www.blm.gov
CLAUDE	https://cordis.europa.eu/project/rcn/39991/factsheet/en
CLUE	http://www.ivm.vu.nl/en/Organisation/departments/spatial-analysis-decision-support/Clue/
CLUSTERS	http://www.clusters20.eu/
CORDIS	http://www.cordis.lu/
CORINE	https://www.eea.europa.eu/publications/COR0-landcover
ECOMONT	https://www.uibk.ac.at/carbomont/ecomont/
EEA	http://www.eea.dk:80/
EIONET	https://www.eionet.europa.eu/
ENVIRONMENT CANADA	http://www.ec.gc.ca/
EUROSTAT	https://ec.europa.eu/eurostat/home?
FLIERS	https://cordis.europa.eu/project/rcn/33988/factsheet/en
GECHS	http://www.gechs.org
GOFC	https://gofcgold.org/
JRC	https://ec.europa.eu/jrc/en
MARS	https://ec.europa.eu/jrc/en/mars
MEDALUS	https://op.europa.eu/en/publication-detail/-/publication/73f845d2-9043-48bb-837e-61df0f34a642
TERI	https://www.teriin.org/
USGS	http://www.usgs.gov/
C. NON-GOVERNMENTAL AGENCIES, ORGANIZATIONS, INITIATIVES	
ECNC	http://www.ecnc.nl/
EFI	http://www.efi.int/
IGBP	http://www.igbp.net/
IHDP	http://www.ihdp.unu.edu/
IIASA	http://www.iiasa.ac.at/
LUC	http://pure.iiasa.ac.at/id/eprint/5210/

APPENDIX 5.A

DEFINITIONS OF KEY TERMS RELATED TO THE CONCEPT OF SCALE



Scale	The spatial, temporal, quantitative, or analytical dimensions used to measure and study any phenomenon
Extent	The size of the spatial, temporal, quantitative, or analytical dimensions of a scale
Resolution	The precision used in measurement
Grain	The finest unit of resolution possible using a particular scale
Hierarchy	A conceptually or causally linked system of grouping objects or processes along an analytical scale
Inclusive Hierarchy	Groups of objects or processes that are ranked as lower in a hierarchy are contained in or subdivisions of groups that are ranked as higher in the system (e.g. modern taxonomic classifications – kingdom, phylum, subphylum, class, family, genus, species)
Exclusive Hierarchy	Groups of objects or processes that are ranked as lower in a hierarchy are not contained in or subdivisions of groups that are ranked as higher in the system (e.g. military ranking systems – general, captain, lieutenant, sergeant, corporal, private)
Constitutive Hierarchy	Groups of objects or processes are combined into new units that are then combined into still new units with their own functions and emergent properties
Levels	The units of analysis that are located at the same position on a scale. Many conceptual scales contain levels that are ordered hierarchically, but not all levels are linked t one another in a hierarchical system.
Absolute scale	The distance, time, or quantity measured on an objectively calibrated measurement device
Relative scale	A transformation of an absolute scale to one that describes the functional relationship of one object or process to another (e.g. the relative distance between two locations based on the time required by an organism to move between them)

Source: Gibson *et al*. 1998, 8

Source: Gibson *et al.* 1998, 8

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ACRONYMS

Acronym	Definition
AEZ	Agro-Ecological Zoning
BLM	Bureau of Land Management (United States of America)
CATLAS	Chicago Area Transportation Land Allocation Study
CBD	Central Business District
CCA	Canonical Correlation Analysis
CLAUDE	Coordinating Land Use/Land Cover Analyses and Data in Europe
CLUE	Conversion of Land Use and its Effects
CLUSTERS	Classification for Land Use Statistics: Eurostat Remote Sensing Programme
CORINE	Coordinated Information on the European Environment
ECNC	European Centre for Nature Conservation
EFI	European Forest Institute
EIONET	European Environmental Information and Observation Network
ENRICH	European Network for Research in Global Change Network
EU	European Union
EUROSTAT	Statistical Office of the European Communities
FAO	Food and Agriculture Organization
FIRS	Forest Information from Remote Sensing
FLIERS	Fuzzy Land Information from Environmental Remote Sensing project
GCOS	Global Climate Observing System
GCTE	Global Change and Terrestrial Ecosystems
GEMS	Global Environmental Monitoring System
GIS	Geographic Information System
GOFC	Global Observation of Forest Cover
GOOS	Global Ocean Observing System
GRID	Global Resource Information Database
GTOS	Global Terrestrial Observation System
HUDS	Harvard Urban Development Simulation (model)
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme
IIASA	International Institute for Applied Systems Analysis
IMPEL	Integrated Model to Predict European Land Use
I-0	Input-Output (Analysis)
ISRIC	International Soil Reference and Information Centre
ITLUP	Integrated Transportation Land Use Package
IUCN	International Union for the Conservation of Nature
JRC	Joint Research Center (of the European Commission)
LANES	Land Cover/Land Use Earth Observation Data Systems
LUC	Modeling Land Use and Land Cover Changes in Europe and Northern Asia
LUCC	Land Use and Cover Change
MARS	Monitoring Agriculture by Remote Sensing
MEDALUS	Mediterranean Desertification and Land Use
NBER	National Bureau of Economic Research
NUTS	Nomenclature of Territorial Units for Statistics
PDE	Population-Development-Environment
PLUM	Projective Land Use Model
SIC	Standard Industrial Classification
SPOT	Systeme Pour L' Observation de la Terre
TERI	Terrestrial Ecosystem Research Initiative
TOMM	Time Oriented Metropolitan Model
TREES	Tropical Ecosystem Environment Observation by Satellite

Acronym	**Definition**
UI	Urban Institute (model)
UNCCC	United Nations Convention for Climate Change
UNCCD	United Nations Convention to Combat Desertification
UN ECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Service
UTP	Urban Transportation Planning

GLOSSARY TERMS

Acidification
The process of change in the chemical characteristic – acidity – of an environmental medium such as water, soils, ecosystems. It is characterized by a lowering of the pH (the measure of acidity) from its 'normal' basic (alkaline) values of around 5.5 to 7 towards lower values characterized as acid. This process has both natural and human causes although the later are help accountant for the speed with which acidification proceeds in the post-industrial era. Acidification concerns mostly water bodies (lakes and rivers), soils, and forest ecosystems.

Activity allocation model
A mathematical model used to determine where activities will be located in a study area. Usually, the area is subdivided into zones and the model assigns activities to zones. Activities are measured variously; e.g. population, employment, residences, retail and/or office floorspace.

Adaptation
An ecological concept which has been transferred to sociology in the context of human ecologic theories. It denotes the adaptation of the physical environment to the characteristics of the social groups that occupy an area or the opposite. Usually, adaptation is a mutual process between society and the environment.

Annulus The ringlike area included between two concentric circles

Appropriated carrying capacity
The biophysical resource flows and waste assimilation capacity appropriated per unit time from global totals by a defined economy or population (Rees 1996).

Behaviorism/behaviorist
A school of thought in psychology which appeared in the 1920s and 1930s. The American psychologist John B. Watson is one of its well-known representatives. It emphasizes objective, observable, and measurable characteristics and excludes emotions, feelings, experience. Organisms are considered to respond to stimuli from the external environment and from their biological functions. In the 1940s and 1950s, the new behaviorism relaxed the deterministic stance of the previous period and attempted to build an empirically-grounded theory of adaptive behavior which allowed room for intervening psychical factors, perception and verbal (nonmeasurable) expressions. B.F. Skinner is among the well-known newer behavioral psychologists. (Adapted from *Encyclopedia Brittanica*).

Bioclimatic zones
An area on earth's surface characterized by particular combinations of climate and biotic communities. Designations of bioclimatic zones include humid, temperate, arid, etc.

Biodiversity
A collective term used to denote the variety and variability in nature. It encompasses three basic levels of organization in living systems: the genetic, species, and ecosystem levels.

Biome
The largest land community unit which it is convenient to recognize. They are produced from the interaction of regional climates with regional biota and the substrate. In a given biome the *life form* of the climax climatic vegetation is uniform. E.g. the climax vegetation of the grassland biome is the grass although the species of dominant grasses may vary in different parts of the biome. The life form of the vegetation provides a sound basis for a natural ecological classification since it reflects the major features of the climate and determines the structural nature of the habitat for animals. (Adapted from E.P. Odum 1971, *Fundamentals of Ecology*).

Carrying capacity
The maximum number of individuals of a species than an area can support. Alternatively, the maximum persistently supportable load of an area (Catton 1986 cited in Rees 1996). The carrying capacity of an area is usually constrained by *limiting factors* – such as water, nutrients, etc. Besides the environmental, the social and the economic dimensions are important in determining the carrying capacity of an area.

Climax community
The final or most stable animal or plant community in a succession series; the final outcome of a slow, orderly progression of changes in communities in an area over time. A climax community is capable of maintaining itself indefinitely as long as the environment is not disturbed by, say, the introduction of some other species or some extreme geological or climate event.

Cobb-Douglas functional forms
A particular mathematical form of a production function of an economic producing unit; i.e. of the relationship between the level of production Q and the amounts of inputs or factors of production – capital K and labor L. A simple Cobb-Douglas function is given by:

$$Q = AK^{\alpha}L^{\beta}$$

where, A, a, and b are econometrically estimated constants. Coefficients a and b have particular relationships which reflect whether the *returns to scale* of production are constant,increasing or decreasing. If the sum of a and b is constant, this means the production function reflects constant returns to scale; i.e. if all inputs are expanded in the same proportion, output expands in the same proportion.

Cohort-survival population projection technique
A population projection technique which takes into account the age-sex distribution of the population as well as the influence of mortality, fertility, natality, and migration. An *age-sex cohort* is a group of individuals of the same sex within the same age range; e.g. 5-9 years old men. The population in each age-sex cohort is projected separately as each age-sex cohort is associated with different birth, death and migration rates. Female cohorts in the range 15-49 years old are also subject to different fertility rates within each age cohort. The projected populations in each cohort at the end of the projection period are added to obtain the total projected population of the study area.

Competition
A term borrowed from Biology and used in Human Ecology to denote the interaction which occurs when individuals of a single species or individuals of more than one species attempt to acquire and use the same resources – such as space.

Cross-sectional
Referring to the same point in time. Cross-sectional analysis is analysis using data from the same point in time (static analysis).

Deductive/Deductivism
A process of thought or reasoning which moves from the general to the specific

Dependent variables
The variables in a relationships whose values depend on the values of other (the independent) variables.

Desertification
The process of land degradation which leads to a drastic reduction of land productivity. Land is rendered unsuitable for any productive activity. It is prevalent in arid and semi-arid areas. Its causes are both natural (dry climate, low rainfall, water shortage) as well as anthropogenic (overgrazing, deforestation, fires, intensive cultivation).

Diffusion theory/diffusion theoretic
Theories which study the spread of a phenomenon over space and time. Traditional subject of research in Cultural Geography. Hagerstrand's (a Swedish geographer) landmark 1954 study "Innovation Diffusion as a Spatial Process" set the broad theoretical structure and initiated a tradition for the study of diffusion processes .

Dominance
A term borrowed from Biology and used in Human Ecology to denote a social structure in which a ranking exists with each animal dominant over those below it and submissive to those above it in the hierarchy.

Ecological fallacy

The problem of inferring characteristics of individuals from aggregate data referring to a population; equivalently, the problem of inferring individual household characteristics using areal unit (spatial) data (Johnston *et al.* 1994; Wrigley *et al.* 1996).

Economic base model and theory

An economic theory and model which analyzes urban and regional growth assuming a division of the economy into *basic* and *non-basic* (or *local* or *population-serving* sectors. Basic sectors are those producing for export and nonbasic are those serving the needs of the basic sectors and of the population.

Efficient set

In multi-objective optimization models, the set of feasible solutions which are non-dominated; i.e. for each non-dominated solution x there is no other solution x' which is better than x. The efficient set is called also "admissible set", "noninferior set", "Pareto-optimal set", "non-dominated set".

Empiricism

A philosophy of science which prioritizes empirical observations over theoretical statements. It assumes that statements deriving from observations make direct reference to real world phenomena and they can be declared true or false without reference to the truth or falsity of theoretical statements. It is a fundamental assumption of positivism challenged by other epistemologies such as realism and postmodernism.

Endogenous

A variable in a mathematical relationship or in a mode whose value is calculated by means of this relationship or model; i.e. it is an output of the model.

Environmental determinism

The doctrine which posits that human activities are controlled by the environment.

Epistemological/epistemology

The study of knowledge acquisition; i.e. how the world of objects and experiences becomes knowledge. An epistemological position makes specific claims as to how knowledge is acquired (under what conditions), transmitted, altered and integrated into conceptual systems. Known epistemologies include: positivism, relativism, realism, existentialism, idealism, structuralism, postmodernism, post-structuralism.

Ethnomethodology

An approach to the study of social phenomena which employs procedures to discover how people make sense and give order to the world. It emphasizes the contextual determination of meaning and concentrates on the unique and the idiographic. It does not accept the possibility of generalization. Qualitative techniques are employed such as participant observation, analysis of official records, naturalistic observation, etc.

Eustatic sea-level rise

It denotes *worldwide changes* (slow and gradual) in the sea level which may be caused by, e.g., melting of continental glaciers. They exclude relative changes in sea level caused by *local* subsidence or elevation.

Eutrophication

The process of enrichment of water in lakes, rivers, estuaries, seas, etc. with nutrients (carbon, sulfur, potassium, calcium, magnesium, nitrogen, and phosphorus) which leads to increased organic growth with consequent undesirable effects. These include: red, brown or blue-green algal blooms, changes in the color of the water and bad odor.

Existentialism

A philosophy whose central concern is the human subject's 'being' in the world. Existentialism gives primacy to existence and then to essence. Among its main position is that all persons are estranged from their creativity and live in a world of objects; any attempt to realize a true human condition is to enter a struggle against estrangement.

Exogenous (variable)

A variable which is assumed to influence another (the endogenous) variable. Synonymous to independent variable.

Explanatory (or, predictor) variable
A variable which is used in a relationship to explain or to predict changes in the values of another variable; the latter called the *dependent* variable.

Extensification
A term used to characterize frequently the pattern of agricultural development which involved production using a low number of inputs per hectare. The opposite of intensification.

Factorial ecology
An approach to the analysis of social phenomena which employs statistical techniques such as factor analysis and principal components analysis to demographic, socio-economic and other data. Its purpose is to test hypotheses about the pattern of areal differentiation of the social structure (mostly in urban areas) as a function of a small number of general constructs derived from the data.

First Law of Thermodynamics
One of the two Laws of Thermodynamics which states that the amount of matter and energy in a system remains constant. Matter is transformed to energy and vice versa. Neither matter not energy can be destroyed nor be produced from zero.

Functionalism
An analytical perspective in which the world is viewed as a set of interdependent systems. Their collective actions and relations reflect repeatable and predictable regularities in which form and function can be assumed to be related. It has influenced heavily theorizing and modeling in geography and planning. Systems analysis has offered tools for a functionalist analysis of spatial and social phenomena. Functionalism has been heavily criticized on both logical and substantive grounds. In the former instance, the unintended or unanticipated consequences of a form of social conduct cannot be used to explain its existence in the first instance; in the latter, functionalism assumes a purpose ("needs" or "goals") without a purposive agent.

Global parameterization
Calculation of the values certain variables in a mathematical model as a function of certain parameters (when direct data for their estimation do not exist). The term "global" denotes that the functional forms used do not change in the applications of the mathematical expression.

Heuristic techniques
Techniques used for modeling a system of interest which do not utilize formal mathematical expressions and techniques (such as statistical or optimization models) but they rely, instead, on rules which are used to guide the representation of the relationships being investigated.

Historical materialism
An analytical method, associated with Marxism, which emphasizes the material basis of social life. It examines the historical development of social relations in order to explain social change. The term was coined by Engels who argued that "life is not determined by consciousness but consciousness by life".

Idealism/Idealistic
A philosophy which posits either: (a) that reality resides in or is constituted by the human mind or (b) that human understanding is limited to perception of external objects. In geography, an idealistic approach accepts that human behavior cannot be described in theoretical terms. Instead, the geographer is concerned with the theories expressed in the actions of the individuals being studied.

Independent variables
The variables in an equation which are assumed to influence the values of the dependent variable. Their values are provided outside the equation as inout for its solution.

Input-Output Analysis/ input-output model
An analytical technique developed by the economist Wassily Leontief which is used to describe the structure of an economy; in particular the relationships (or, linkages) between the economic sectors of the study area (nation, region, groups of nations, groups of regions). It assumes that changes in the output of the economic sectors of the study area are caused by changes in the demand for their products.

Instrumentalism (instrumental approach to theory)
A philosophy of science and an approach to theory development which is concerned with developing computational devices to describe observed relationships but does not question the truth or falsity of the theoretical statements produced. Mathematical models are the most direct expression of instrumentalism especially when they are directed to assessing the goodness-of-fit of a data set to the mathematical relationships specified without being concerned with the processes which produce these patterns.

Intensification
A term used to characterize agricultural production which uses a high amount of inputs per hectare. It is the opposite of extensification.

Invasion
A concept borrowed from ecology and used in Human Ecology to describe the process of spatial change whereby one group moves into (invades) the area occupied by another group and succeeds it.

Isochronal
A surface or a line containing points which are at the same distance (measured in time units) from a given point.

Lagrange multiplier
In an (constrained) optimization model, the Lagrange multiplier is a quantity – associated with each constraint, which shows how much the objective function will change (increase or decrease) if the respective constraint changes by one unit. The larger the value of the Lagrange multiplier the greater the sensitivity of the objective function to the respective constraint.

Land use/activity coefficients/ratios
Coefficients showing the ratio of the area of land to the magnitude of a land using activity; for example, the ratio of residents per hectare, the ratio of sales per square meter, crop yield per hectare.

Laws of Thermodynamics
There are two basic laws of Thermodynamics which are used in the study of the economy-environment relationship – the First and the Second law (see the corresponding lemmas in this glossary).

Location theory A body of theories which seek to describe, explain, and prescribe the location of economic activities in space. Most of the theories are based on notions of neoclassical economics. For a concise, “bird’s eye” presentation, the reader is referred to the relevant lemma in the Dictionary of Human Geography (Johnston *et al.* 1994).

Marginalization
The process of an entity (e.g. person, social group, organization) or activity (e.g. agriculture) becoming marginal within – moving to the margins – of the larger context it exists and operates. A marginalized entity or activity looses its importance within this broader system, it is ignored, underrepresented and under-served.

Materialist
Denotes a philosophical position which emphasizes the material basis of human entities, activities, processes and development.

Metaproblem
A problem whose definition involves an indefinite, infinite, and incompletely known (and defined) number of variables.

Mode of production
The set of relationships through which a society structures and organizes productive activities. It is a characteristic which distinguishes societies on the basis of their socio-economic organization. Representative modes of production: precapitalist, capitalist, socialist.

Modifiable areal unit problem
The problem created in the analysis of spatial data when the size and the boundaries of the zones used change. It is analyzed in two components: "(a) the *scale effect* is the tendency, within a system of modifiable areal units, for different statistical results to be obtained from the same set of data when the information is grouped in different levels of spatial resolution … (b) the *zoning effect* is the variability in statistical results obtained within a set of modifiable areal units as a function of the various ways these units can be grouped at *a given scale* and *not* as a result of the variation in the size of those areas – i.e. the difference in results which follows from merely altering the boundaries or configurations of the zones at a given scale of analysis" (Wrigley *et al.* 1996, 23).

Multicollinearity In statistical multiple regression models, when the independent variables are related between them, the problem of multicollinearity arises. It results in regression coefficients which may not be statistically significant as the coefficients of interrelated independent variables reflect – to a lesser or greater extent – the influence which one variable exerts on another.

Multiple regression analysis
A statistical technique for analyzing the mathematical relationship between two or more variables. One of the variables is called the dependent variable as its values are assumed to depend on changes in the values of the other (one or more) *independent* (or, *explanatory*) variables.

Multivariate statistical techniques
An umbrella term which includes a variety of statistical techniques which analyze the relationships between many variables. Multiple regression analysis belongs to these techniques.

Neighborhood effects
A term used to denote the unintended – positive or negative – impacts of an activity upon other activities. They are also called externalities, external effects, side-effects.

Ordinary Least Squares
A commonly used technique for estimating the coefficients of a regression equation.

Parameterization
The process of expressing relationships among variables as a function of parameters and studying these relationships as functions of changes in the parameters.

Pareto-efficiency criterion
The criterion of choosing among the solutions in a multiobjective optimization problem. A solution is Pareto-efficient if there is no other solution which improves one objective, at least, without reducing the value of the other objectives.

Pareto optimal
A solution in a multiobjective optimization problem which satisfies the Pareto-efficiency criterion. Equivalent to the term "Pareto-efficient". Applied to the efficient allocation of resources, Pareto optimality is achieved when it is impossible to change an allocation that would increase the satisfaction of some people without reducing the satisfaction of some others. In the case of income distribution, a pareto optimal income distribution is one which cannot be changed to make one individual better off without making at least one other individual worse off.

Phenology
The study of the temporal aspects of recurrent natural phenomena. Equivalently, manifestations of a biological phenomenon (particularly of an organism) as a function of time. Example, the phenology of pollimation. (Based on Lincoln *et al.* 1982)

Phenomenology
A philosophy emphasizing the importance of reflecting on the ways in which the world is made available for intellectual inquiry; it stresses the role of language and discourse in making the world intelligible. It claims that "observation" and "objectification" are not as simple as assumed in conventional scientific analysis. It rejects the separation of "subject" from "object" and stresses their being intimately interrelated.

Physiographic determinism
The philosophical approach to the study of the various aspects of the nature-society relationship that gives priority to the influence of the physiographic characteristics of an area (relief, climate, hydrology, geology, etc.). It can be considered equivalent to the term "environmental determinism." It is also used to guide decision making in the context of planning in which case the physiographic characteristics of the study region determine the possibilities for and constraints on the development of various activities.

Positivism
A philosophy of science which was proposed originally by August Comte in the early 19th century. Its primary purpose was to distinguish science from metaphysics and religion. Broadly, it accepts that: (a) scientific statements should be based on empirical observations and facts; (b) the (quantitative mostly) methods of the natural sciences can be extended to the study of social phenomena; (c) general, universal laws is the ultimate goal of scientific inquiry; i.e. the search for empirical regularities, for "law" and "order".

Postmodernism
A recent movement in philosophy, the arts and social sciences characterized by scepticism towards the grand claims and grand theory of the modern era, and their privileged vantage point, stressing in its place an openness to a range of voices in social enquiry, artistic experimentation and political empowerment (Johnston *et al.* 1994).

Predictor (or, explanatory) variables
The variables which are used to explain the variability of another variable (the dependent variable). Equivalently, they are called independent variables.

Propulsive industry
In growth pole theory, the industrial sector whose growth diffuses over the whole area and causes the growth of other sectors and activities.

Ratio variable
A variable measured on the ratio scale – i.e. a scale which has an absolute origin (the zero point), it distinguishes intervals in a variable and the distances between intervals are comparable. All four arithmetic calculations (addition, subtraction, multiplication, division) are possible on a ratio scale. Ratio variables are known broadly also as quantitative variables.

Realism/realist
A philosophy of science which uses abstraction to identify the *necessary/causal* powers of specific *structures* which are realized under *contingent/specific*conditions. It regards the world as differentiated, stratified, and made up not only of events (as positivism does) but also of *mechanisms* and *structures*. Structures are seen as sets of internal relations which have characteristic ways of acting; i.e. they possess "causal powers and liabilities" (Sayer 1984) by virtue of what they are and which are, thus, necessary. Realist analysis tries to identify causal chains which place particular events within these deeper mechanisms and structures.

Reductionist
An approach to the study of a phenomenon in general which reduces its multiple dimensions and facets into a few ones which can be manipulated within some form of a formal model of the phenomenon.

Salinization
The accumulation of salts in soil which may lead to a form of serious soil degradation. The causes of salinization are mainly: (a) poorly drained soils – the excess water remaining in the soil evaporates and the salts contained in it are deposited in the soil; (b) excess water logging causes saltwater intrusion to the water table which is taken up by the roots of the plants, thus increasing the salt content of the soil.

Saltwater intrusion
Intrusion of saltwater into the water table caused by overpumping of water. This lowers the water table below the sealevel causing, thus, the intrusion of sea water into the (fresh) water table.

Semantic
Refers to meaning. A semantic category is a category of meaning. E.g. one semantic category is that of a "cause" while another is that of "effect".

Seminet revenues
The profit available from each activity at a site which does not include the rents paid to the owners of land and capital (Koopmans and Beckman 1957).

Social area analysis
A theory and technique developed by two American sociologists – Shevsky and Bell (1955) – to relate changing urban social structure and residential patterns to the processes of economic development and urbanization.

Soil nitrate pollution
A form of soil pollution caused by the retention and overconcentration of nitrates contained in the fertilizers applied to soils.

Spatial autocorrelation
The presence of strong relationships among observations taken from points in space. It results in biased regression coefficients. Special statistical techniques, known as Spatial Statistics and Spatial Econometrics, need to be applied to correct the problems associated with spatial autocorrelation.

Stochastic process
A process whose outcomes depends on chance elements – i.e. they are expressed as probabilities.

Stratospheric ozone depletion
The reduction in the thickness (density) of the ozone layer which is at the stratosphere – the layer of the atmosphere which is above the troposphere, about 10km above the earth's surface. The stratospheric ozone layer protects living organisms from the excessive ionizing radiation of the sun.

Structuralism/structuralist
A dominant current in postwar French philosophy originating in the work of Raymond Barthes in literary theory, Jean Piaget in psychology, and Claude Levi-Strauss in anthropology. It involves moving beneath the visible and conscious designs of social phenomena in order to reveal an essential logic which is supposed to bind these designs together into enduring, underlying structures.

Succession
A concept borrowed from ecology and used in Human Ecology to describe the process of spatial change whereby one group moves into (invades) the area occupied by another group and succeeds it.

Sustainability
The property of a (mostly living or human) system to maintain its functions and productivity constant over time. The related term sustainable development builds on the concept of sustainability but considers the conditions under which sustainability can be achieved. Briefly, these are: economic efficiency, environmental protection and social justice.

System of simultaneous equations
A system of equations which are solved simultaneously. It is used to model (interdependent) processes which occur simultaneously in the real world; e.g. the simultaneous determination of demand and supply, the simultaneous determination of the land use and transportation characteristics in a metropolitan region.

Systems analysis/theory
Refers to a group of mathematical techniques – developed mostly in control engineering – for the analysis of systems; i.e. of groups of elements which are related to one another directly or indirectly to some degree.

Technical coefficients (in Input-Output Analysis)
Quantities that show the amount of the output of one sector necessary for the production of a one unit of output of another sector. They reflect the state of technology at the time the Input-Output Table is constructed.

Theorization tradition
A term used in this contribution to denote the particular way theory is constructed for the description and explanation of a phenomenon. It involves the way of thinking about and conceptualizing reality which is influenced, among others by: (a) the broader value system adopted which affects the mode of conceptualizing real world entities and the relationships between them, (b) the value system, the culture of the discipline within which the theory is developed. The latter reflects certain epistemological positions and influences the choice of the spatial and temporal frameworks, the objects of analysis, the level of abstraction at which reality is represented.

Total system
A term used in this contribution to denote the totality of interactions between nature (or, environment), economy, society (including politics and institutions), and culture.

T-period competitive equilibrium model
A competitive general equilibrium model structure where agents are assumed to decide on current and future periods over a finite time horizon, $t = 1, 2, \dots T$.

Two-Stages Least Squares Analysis
A special technique for estimating the regression coefficients in simultaneous equation statistical models.

Utilitarian
Adhering to utilitarianism, a philosophical approach according to which the moral criterion of human action is the personal interest; ethical choices are made on the basis of personal benefits. The utilitarian motto is: “the most good for the most people”.

Utility
The satisfaction an individual derives from the consumption of a bundle of goods and services (including those which are particular to a location).

Utility function
A function which relates levels of utility to the attributes of the goods and services associated with these levels. The utility function of an individual is assumed to reflect his/her preferences for the goods consumed.

Walrasian
After Leon Walras, one of the founders of neoclassical economics. Refers to the model of an ideal market economy.

Welfare Economics
The branch of economics which deals with the analysis of social, aggregate welfare at the level of a community (of any size). It involves the thorny task of aggregating individual utility functions into a social welfare function expressing the preferences of the community for various goods and services.

Xerophylic
A plant which grows in arid areas (where water is in short supply).

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