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LINKING SPATIAL STATISTICS WITH GIS: OPERATIONAL ISSUES IN THE *SPACESTAT-ARCVIEW* LINK AND THE *S+GRASSLAND* LINK

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ABSTRACT: The extension of the functional capacity of geographic information systems (GIS) with tools for exploratory spatial data analysis (ESDA) has been an increasingly active area of research in recent years. In this paper, two operational implementations that link spatial analysis software with a GIS are considered more closely. They consist of a linkage between the *SpaceStat* software for spatial data analysis and the *ArcView* GIS (based on so-called loose coupling), and the *S+Grassland* Link between *S-PLUS/SpatialStats* and *Grassland* GIS (based on so-called close coupling). The emphasis is on the implementation of methods of exploratory spatial data analysis to describe spatial distributions, visualize spatial patterns, and assess the presence of spatial association. Conceptual and technical issues related to the implementation of these approaches are addressed and some ideas are formulated on future directions for linking ESDA and GIS.

Key Words: ESDA, *S-PLUS, SpaceStat*

I. Introduction

The integration of spatial statistical methods and GIS has been an active topic of research in both the academic and commercial GIS communities in recent years [Goodchild (1987, 1992), Fischer and Nijkamp (1993), Fotheringham and Rogerson (1994), Painho (1994), Fischer, Scholten and Unwin (1996)]. Different strategies have been proposed to establish a link between the two [Openshaw (1991), Anselin and Getis (1992), Goodchild et al. (1992); Bailey (1994), Haining (1994), Openshaw and Fischer (1995)]. These strategies can be conceptualized as ways to combine the "traditional" spatial analysis functionality of the GIS (e.g., spatial queries, buffering, overlay) in a "GIS Module" with spatial statistical and data analysis methods in a "Spatial Data Analysis Module" [Anselin et al. (1993)]. One approach towards implementing the combination of these two modules into an overall framework for spatial analysis consists of incorporating elements of one into the other (a so-called encompassing approach), such as the addition of GIS capabilities to a statistical software package or the extension of a GIS with statistical functionality. The latter is typically not included in the standard software release but is made possible by taking advantage of macro or script languages supported in GIS software. Examples of this are the use of the AML (Arc Macro Language) for *Arc/Info* and the Avenue script language for *ArcView* to extend the functionality of the GIS with EDA tools [Batty and Xie (1994)] or descriptive spatial autocorrelation statistics [Ding et al. (1992), Bao et al. (1995), Can (1996)]. The advantage of such an approach is that the added functions are fully integrated into the familiar GIS data model and user interface. However, the user bears the full burden of both identifying the appropriate methods and developing effective scripts. Moreover, the scripting environments are somewhat limited in terms of the size of data sets that can be handled and often seriously deficient in terms of speed.

A different strategy consists of developing an efficient linkage between existing commercially available GIS and statistical software packages. A number of taxonomies have been suggested to implement such a linkage, such as loose coupling vs. seamless coupling, a unidirectional link vs. a bi-directional link and a static link vs. a dynamic link [for reviews, see, e.g., Anselin and Getis (1992), Goodchild et al. (1992), Anselin et al. (1993), Symanzik et al. (1994, 1996)]. There are now several examples of such approaches, developed both in academic environments [e.g., Farley et al. (1990), Williams et al. (1990), Symanzik et al. (1994, 1996, 1997), Anselin and Bao (1997)] as well as in the commercial sector such as the *S+GISLink* [MathSoft (1996b)] and the S+*ArcView* Link [Bao and Martin (1997)].

In this paper, we contrast two different approaches to linking a GIS and a spatial statistical module. One is based on a loose coupling strategy by means of an efficient interchange of input and output files between the *SpaceStat* spatial data analysis software [Anselin (1992, 1995a)] and the *ArcView* GIS [ESRI (1996)]. The other is designed as a seamless integration (close coupling) between the *S-PLUS* statistical computing environment [Mathsoft (1996a)] and the *Grassland* GIS [L.A.S. (1996)]. For each of these approaches we next briefly describe the overall architecture, linkage mechanism and operational implementation. We close with a comparison of the relative merits of these approaches and some thoughts on future developments.

II. The *SpaceStat-ArcView* Link

The link between *SpaceStat* and *ArcView* is an extension and implementation of the prototype suggested in Anselin et al. (1993), based on loose coupling between *ArcView* as the visualization engine and *SpaceStat* as the spatial data analysis engine. Its main objective is to provide an efficient way to display the results of spatial statistical analyses by means of the

GIS and to obtain locational information for use in the statistical analysis from the GIS.

SpaceStat [Anselin (1992, 1995a)] is a software package for the analysis of spatial data developed in the *GAUSS* programming environment [Aptech (1995)] for DOS operating systems. *SpaceStat* includes a broad range of test statistics for both global as well as local spatial autocorrelation, and econometric estimation methods and specification tests for regression models that incorporate spatial dependence (spatial autoregressive models). In addition, *SpaceStat* has extensive capabilities to construct, manipulate and analyze spatial weight matrices, an important tool in the analysis of spatial autocorrelation.

ArcView is currently one of the most popular desktop GIS software environments [ESRI (1996)], primarily geared to the manipulation of vector data. *ArcView* can easily be customized by means of scripts written in the object oriented Avenue script language (supported by *ArcView* 2.1 and higher) and has recently been extended with optional modules for the analysis of raster data (the Spatial Analyst module) and network data (the Network Analyst module).

2.1 Architecture

The *SpaceStat*-*ArcView* Link is characterized by the following features: (1) a focus on exploratory spatial data analysis (ESDA) of lattice data; (2) a division of labor between the *ArcView* GIS used for the visualization of the statistical results and *SpaceStat* used for the statistical computation; and (3) an implementation targeted at PC platforms and windows environments.

The linkage between *ArcView* and *SpaceStat* is based on a loose coupling approach by means of a bi-directional data transfer. Since *SpaceStat* currently still uses the DOS version of *GAUSS* and *ArcView* runs under Windows, there is no direct mechanism to call internal *SpaceStat* functions from the *ArcView* environment. Although the recent MS windows platforms (Windows 95 and Windows NT) allow *SpaceStat* to run in a multi-tasking environment with *ArcView* in a separate window, no direct conversation can be established between the two programs.

Data are passed between the two environments using auxiliary files with standardized file names and data formats. Specifically, spatial information is moved from *ArcView* to *SpaceStat* for analysis, and location-specific results are passed back from *SpaceStat* to *ArcView* for visualization. Examples of spatial information are coordinates (such as the X and Y coordinates of the centroid of a polygon) and topological information on the spatial arrangement of selected points or areal units (such as spatial neighbor contiguity). Location-specific results include computed spatially transformed variables (such as spatially lagged variables to construct spatial bar charts or spatial pie charts), outliers (to be visualized in a box plot or box map), a Moran scatterplot, and local indicators of spatial association such as the Local Moran and Gi statistics [for technical details, see Anselin and Bao (1996, 1997)].

2.2 Linkage Mechanism

The *SpaceStat*-*ArcView* Link is implemented by customizing the *ArcView* user interface (Menu, Button, Tools) and adding functions written in Avenue. These functions fall into two categories: (1) data output to file formats compatible with *SpaceStat*; and (2) joining and mapping of *SpaceStat* output (report files) in a View window. The linkage is static and indirect in the sense that all the *SpaceStat* commands have to be issued within *SpaceStat* and cannot be called from within *ArcView* (and vice versa). All data transfers are via intermediate ASCII (text) files with formats designed to be compatible with both *SpaceStat* and *ArcView*.

2.3 Operational Implementation of the *SpaceStat*-*ArcView* Link

The *SpaceStat*-*ArcView* Link is implemented primarily in the *ArcView* environment, by means of customized menus, buttons and tools associated with Avenue programs [note that in the latest incarnation of this link, the role of the Avenue scripts is limited to providing a shell for special-purpose functions included in a DLL (Dynamic Link Library); see Anselin and Smirnov (1997) for details]. Specifically, two additional menus and a few extra buttons and tools have been added to the standard View window: a Data menu and an Explore menu.

The Data menu consists of six commands divided into three categories: (1) the auxiliary manipulation of spatial information such as adding the X-Y centroid coordinates of polygons and constructing an indicator variable for selected locations; (2) the construction of spatial boundary files based on the information in an *ArcView* Shape file; (3) the data transfer between *ArcView* and *SpaceStat*, such as exporting selected attribute data from *ArcView* to *SpaceStat*, and importing and joining output from the *SpaceStat* report files into *ArcView*.

The Explore menu contains eight functions to implement ESDA, organized into three groups: (1) visualization of the spatial distribution of the data; (2) visualization of spatial autocorrelation in attribute variables; and (3) visualization of local spatial association. These functions are each associated with specific output files generated by the corresponding

SpaceStat commands [see Anselin (1994, 1995b, 1997) for more technical details].

The first group of Explore commands are simple descriptive statistics: Histogram, Box Plot and Box Map. The Histogram is implemented as a standard bar chart for the current selected feature displayed in the View window, following an "Equal Interval" classification [note that in *ArcView* version 3.0a histogram is included as a standard feature]. A tool button is designed to identify the selected histogram interval and highlight the corresponding location in the View map. The Box Plot is implemented as a quartile map using the data from the quartile report generated by *SpaceStat*. A "graphic" box plot is also added to the View, which include the upper quartile, lower quartile, outliers, median, and mean. The Box Map is a quartile map augmented with outlier indicators generated from the *SpaceStat* box map Report File (boxmap.txt). In Anselin and Smirnov (1997), these simple descriptions of spatial distributions are implemented as fully dynamically linked windows by means of external DLL functions instead of Avenue scripts, resulting in increased speed and flexibility.

The second group of Explore commands is derived from spatial transformations in *SpaceStat*. The commands include the Spatial Lag Bar Chart and Spatial Lag Pie Chart. Using a Report File (sptran.txt) from *SpaceStat* that contains the spatial lags for the variables of interest, both functions create *ArcView* spot symbols for a graphic representing respectively a pie chart or bar chart for all selected polygons.

The third group of Explore commands visualizes the results of local indicators for spatial autocorrelation computed in *SpaceStat*. These include a Moran Scatterplot and Map, LISA Local Moran Map and G-Stat Map. Each of these functions requires the input of a *SpaceStat* Report File with a fixed file name prefix (such as MS_, LM_, or GI_) followed by the name of the spatial weights file for which the spatial statistics were constructed.

In addition to those functional menus, a number of tool buttons are implemented for the identification of a dynamic linkage between the maps, tables and charts in different application windows. Once those tools are activated, a rudimentary form of dynamic linking is established between the selected spatial units in different "views" of the data.

III. The *S+Grassland* Link

The main objective behind the *S+Grassland* Link [Bao (1997)] is to extend the functionality of the *Grassland* GIS with the statistical modeling and visualization capabilities of *S-PLUS* by means of a seamless integration or close coupling. In this integration, *S-PLUS* functions can be called directly from the *Grassland* interface, without the need to use intermediate files for data exchange.

S-PLUS [Mathsoft (1996a)] is a commercial statistical software package based on the S language, which was originally developed by AT&T Bell Laboratories. *S-PLUS* contains over 2,000 functions and is easily extensible either by user-written functions or by means of several add-on modules. One of these is *S+SpatialStats* [MathSoft (1996c)], which contains functions to carry out the analysis of spatial point patterns, geostatistical modeling, descriptive spatial statistics, and spatial regression analysis.

Grassland [L.A.S. (1996a)] is a recently commercialized version for Windows operating systems of the *GRASS* GIS, originally developed by the U.S. Army [USACERL (1993)]. The *Grassland* Graphical User Interface (GUI) is developed in the Sun Microsystems *Tcl/Tk* (Tool Command Language /Tool Kit) scripting language [Ousterhout (1994)]. Each *Grassland* infrastructure component has a corresponding *Tcl* extension loaded dynamically at boot time. *Grassland* provides users a tool for the manipulation of raster and point data and several standard spatial analysis functions such as overlay, buffer zone analysis, and terrain analysis.

3.1 Architecture

The *S+Grassland* Link is characterized by the following features: (1) a seamless integration of *S-PLUS* functions with *Grassland*; (2) the application of statistical analyses to raster data as well as vector data (such as the attribute data from point and polygon layers); and (3) the application of statistical analyses to the multiple data layers.

In contrast to most other GIS software, *Grassland* provides the URL (Uniform Resource Locator) connection to many geospatial data sources using the *OGDI* (Open Geospatial Datastore Interface) [L.A.S. (1996b)] technique for standardized access and transfer of geospatial data, which allows an application to connect to any geographic dataset via a given data driver and retrieve its contents regardless of its nature. The *OGDI* is provided as a C utility library. Geospatial data are retrieved by a specific data driver and moved into buffer memory, which can then be accessed by means of the utility functions provided by the *OGDI* library. With some specific data drivers developed for the *OGDI*, different types of spatial data sources can be accessed (including *GRASS*, *Arc/Info*, *ADRG*, *VRF*, and *DTED*).

In *S-PLUS* 4.0, the *S+API* (Application Programming Interface) is provided as a C utility library for *S-PLUS* [MathSoft, (1997a, 1997b)]. With *S+API*, all the *S-PLUS* functions and data objects can be accessed externally by other application environments.

This interface is based on a combination of the *Tcl/Tk, OGDI* and *S+API* techniques. The linkage between *Grassland* and *S-PLUS* is a close coupling with a bi-directional conversation. Selected data are exported from *Grassland* to *S-PLUS* and *S-PLUS* objects and functions are accessed directly from the *Grassland* environment.

3.2 Linkage Mechanism

The *S+Grassland* Link is accomplished by means of several DLL utility functions. These include functions to export data and pass commands from *Grassland* to *S-PLUS*, and an *S-PLUS* data driver to access *S-PLUS* objects from within *Grassland*. The GRASS data can be retrieved and transformed into the *S-PLUS* object structure via *S+API*. The *S-PLUS* data driver is composed of *Tcl/Tk* script programs and C routines. With the *S-PLUS* data driver, an URL connection can be established between *Grassland* and the *S-PLUS* workspace from the Librarian window. Once an URL connection is established, *S-PLUS* objects and results from statistical analyses can be accessed directly from *Grassland*. The link between *Grassland* and *S-PLUS* is therefore direct and dynamic.

In *Grassland*, the types of geo-spatial data include Raster, Area, Point, Line, and Text. To make the *S-PLUS* object structure compatible with the GIS, several types of spatial objects are defined in *S-PLUS* for geo-objects: Raster, Point, Text, and Pmap. The Raster data is an integer matrix object that contains the raster map information. The Point data is a data frame that contains the X and Y coordinates information and other attributes. The text data is a single vector (*.out) that contains the attribute information or the results from an *S-PLUS* analysis. The probability map is an integer matrix object (*.map) that contains the predicated probability from a generalized linear regression analysis.

This interface introduces the concept of an *S-PLUS* Geospatial Workspace (SGW). An SGW is a subdirectory containing a series of *S-PLUS* workfiles for spatial objects. Each SGW contains a special *S-PLUS* object (_GRS) that holds the parameters for the geospatial reference information such as the projection and global boundaries. This special *S-PLUS* object is automatically created by the *S+Grassland* interface. All individual data layers under a SGW are subject to the global boundaries defined in its global geospatial reference object. For each individual *S-PLUS* spatial object, there is also an associated *S-PLUS* object (*.grs) that is created for storing the individual geospatial reference information.

3.3 Operational Implementation of the *S+Grassland* Link

The *S+Grassland* link is integrated within the existing *Grassland* windows user interface. The new functions needed to establish the *S+Grassland* Link are implemented by editing existing *Grassland Tcl/Tk* scripts and adding new menus to the Library window and the Mapviewer window.

By applying the *OGDI* and the *S+API* techniques, some new Tcl/C extensions (DLLs) have been developed for the interface. These introduce a number of new procedures in the Tcl interpreter, such as launching an *S-PLUS* window session, exporting the GIS data from *Grassland* to *S-PLUS*, constructing a spatial neighbor weight object, and estimating a probability map by applying a general linear regression to sampled data from selected multiple layers.

From *Grassland*, selected geographical data can be exported to *S-PLUS* either from the Librarian or the Mapviewer window. Raster data are exported to *S-PLUS* as a matrix object. Area and Point data are exported to *S-PLUS* as a data frame that contains X and Y coordinates and associated attribute data. Text data are exported to *S-PLUS* as a data frame that contains X and Y coordinates and the attribute text data.

In the other direction, with the *S-PLUS* data driver designed for the *Grassland*/*OGDI*, *S-PLUS* objects can be accessed directly from *Grassland* via an URL connection from the Librarian window. The "Open Connection" dialog in the "File" menu establishes an URL connection with the targeted workspace and lists the *S-PLUS* geospatial objects (Raster, Point, Text, Pmap) in the workspace. These objects can be dragged into the Mapviewer window for display.

This link between the two processes involves a number of steps: identify a coverage (data layer) inside *Grassland*; choose a region of interest (a sub-regional boundary); open an *OGDI* data source via an URL connection; extract spatial coverage using the *OGDI*; establish a connection with *S-PLUS*; transform the *OGDI* data structure to an *S-PLUS* object structure; write the data down to an *S-PLUS* workfile; write the geospatial reference data to a related *S-PLUS* workfile; write the global geospatial reference data to a *S-PLUS* object (_GRS) in the case of a new SGW; send *S-PLUS* commands to *S-PLUS*; return the analytical results to *Grassland*; close the URL connection; and close the *S-PLUS* connection.

IV. Main Differences and Similarities between the *SpaceStat-ArcView* and *S+Grassland* Link

One important feature of these two links is that they both provide functions to construct the spatial weight matrices contiguity needed for spatial statistics from boundary in the GIS environment. The spatial weight matrix is an essential part in the computation of spatial autocorrelation statistics and in spatial regression analysis. In *S+Grassland* Link, the spatial weight matrix is constructed directly from a selected polygon (Area) data layer and exported to *S-PLUS* as a spatial neighbor object. This is essentially the same as the approach taken in *SpaceStat-ArcView*, except for the difference in formats of the weights files.

A major difference between the *S+Grassland* Link and *SpaceStat-ArcView* is the seamless integration of *S-PLUS* functions into *Grassland*. This is accomplished by adding new menu items or buttons to the *Grassland* GUI that make the data transfer (to *S-PLUS*), function execution (in *S-PLUS*) and data visualization (in *Grassland*) a one-click operation, transparent to the user. For example, a menu item can be added to Estimate a Probability Map, which is implemented by estimating a generalized linear model in *S-PLUS* and generating predicted values.

V. Strategies for Future Development

The linkages between spatial statistical functionality and a GIS outlined in this paper are still fairly rudimentary. However, they illustrate some important concepts. In order to establish an effective linkage, it is necessary to develop efficient formats and data structures to enable a bi-directional data exchange between the GIS and the statistical software. These data structures must respect the complexities incorporated in spatial data, such as location, projection and topology. This can be implemented in a fairly simple manner, as with the text file formats used in the *SpaceStat-ArcView* Link, with obvious limitations. Alternatively, a more elaborate strategy can be pursued, as in the geospatial objects implemented in *S+Grassland* Link. More importantly, to establish a real-time functional integration between the two software packages, an indirect conversation by means of loose coupling is clearly limited, at least in principle. Instead, the elegant solution obtained by the use of the *OGDI* techniques combined with the *S-PLUS* API provide the tightest possible coupling. In practice, however, one still needs to consider performance issues related to the communication between the packages, as illustrated by the many steps encompassed in a single menu item in the *S+Grassland* GUI.

An altogether different issue pertains to the types of statistical techniques that are most effectively included in an integrated framework. Clearly, the temptation will exist to use any technique that is available, even though many/most standard statistical approaches (such as classical linear regression) become inappropriate in the presence of spatial autocorrelation, which is predominant in the spatial data sets manipulated by GIS. Instead of linking a comprehensive statistical (or spatial statistical) module with the GIS as a single piece of software, it may perhaps be more effective to implement selected methods in small self-contained software applets that can be invoked from within the GIS. Clearly, the reverse strategy is promising as well, to implement small applets incorporating GIS functionality. An API such as *S+API* may provide the first step towards such a decentralized approach that would allow the individual user to customize the spatial data analysis "toolbox" for each application. In this respect, it still remains to be seen whether "traditional" statistical packages such as *S-PLUS* and *SpaceStat* or comprehensive GIS such as *ArcView* and *Grassland* will be the basis for the tools of the future, or instead become replaced by JAVA-based or similarly conceived free-standing applets. This constitutes a very promising area of future research.

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