2017

Baltimore City Reservoir Watershed Forests Deer Exclosure Study: Deer Impact in an Even-aged, Second Growth, Hardwood Forest Over a Ten Year Period

Walter Buck

Follow this and additional works at: <https://researchrepository.wvu.edu/etd>

Recommended Citation

Buck, Walter, "Baltimore City Reservoir Watershed Forests Deer Exclosure Study: Deer Impact in an Even-aged, Second Growth, Hardwood Forest Over a Ten Year Period" (2017). *Graduate Theses, Dissertations, and Problem Reports*. 5280.

<https://researchrepository.wvu.edu/etd/5280>

This Thesis is protected by copyright and/or related rights. It has been brought to you by the The Research Repository @ WVU with permission from the rights-holder(s). You are free to use this Thesis in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you must obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/ or on the work itself. This Thesis has been accepted for inclusion in WVU Graduate Theses, Dissertations, and Problem Reports collection by an authorized administrator of The Research Repository @ WVU. For more information, please contact researchrepository@mail.wvu.edu.

**Baltimore City Reservoir Watershed Forests Deer Exclosure Study:
Deer Impact in an Even-aged, Second Growth,
Hardwood Forest Over a Ten Year Period**

WALTER BUCK

Thesis submitted to
Davis College of Agriculture, Natural Resources and Design
At West Virginia University

in partial fulfillment of the requirements for the degree of

Master of Science in Forestry

David W. McGill, Ph.D., Chair
Jingjing Liang, Ph.D.
Anne Hairston-Strang, Ph.D.

School of Natural Resources

Morgantown, West Virginia
2017

Key words: white-tailed deer, deer exclosure, oak regeneration, invasive plants, even-aged management, shelterwood method, fire-disturbance regime, Baltimore City Reservoir Forests

© 2017 Walter Buck

ABSTRACT

Baltimore City Reservoir Watershed Forests Deer Exclosure Study: Deer Impact in an Even-aged, Second Growth, Hardwood Forest Over a Ten Year Period

Walter Buck

White-tailed deer (*Odocoileus virginianus*) have the potential to change forest community dynamics by affecting the persistence of individual tree species and altering overstory composition. We evaluated the Baltimore City Reservoir Watershed Forests Deer Exclosure Study for a better understanding of the effects of over-browsing in this hardwood forest. The study examined the effects of deer browsing over a ten year period, using 20 fenced deer exclosure plots (8x8 feet), paired with unfenced reference control plots. Tree seedling and sapling abundance was compared between the fenced deer exclosure plots and the unfenced control plots over the ten year period. Total tree species recorded were more abundant in the fenced exclosure plots, but the difference was not significant. Oak species (*Quercus spp.*) however, were significantly greater in abundance with the fenced exclosure plot treatments. Our findings suggest that chronic deer herbivory is affecting oak regeneration and may threaten canopy recruitment of oak species in this closed canopy watershed forest.

Understanding the role of deer in forest community dynamics is important in the development of forest management policies and fulfillment of watershed conservation goals. Our assessment of the findings from the Baltimore City Reservoir Watershed Forests Deer Exclosure Study could contribute to a better understanding of the potential impacts from deer at these important watershed forests.

ACKNOWLEDGEMENTS

My sincere appreciation is expressed to the Baltimore City Department of Public Works, in particular Clark Howells, Watershed Manager, for providing me the opportunity to evaluate the Baltimore City Reservoir Watershed Forests Deer Exclosure Study for this thesis project. I thank Ryan Mazeska and Bill Felter for their work in field data collection.

I recognize the State of Maryland Department of Natural Resources Forest Service and Robert Northrop who implemented the Baltimore Deer Exclosure Study. I thank Dr. Anne Hairston-Strang for providing advice and support while serving on my graduate committee, and Rob Feldt for assisting in GIS and graphic support.

A debt of gratitude is owed to West Virginia University and the people who assisted me during the course of my studies. I thank my graduate committee members, Dr. Jingjing Liang for providing advice with statistical modeling, and Dr. David McGill for serving as committee chair and making my endeavor to complete this thesis study possible.

I dedicate this thesis to Dr. Ray Hicks, who inspired me to be a forester.

TABLE OF CONTENTS

INTRODUCTION	1
LITERATURE REVIEW	3
History of the Baltimore City Reservoir Watershed Forests.....	3
Conservation Movement	7
Oak Regeneration	11
Fire-Disturbance Regime	15
Even-aged Management	20
The Impact of Deer	22
METHODOLOGY	26
Study Area	26
Deer Population	29
Forest Conservation Plan	29
Tree Regeneration	31
Deer Exclosure Study	34
Vegetation Data Collection	39
Statistical Analyses	39
RESULTS	41
Diversity of Tree Species	41
Dominant Species	41
Treatment Response	44
Role of Invasive Species	49
DISCUSSION	51
Deer Browsing	51
Seedling Density Variation	52
Direct and Indirect Effects of Deer Browsing	53
Oaks	56
Deer Density	57
Exclosure Study Limitations	60
Future Study Recommendations	62
Management Recommendations Discussion	63
Recommendations Summary.....	70
LITERATURE CITED	72

LIST OF FIGURES

Figure 1: Baltimore County and Baltimore City Forest Areas by Commercial Types 1914, Maryland Board of Forestry (Northrop 2001)	5
Figure 2: Plantings of loblolly and eastern white pine on Liberty Reservoir Watershed. Growth of loblolly exceeds eastern white pine (Reigner and Sushko 1960)	9
Figure 3: Baltimore City Reservoirs personnel harvest trees and mill them at Liberty Sawmill. (City of Baltimore Department of Public Works 1981).....	9
Figure 4: Example of straight and vigorous oak sprout which replaces the poorly formed stem top-killed by prescription fire (Brose and Van Lear 1997)	18
Figure 5: The location of the Baltimore City Reservoir Forests in Maryland - Loch Raven, Liberty, and Pretty Boy (Feldt 2010)	27
Figure 6: Baltimore City Reservoir Forests - Inventory Findings (Northrop 2001)	32
Figure 7: Liberty Reservoir Forest (Feldt 2010)	35
Figure 8: Loch Raven Reservoir Forest (Feldt 2010)	36
Figure 9: Prettyboy Reservoir Forest (Feldt 2010)	37
Figures 10a and 10b: Deer exclosure plots LR 16A and L15A.....	38
Figure 11: Species abundance in exclosures and controls, 2001-2010	42
Figure 12: Oaks, hickories, and oaks and hickories regression graphs.....	46
Figure 13: All stems, all shrubs, and all trees regression graphs.....	47
Figure 14: Invasive shrubs and invasive trees regression graphs.....	48
Figures 15 and 16: Deer exclosure plots L28F and LR 34A.....	50
Figure 17: Deer impact index (Hicks 1998, Marquis et al. 1992)	59
Figure 18: Mortality (%) of advance regeneration as fire intensity increases in shelterwood stands. (Brose and Van Lear 1997)	68
Figure 19: Loch Raven Reservoir Forest (Smith 2009)	71
Figure 20: Liberty Reservoir (Ten Thirty One Aerial 2016).....	81
Figure 21: Loch Raven Reservoir Forest (Mid-Atlantic Hiking 2016).....	82
Figure 22: Prettyboy Reservoir Forest	83

LIST OF TABLES

Table 1: Baltimore City Reservoir Forests - Inventory Findings (Northrop 2001)	32
Table 2: Liberty Reservoir Forest - Deer Study Sites (Northrop 2001)	35
Table 3: Loch Raven Reservoir Forest - Deer Study Sites (Northrop 2001).....	36
Table 4: Prettyboy Reservoir Forest - Deer Study Sites (Northrop 2001)	37
Table 5: Species Abundance in Fenced Exclosure Plots and Unfenced Control Plots.....	43
Table 6: Summary of Regression Estimates.....	45

INTRODUCTION

The threat of white-tailed deer (*Odocoileus virginianus*) over-abundance to the ecological integrity of eastern forests in the United States is an ongoing concern to forest and wildlife managers (Abrams and Johnson 2012.). As a keystone herbivore species, deer have a disproportionately large ecological impact on forest ecosystems (Waller and Alverson 1997). Sustained selective deer herbivory limits tree seedling survival and sapling growth, affecting canopy composition and structure. Deer alter composition, density, and diversity of the forest understory layer, inhibiting canopy tree regeneration and recruitment, potentially influencing successional dynamics (McGarvey et al. 2013, Horsley et al. 2003). Potential economic and ecological costs of unprecedented deer numbers and unabated herbivory are great, impacting the timber industry, and affecting vertebrate and invertebrate life throughout many eastern forest ecosystems. Consequences could potentially extend over decades, and perhaps centuries (Waller and Alverson 1997).

Oak tree species (*Quercus spp.*) regeneration is of special interest because of its importance as a commercial tree species, and for forest ecosystems as a mast-producer for wildlife species (Abrams 2003). Oak is the foundation tree species for many eastern hardwood forests that support wildlife (McShea et al. 2006). Over the millennia, oaks have dominated the forest overstory throughout Eastern North America (Abrams and Johnson 2012, Abrams 2002, Abrams et al. 1995), yet are often poorly represented as regeneration and recruits in the understory of old-growth and managed second growth stands (Rentch et al. 2003, Lorimer 1993, McGee 1984, Carvel and Tyron 1961). In some eastern hardwood forests, intense white-tailed deer herbivory along with other anthropogenic impacts have contributed to the virtual cessation of oak regeneration and recruitment, leading to forest succession to less browse favored and

more shade tolerant tree species, and encroachment of invasive plant species (Abrams and Johnson 2012, Nowacki and Abrams 2008, Cote et al. 2004).

It is imperative for forest and wildlife managers to assess the effects of chronically over-abundant deer populations, and take actions to minimize the economic and ecological costs. This thesis project evaluates a deer exclosure study at the Baltimore City Reservoir Forests, implemented by the State of Maryland Department of Natural Resources Forest Service for the Baltimore City Department of Public Works. The objective of this thesis study is to assess differences in oak seedling and sapling abundance between deer-excluded fenced plots and unfenced reference control plots, over a ten year period, under a closed canopy, even-aged, second growth, hardwood forest in Central Maryland. It is hypothesized that there will be significantly greater density of oak tree seedlings and saplings where deer were excluded.

CHAPTER 1: LITERATURE REVIEW

History of the Baltimore City Reservoir Watershed Forests

When European settlers came to the Chesapeake Bay region in the seventeenth century, they found a seemingly endless forest covering approximately 95% of the watershed (Northrop 2001, Kraft and Brush 1981). This ancient forest appeared uniform, in static balance with the environment. The forest was in fact a dynamic ecosystem. The species mix and age of forest plants and animals were shaped by disturbances, both natural and influenced by humans (MacCleery 1992). Fire disturbance, initiated by lightning and Native American activity, was a recurring and pervasive force in the pre-settlement forests of the region (Abrams et al. 1995). Native Americans influenced and shaped the forest ecosystem, periodically burning thousands of acres to improve game habitat, drive game for hunting, and remove cover for potential enemies (Northrop 2001). Native herbivores, including elk, forest bison, and white-tailed deer consumed plants, contributing to shaping the region's forests (Hicks 1998).

Following European settlement, anthropogenic disturbances accelerated with an increase in forest clearing, widespread fires followed by fire suppression, and the introduction of exotic plants, insects and disease, which transformed the forested landscape over the next 350 years (Abrams 2003, Foster et al. 1998). Forest composition and structure would undergo unprecedented change, including extirpation of American chestnut (*Castanea dentata*), suppression of oak (*Quercus spp.*) regeneration, and the spread of invasive plant species (Abrams 2003, Keever 1973).

European settlers cleared forests for a growing agrarian population, and lumber as a major export to England. The colonists had cleared approximately 25% of the forests in the Baltimore region by the 1700s. One million people lived in the Baltimore region by 1850 with

40-50% of the forests gone, cleared for commercial agricultural crops like tobacco, energy for heating and cooking, and a growing iron industry (Northrop 2001). Huge swaths of forest were cleared to supply timber for the production of charcoal to fire iron ore smelting furnaces (Hicks 1998). A single 1000-ton iron works required for operation, 20,000 to 30,000 acres of forest (Northrop 2001).

By 1890 the loss of forest habitat, along with unrestricted hunting, had a dramatic effect on native wild-life species. White-tailed deer had been eliminated from much of its range to the point of extinction (Northrop 2001, McCleery 1992).

The industrial revolution in the United States resulted in a logging boom from 1860-1920. Almost all eastern forests that had any merchantable value were cut over during this period. The logging boom had a more dramatic effect on our present day hardwood forests than any single event in the historical record (Hicks 1998). By the twentieth century, approximately 70% of the land in the Baltimore region was no longer covered by forest. The Maryland State Forester Survey of 1929 for Baltimore County concluded that the remaining forests were primarily on land not suited for agriculture. The 1929 Geological Survey also concluded that the Baltimore County forest landscape consisted primarily of steep slopes and ridges, and bottom-land forest types. The region's forests had been dramatically reduced and fragmented, with its composition and structure simplified by selective and intensive harvesting (Northrop 2001, Besley 1929, Brush et al. 1977).

Fig. 1: Baltimore County and Baltimore City Forest Areas by Commercial Types 1914, Maryland Board of Forestry (Northrop 2001).

The composition of the remaining forests was characterized as the oak-chestnut association (Northrop 2001). American chestnut was the dominant tree species in the deciduous forests of Eastern North America going into the twentieth century (Braun 1950, Russel 1987). Approximately 26-50 percent of tree species in Maryland forests were composed of American chestnut (Buttrick 1915). According to Krebs (1985) it made up 40% of the forest overstory in the Baltimore region (Northrop 2001). For 2000 years American chestnut thrived (Davis 1983, Paillet 2002), and according to Wang, et.al. (2013) was the most widespread and abundant tree species in Eastern North America since the last glaciation.

Considered one of the most valued tree species for its versatility in the United States, American chestnut was used for primary and secondary wood products, and its nuts were an important food source for people, livestock and wildlife (Emerson 1846, Zeigler 1920). This valuable tree, both economically and ecologically, would be reduced to functional extinction by chestnut blight (*Cryphonectria parasitica*) over the first half of the twentieth century (Freinkel 2008).

According to Freinkel (2008), the loss of American chestnut is unrivaled in the history of human-wrought ecological disasters. Virtually all mature American chestnut trees succumbed to the blight (Anagnostakis 2002), and today persists as understory sprouts and saplings originating from the killed tree root systems (Russell 1987, Stephenson et. al.1991), with a cycle of sprouting, blight infection and die-back (Paillet 2002).

The oak-chestnut community has been replaced by an oak association complex (Stephenson et al.1991). Loss of American chestnut in the Eastern United States may have contributed to an increase in oak and hickory (*Carya spp.*) after 1900 (Braun 1950). According to Braun (1950), American chestnut has been replaced throughout the Piedmont forests by oaks,

hickories, yellow-poplar (*Liriodendron tulipifera*), and American beech (*Fagus grandifolia*). Shade tolerant red maple (*Acer rubrum*) historically was not a major component of forests dominated by American chestnut (Wang 2013, Braun 1950); however, it has become more common with changes in disturbance dynamics (Wang 2013, Abrams 1998, Nowacki and Abrams 2008). With exclusion of fire disturbance from the region's forests during the twentieth century, successional replacement of oaks is likely (Abrams et al. 1995, Abrams and Downs 1990, Mikan et. al 1994). Past fires most likely acted to check the successional replacement of oaks, as well as American chestnut, by shade tolerant species such as red maple. Oak and American chestnut species share the fire adaptation of sprouting, which likely contributed to their regeneration and perpetuation (Abrams 1992, Russell 1987).

Conservation Movement

After over a century of exploitation and degradation of the nation's natural resources, public concern was growing, leading to the conservation movement in the early twentieth century. President Theodore Roosevelt recognized that the nation's natural resources were not inexhaustible and took key steps in conservation with passage of the National Reclamation Act in 1902, leading to creation of the U.S. Forest Service in 1905 (Ganoë 1931). In the coming century, eastern forests would begin to recover through natural and artificial regeneration (Hicks 1998).

In Maryland, the city of Baltimore took steps to conserve and protect its fresh water resources which supplied drinking water to its growing population. Starting in 1910 and over the next 37 years, the city would purchase 17,300 acres of the Gunpowder and Patapsco River Watersheds north of the city, expanding the Loch Raven Reservoir, and establishing the

Prettyboy and Liberty Reservoirs (Reigner and Ningard 1967, Reigner and Sushko 1960). The watershed's forests, like those throughout the region had been dramatically reduced and fragmented, cleared for agriculture and the timber industry. Erosion and sediment control were the primary concerns for protecting water quality in the Baltimore Reservoirs. A program of reforestation was initiated in 1912, with the first tree plantings on the Loch Raven Watershed. Forest management focused on planting trees to control erosion, and fire protection (Reigner and Neigard 1967, Reigner and Sushko 1960, Northrop 2001). Accurate fire records were not kept on the reservoir forests prior to 1954; however, fires were known to have been frequent and destructive. In 1960, signs of fire damage were reported to be common on 876 acres of the Prettyboy Reservoir Forest (Reigner and Sushko 1960).

In 1954 a comprehensive forest management program was implemented, under the control of the Watershed Control Division, with water protection remaining a priority. The program objectives were stated to be the coordinated conservation of forest, soil, and water, based on multiple-use of the watershed lands for improvement of timber resources and recreation. A full-time professional forester was employed to implement the program (Reigner and Sushko 1960). The program called for continued tree plantings, and by 1967 it was reported that 3,250 acres had been planted with trees, mostly loblolly pine (*Pinus taeda*) and eastern white pine (*Pinus strobus*) (Fig. 2), (Reigner and Ningard 1967, Reigner and Sushko 1960). Other coniferous species used in reforestation included Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), red pine (*Pinus resinosa*), white spruce (*Picea glauca*), and Douglas fir (*Pseudotsuga menziesii*). White spruce and Douglas fir were reported by Maslin (1991) to have died out in the watershed forests. Hardwood species utilized in reforestation included northern red oak (*Quercus rubra*), yellow-poplar (*Liriodendron tulipifera*), white ash (*Fraxinus*

Fig. 2: Plantings of loblolly and eastern white pine on Liberty Reservoir Watershed. Growth of loblolly pine exceeded eastern white pine (Reigner and Sushko 1960).

Fig. 3: Baltimore City Reservoirs personnel harvest trees and mill them at Liberty Sawmill. (City of Baltimore Department of Public Works Bureau of Water and Waste Water 1981).

americana), green ash (*Fraxinus pennsylvanica*), shagbark hickory (*Carya ovata*), black cherry (*Prunus serotina*), black walnut (*Juglans nigra*), sugar maple (*Acer saccharum*), black locust (*Robinia pseudoaccacia*), and northern catalpa (*Catalpa speciosa*), (Redman 2004 and Maslin 1991).

In 1955 it was determined that the standing timber in the reservoir forests had acquired considerable value. The naturally regenerated forests were predominantly oak-hickory, with yellow-poplar, red maple, American beech, Virginia pine (*Pinus virginiana*), and pitch pine (*Pinus rigida*), (Reigner and Sushko 1960). Under the supervision of the watershed forester, timber harvesting operations commenced with construction of a permanent saw mill at Loch Raven Reservoir Forest and purchase of heavy equipment. A crew of 17 men was assigned to sawmill and logging operations, and was also responsible for constructing a permanent road system throughout the watershed (Reigner and Sushko 1960). Timber was harvested as a source of income and to supply lumber to various city agencies (Redman 2004, City of Baltimore DPW 1981). During the four and half year period from 1955 to 1960, 6,441,430 FBM of lumber was manufactured and valued at \$519,853 (Reigner and Sushko 1960). By 1967, 15,000,000 FBM of lumber, valued at \$1,600,000, had been manufactured at the Loch Raven Mill. In 1967 sawmill operations were moved from Loch Raven to the Liberty Reservoir Forest (Fig. 3), (Reigner and Ningard 1967).

According to Sushko and Reigner (1960), management objectives for the reservoir forests included the development of an all-aged stand along with stand improvement, selecting over-mature, defective and low-vigor trees for removal, and release of the more vigorous merchantable growing stock. Public recreation in the 1950's included boating and fishing, and

the introduction of deer hunting with bow at the Prettyboy Reservoir Forest (Reigner and Sushko 1960).

Oak Regeneration

The latter half of the twentieth century brought new problems and challenges for forest managers. Few problems have been more challenging than the lack of tree regeneration in the oak-hickory dominated forests of the Eastern United States. Regeneration adequacy has emerged as an important issue of concern in the region (McWilliams 1995, Loftis and McGee 1993). Native deciduous tree species in the region depend almost exclusively on advance regeneration for development of new stands following harvest (McWilliams 1995, Marquis et al. 1992).

Oak regeneration is of special interest because of its importance as a commercial tree species, and for the ecosystem as a mast producer for many wildlife species (Abrams 2003). Oak is the foundation tree species for many eastern hardwood forests that support wildlife (McShea et al. 2006). Oaks dominate the overstory throughout Eastern North America, yet are often poorly represented as regeneration and recruits in the understory of old-growth and managed second-growth stands (Rentch et al. 2003, Lorimer 1993, McGee 1984, Carvell and Tryon 1961). On medium and better quality growing sites where timber silviculture is justified, adequate advance oak regeneration is especially difficult to obtain. Under both even-aged and uneven-aged silvicultural systems, oak stands are converting to non-oak hardwood species (Chadwell and Buckley 2003, Lorimer 1989, McGee 1984). According to Chadwell and Buckley (2003), competition from non-oak hardwood species may lead to oaks no longer remaining as the dominate hardwood species in Eastern U.S. forests in the future. The failure of oak stands to

regenerate, in almost all cases, can be attributed to the absence of adequate advance reproduction or inability of oak reproduction to outgrow competition when released (Crow 1988). Crow (1988) describes the situation as a paradox, a species that is dominant on the landscape yet difficult to regenerate.

To understand the underlying causes of the regeneration problem in oaks, physiological attributes of oak species should be considered. Oaks are slow growing and the physiological mechanisms are complex (Abrams 2003). White oaks (subgenus *Leucobalanus*) and red oaks (subgenus *Erythrobalanus*) share attributes, and have important differences. In the reservoir forests, white oak (*Quercus alba*) and northern red oak (*Quercus rubra*) are the dominant oak species in their respective subgenera, and have the greatest value commercially.

Oaks yield large acorns (seeds) which contribute to high initial growth of seedlings, but tend to have large year-to-year variations in acorn production and can be stored only briefly (Abrams 2003, Crow 1988). Acorns are an important food source for wildlife. Some of the earliest studies indicate acorn predation adversely effects oak regeneration (Abrams 2003, Janzen 1971). Conversely, some studies suggest that the burial of acorns by rodents and birds contributes to the regeneration of oaks. The acorn crop yield in a given growing season may have an effect on the amount of oak regeneration that follows. The more abundant the acorn crop, the more acorns are available for possible regeneration (Crow 1988). The acorn maturation and germination process differs between the red oak and white oak subgenera. White oak acorns mature during one growing season and germinate in the fall. Northern red oak acorns require a stratification process during two years of maturation before germination can take place (Crow 1988, Abrams 2003). This longer period of maturation increases the exposure time in which acorns are at risk to predation, and increases the possibility of regeneration failure.

The large cotyledons of acorns have substantial reserves of carbohydrates and nutrients, dedicated to initial root development prior to shoot emergence. This mechanism may allow oak seedlings in early development to survive low light conditions under the forest canopy (Crow 1988). According to Abrams et.al (1995), upland oaks are considered to have low to moderate shade tolerance. During the growing season, oak seedlings usually produce a single flush of small leaves, with little shoot growth during a two to three week period. When cotyledon reserves are depleted, low light conditions under the forest canopy may restrict growth and lead to seedling mortality. Carbon dioxide fixation rates may be insufficient to offset seedling respiration. Light will be a limiting factor for continued growth and survival of the seedling (Crow 1988). The survival and growth of oak species are dependent on adequate understory light levels (Carvell and Tryon 1961), and studies suggest that understory light levels may allow oak seedlings, saplings, and pole-sized trees to persist in the understory for long periods of time (white oak 60-90 years and red oak 50 years), (Rentch et al. 2003). Few contemporary stands however, demonstrate the ability for oaks to persist in the understory for such extended periods of time. Lack of disturbance at the canopy and understory levels are contributing factors. Establishment and survival of oaks in the understory may be explained by the growth strategies of oak species, and canopy gap openings providing adequate light levels (Rentch et al. 2003). Canopy gap openings may also provide the light necessary for recruitment of advanced oak regeneration into the overstory.

Oaks reproduce by sprouts as well as seeds. Seedlings often experience top die-back during the winter, re-sprouting in the spring. According to Crow (1988), most oak seedlings originate as sprouts from established root systems, and exposure to sunlight stimulates growth in height. For successful oak regeneration, silvicultural systems should be focused on management

of sprouts from developing root systems, leading to accelerated growth after harvest and canopy removal (Crow 1988).

Studies have suggested that oak species share ecophysiological adaptations for fire and drought resistance. Oaks may have developed a growth strategy and regeneration advantage for survival by adapting to an environment with repeated understory fire disturbance (Abrams 1996, 1990, 1992). According to Abrams (1996), and Abrams and Downs (1990), adaptations to fire may include the following: 1.) prolific sprouting with extensive and deep rooting, 2.) increased germination rates in response to fire-created seedbeds, 3.) thick bark, with white oaks (subgenus *Leucobalanus*) having the ability to wall off or compartmentalize fire scars and provide resistance to rotting by producing tyloses, eccentric outgrowths of cell walls. These adaptations to fire by oaks should provide a regeneration advantage, in the presence of repeated understory burning, over other hardwood species that are more fire sensitive like red maple and other shade tolerant species. With repeated exposure to understory burning, fire-sensitive non-oak hardwood species that compete with oak for resources should have a relatively greater risk of mortality.

Research has suggested that oaks may have greater adaptation to conditions of drought than other hardwood species, and compete more successfully on drier sites with poor soils (Chadwell and Buckley 2003, Abrams 1990). According to Abrams (1996), and Abrams and Downs (1990), adaptations to drought by oak species include deep rooting which provides overnight rehydration, and xerophytic leaves with greater thickness, mass per unit area and stomatal density, which provide greater photosynthesis and transpiration rates relative to many non-oak hardwood species. All of these attributes should benefit the regeneration of oaks in competition with non-oak species. In the Eastern U.S., white oak species, in comparison to red

oak species, have relatively greater resistance to drought as well as fire (Abrams 2003, Crow 1988).

. The dominance of oak species in the overstory of forests in much of the Eastern U.S. today is an indication that oaks were historically successful regenerators. Studies reveal that oak species are currently under-represented in the understory, with the composition of these forests transitioning to later successional shade tolerant hardwood species including red maple (Crow 1988, Rose 2008). Canopy dominance of oak is dependent on advanced oak regeneration in the understory (Rentch et al. 2003, Carvell and Tryon 1961, Larsen and Johnson 1998). Studies found several factors contributing to the current oak regeneration problem, including suppression and elimination of fire across forest landscapes, associated mesophication of forest microenvironments, encroachment of invasive plant species, and unprecedented deer populations and levels of herbivory (Chadwell and Buckley 2003, Nowacki and Abrams 2008).

Fire-Disturbance Regime

Abrams (2002) describes fire disturbance as playing a critical role in the rise and perpetuation of oak species during the Holocene time period in what is now the Eastern U.S. According to Rose (2008) and Lorimer (1985), prior to European settlement the ecology of oaks in the region was intrinsically linked to fire, initiated by Native Americans as well as lightning. Shumway et al. (2001), in a study documenting a 400 year history of fire and associated oak recruitment in an old-growth oak dominated forest in Western Maryland, found support for the hypothesis (Lorimer 1985, Abrams 1992) that oak forests in the Mid-Atlantic region regenerated as a consequence of periodic, low-intensity, understory fires before and after European settlement.

In the pre-settlement forests of the Mid-Atlantic region, white oak was the dominant oak species (Abrams 2003). From the early 1600's to the early 1900's, oak recruitment was persistent in this Maryland forest and coincided with repeated understory burning. The suppression of fire after 1930 was followed by recruitment of non-oak species, including shade tolerant red maple and black birch (*Betula lenta*). With elimination of fire, abundance of these shade tolerant fire-sensitive species appears to have further increased, while recruitment of all oak species has been reduced (Shumway et al. 2001, Abrams 2003). Fire suppression policies after 1930 led to disruption of the fire-disturbance regime which had previously favored oak species regeneration over non-oak fire sensitive species across forests in the region (Brose and Van Lear 1998). Rose (2008) found low oak regeneration potential across Virginia with species composition shifting towards mesophytic shade tolerant and fire-sensitive hardwood species, particularly red maple and blackgum (*Nyssa sylvatica*). With the continued absence of disturbance, later successional shade tolerant hardwood tree species may continue to increase in abundance with further reductions in oak species. Rentch et al. (2003), suggest that species composition change in eastern hardwood forests, from oak to other hardwood species, may be the result of changes in the historic fire disturbance regime. No surface-level disturbance other than fire (frequent low intensity fire) favors oak species more, in competition with other hardwood species (Rentch et al. 2003).

The dominance of oak species in the overstory of eastern hardwood forests may be explained by the unique germination and growth strategies of oaks, in combination with a disturbance regime of moderate canopy openings followed by fire (Brose and Van Lear 1998). Brose and Van Lear (1998) describe a germination strategy providing oaks a competitive advantage in the presence of ground fire. Oaks and hickories possess hypogeal germination

where cotyledons remain within the seed. With many acorns and hickory seeds buried by wildlife, the root collar and dormant buds develop under the soil surface, insulated and protected from surface fire. Brose and Van Lear (1998) attribute the growth strategy of oaks contributing to a stronger competitive position in stand development. They found improved oak seedling stem form and height growth, following winter and spring prescribed burning. Following fire, the large root system of oak seedlings generally sent up a single vigorous straight stem from a strongly anchored sprout with no rot, leading to the greater probability of developing sound timber trees (Fig.4). Oak and hickory seedlings also demonstrated accelerated height growth over a two year period following prescribed fire, a competitive advantage over fire-sensitive non-oak species.

Conversely, several prescribed fire studies found no benefit to oak regeneration, and that fire may not always be a viable silvicultural tool for regeneration of oak stands (Rose 2008, Crow 1988). Other studies found however, that multiple periodic burning may increase oak advanced regeneration over a single fire (Van Lear and Waldrop 1989). In West Virginia, large increases in advanced regeneration were reported by Carvel and Tryon (1961) in stands repeatedly burned over a 20 year period. Success of prescribed fire may also depend on timing or season in which fire occurs, as well as the time interval between burning. Brose and Van Lear (1998) found spring and summer fires resulted in greater mortality for red maple and yellow poplar, compared to burning during the winter season. Fire sensitive non-oak species burned during the growing season, when carbohydrate reserves are lowest, were found to have reduced rootstock survival and height growth (Brose and Van Lear 1998).

Fig.4: Example of a straight and vigorous oak sprout (left) which replaces the poorly formed stem (right) top-killed by prescription fire (Brose and Van Lear 1998).

A time interval of several years between timber harvest and burning is also critical for successful prescribed fire. This time interval is needed for development of oak seedling root systems, to reduce mortality, and provides time for competing fire-sensitive non-oak species to germinate and become vulnerable to fire (Brose and Van Lear 1998, Clark 1968).

Managing for regeneration of oak is problematic on productive mesic sites with fertile deep moist soils. Fire-tolerant oaks have evolved on these sites in the presence of fire disturbance, competing with fire-sensitive non-oak species. With the suppression and elimination of fire disturbance on these sites, the compositional shift from oak species to fire-sensitive species (mesophytic hardwoods) has been rapid, in comparison to dry and poor growing sites. In the absence of fire disturbance regimes, understory environmental conditions are shifting to ever increasing mesic conditions (Nowacki and Abrams 2008). In what Nowacki and Abrams (2008) describe as an escalating cycle of mesophication, conditions for shade tolerant species continually improve, and worsen for shade intolerant fire-adapted oak species. The dense canopy leaf area of shade tolerant mesophytic tree species cast heavy shade in the understory, increasing relative humidity and decreasing radiation and wind strength, contributing to moist cool microclimates (Nowacki and Abrams 2008, Nauertz et al. 2004). These conditions result in an increase in mesophytic tree fuel-bed inputs, consisting of moisture-holding leaf litter and rapidly decaying woody debris, which may contribute further to diminishing burning conditions on the forest floor (Nowacki and Abrams 2008). The mesophication process can be rapid, and reversing the process difficult. Re-establishing fire-adapted ecosystems requires greater energy (fire) to reverse conditions and restore fire-disturbance regimes with oak species (Nowacki and Abrams 2008, Beisner et al. 2003).

Even-aged Management

The even-aged condition of many contemporary second growth forests in the region, including the Baltimore Reservoir Forests, lends itself to even-aged management and is considered the best choice of silvicultural systems for natural regeneration of oak stands (Rentch et al. 2003, Sander et al. 1976). The regeneration process in even-aged oak stands often spans 20 years from acorn production, germination, seedling and sapling development, and growth into dominant and codominant positions in the overstory (Brose and Van Lear 1998). Uneven-aged silviculture can successfully regenerate oak stands if competitive regeneration resources exist at the time of overstory removal (Loftis 2004); however, uneven-aged silvicultural systems are challenging to manage without application of expensive multiple cultural treatments for the control of competitive shade tolerant species (Rentch et al. 2003). Chadwell and Buckley (2003) found in the southern Appalachians, the absence of larger size class oak seedlings and saplings, and suggest pre-harvest silvicultural treatments may be required to stimulate adequate oak regeneration, and re-establish oak stands following future harvests. Literature reveals silvicultural treatment guidelines and decision charts for even-aged mixed oak stands, with the goal of 30-35% restocking in future stands by the third decade (Steiner et al. 2008, Gould 2005). The success of silvicultural prescriptions is dependent on first, the oak stand's regeneration potential, capacity of advance regeneration (oak seedlings < 2 in. dbh and stump sprout stems > or = 2 in. dbh) to capture growing space after overstory removal, and second, the reduction of competitive understory vegetation (Steiner et al. 2008, Loftis 2004, Gould 2005).

The presence of competitive advanced oak regeneration prior to final overstory removal and its timely adequate release is critical to the regeneration of oak stands. Oaks become more competitive by increasing the number and size of advance reproduction, enhancing the ability of

advanced reproduction to sustain increased height growth after release (Loftis 2004, Crow 1988). Decreasing the abundance of non-oak competitors increases oak reproduction and their competitiveness (Chadwell and Buckley 2003, Lorimer 1993). The timely and sufficient release of oak advanced regeneration is critical for further development into co-dominant and dominant canopy position. The silvicultural prescription chosen and subsequent pattern of tree removal is crucial to successful release (Loftis 2004 and Crow 1988).

The scarcity of seedling and sapling advanced regeneration in the Mid-Atlantic region, brings into question the presence of oak species in future stands, and may require pre-harvest treatments to stimulate adequate advanced oak regeneration (Chadwell and Buckley 2003, Rentch et al. 2003). Pre-harvest silvicultural treatments may include: 1.) herbicides to remove lower and mid-canopy trees leaving the main canopy intact, increasing survival and growth of advanced oak regeneration as well as reducing competition from other species before and after overstory removals, 2.) prescription fire to make oaks more competitive and reduce competition (Loftis 2004), 3.) light shelterwood cuts or heavy thinning in heavily shaded mesic stands, removing up to 40% basal area of the understory with overstory gaps, increasing light levels for oak seedling establishment without stimulating growth of competition (Loftis 2004, Steiner et al. 2008). Forest managers should give consideration to the additional costs incurred for repeated stand treatments, requiring an accurate costs/benefits analysis.

Even-aged silviculture with overstory removal by either clearcut or shelterwood prescription has been successful in regenerating oak stands, when competitive regeneration sources are present in the understory, resulting from intrinsic processes or prior disturbances (Loftis 2004). The shelterwood method, which creates canopy gaps with canopy removals, is broadly recommended for regenerating oak stands and is preferred in even-aged management

(Steiner et al. 2008, Rentch et al. 2003). Shelterwood treatments manipulate overstory density, understory light levels, and understory competition. This improves the understory growing environment, increasing the size (growth) and density (number) of oak seedlings (Rentch et al. 2003, Steiner et al. 2008). Competing shade tolerant non-oak species, e.g. red maple and black cherry, have the ability to respond more rapidly to changing conditions (morphological and physiological plasticity), (Rentch et al. 2003, Abrams 1998). Silvicultural treatments for the reduction of these competing species in the understory are crucial for oak stand regeneration. For second growth stands managed for oaks, studies found combining prescription fire with a shelterwood treatment to be the most effective method for creating understory and overstory disturbance, reducing understory competition and shade (Rentch et al. 2003, Brose and Van Lear 1998). Steiner et al. (2008) recommend shelterwoods be prescribed only when 65% or more of sample milacre (3.7 ft. radius) plots in the stand contain oak seedlings, and found shelterwoods should be scheduled immediately following a heavy acorn crop, or risk failure to supplement the oak regeneration cohort. High acorn crops may occur as infrequently as once in a decade, giving forest managers a reason to consider deferring treatments (Steiner et al. 2008).

THE IMPACT OF DEER

White-tailed deer populations in Maryland were small and scattered at the turn of the 20th century as a result of over-hunting and loss of habitat (Maryland DNR 1998). Starting in the early 1900s, the Maryland Game and Inland Fish Commission initiated deer restoration efforts with modern wildlife management practices which included hunting restrictions, effective conservation law enforcement, and deer relocation. By the mid-1950s the commission reported positive results with a growing deer population throughout the state (Maryland DNR 1998).

Over the next 40 years deer adapted and flourished. By the 1990s, an escalating deer population brought concern over environmental impacts, including destruction of forest vegetation and tree regeneration (Gilgenast et al. 2009). In response to these growing concerns, the Maryland Department of Natural Resources (DNR), in conjunction with the Wildlife Advisory Commission, initiated a statewide deer management plan in 1998. The plan supported a strategy to maintain deer populations through regulated hunting, at levels necessary to ensure compatibility with human land uses and natural communities (Maryland DNR 1998).

Silvicultural management goals for regenerating oak stands are complicated by unprecedented levels of deer herbivory, which may be the most widespread barrier to oak regeneration (Nowacki and Abrams 2008, McWilliams 1995, Marquis 1981). As a keystone herbivore in eastern forests, white-tailed deer have disproportionately large impacts on forest communities, in comparison with other forest dwelling wildlife. Deer can alter forest community structure by affecting the abundance and distribution of tree seedlings (Waller and Alverson 1997). Boerner and Brinkman (1996) concluded that deer herbivory has a greater effect on seedling longevity and mortality than environmental gradients or climatic factors. Research found high deer densities in Pennsylvania reduced regeneration of hardwood species to below acceptable stocking levels. Hardwood seedling and sapling tree species palatable to deer, e.g. oaks and hickories, were suppressed and eliminated in favor of less palatable species, e.g. black cherry and American beech. Stand understories sometimes converted to predominately fern and grass species after repeated heavy deer browse (Waller and Alverson 1997). The dominance of fern in the understory may lead to further reductions in oak regeneration. Regeneration studies suggest some fern species produce allelochemicals, reducing oak seedling root growth and increasing mortality (Crow 1988).

Increased deer herbivory has contributed to homogenization of forest vegetation in the Eastern United States and may be driving tree diversity to historic lows, directing succession to species less palatable to deer (Nowacki and Abrams 2008). Studies found deer herbivory diminished tree species diversity and density, and also reduced height development. In harvested stands with high deer densities, tree diversity may be reduced with the extirpation of species preferred by deer, in favor of species resilient to herbivory (Horsley et al. 2003). Driven by the destructive effects of deer, these forests may be undergoing what Rawinski (2014) defines as retrogressive succession, temporal changes leading to simpler ecological communities with diminished structural complexity and biomass, and fewer species. In other words, forests of the region are disintegrating, in some cases trees no longer replaced by trees but by native and invasive grasses and ferns (Rawinski 2014). In Northern Pennsylvania forests, Horsley et al. (2003) suggest increased levels of fern, as a result of deer herbivory, represent an alternate stable state which will be difficult to reverse even when the agent for the change, deer, is eliminated. The presence of invasive species, e.g. Japanese stiltgrass (*Microstegium vimineum*), may not be the cause of forest degradation but rather a symptom of deer impact. Deer exclosure studies suggest however, that native plant species can out-compete Japanese stiltgrass in the absence of deer browsing (Knight et al. 2009).

Seeds of invasive and native plants, consumed by deer, remain viable in fecal pellets and are spread throughout forest landscapes. In Connecticut, Williams and Ward (2006) collected and analyzed deer pellets, and found 56% of seeds identified to be invasive species. Natural diversity is lost as invasive species gradually dominate forest ecosystems, accelerating community homogenization (Olden 2006). In 1960, invasive honeysuckle (*Lonicera maackii*)

was reported to be a problem in pine plantations at the Baltimore Reservoir Forests (Sushko and Reigner 1960).

As a result of negative effects from deer herbivory, combined with fire suppression, forest ecosystems may be approaching near-irreversible state shifts, necessitating the urgency for setting restoration priorities, including deer population reductions and implementation of prescription fire (Nowacki and Abrams 2008).

The long-term influence of persistent deer browsing on forest stand dynamics is not well understood (McGarvey et al. 2013). Researchers study the effects of deer on forest ecosystems by measuring differences in forest understory composition and vegetation between fenced and unfenced plots (Abrams and Johnson 2012). Deer exclosure studies are often temporally limited, lasting less than 10 years (McGarvey et al. 2013, Rossell et al. 2007, Tilghman 1989). The Baltimore City Reservoir Watershed Forests Deer Exclosure Study, conducted from 2001-2010, offers an opportunity to study the long-term impact of deer on oak tree species regeneration. This study assesses the differences found in oak regeneration between the fenced and unfenced plots, and makes recommendations for future studies and forest management at the Baltimore Reservoir Forests.

CHAPTER 2: METHODOLOGY

Study Area

The study was conducted at the three Baltimore Reservoir Forests, Loch Raven, Liberty, and Pretty Boy. The reservoir forest areas are located north of the city, in Baltimore and Carroll Counties, Maryland, U.S.A. (Fig. 5): Loch Raven 39.4579°N 76.5739°W (NAD 83), 239 ft. MSL elev., 5,600 acres; Liberty 39.4178°N 76.8788°W (NAD 83), 413 ft. MSL elev., 6,100 acres; Pretty Boy 39.6198°N 76.7075°W (NAD 83), 476 ft. MSL elev., 5,880 acres (USGS 2013, Northrop 2001).

The reservoir forests are located in the Piedmont Physiographic Province, situated between the Blue Ridge and Coastal Plain physiographic provinces. These regions are broad-scale subdivisions based on geologic structure and history (USGS 2013, MDE 2014). Piedmont bedrock is a complex array of metamorphic and igneous rock, which weathered to form the parent material for the region's soils. The highly crystalline schist and gneiss formations are some of the oldest rock in the geologic time scale, dating back to the pre-Cambrian age. Other rock types which over-lie these older formations and are exposed in places include marble, quartzite, and younger intrusions of gabbro, serpentine, granite, and diabase. The primary soil type associations in the watershed are Chester-Glenelg, Manor-Glenelg, Glenelg-Chester-Manor, Baltimore-Conestoga-Hagerstown, Beltsville-Chillum-Sassafras, and Mt. Airy-Linganore (USDA SCS 1976).

Topography of the watershed is generally gently sloping, and the soils characterized as mainly deep and well drained to moderately well-drained. The soils of Baltimore County are generally low in fertility and naturally acidic. The potential woodland productivity for soil type

Fig. 5: Location of Baltimore Reservoir Forests (Feldt 2010).

associations of the reservoir forests is estimated to be the average oak site index 85 ft., base age 50 years ($SI_{50} = 85$). Average basal areas were recorded for Liberty 86 ft.²/ac. and Loch Raven 94 ft.²/ac. The dominant forest type is described as oak-hickory and oak-yellow-poplar (USDA SCS 1976). The reservoir forests are even-aged, with trees of the same size class predominating. The forests are considered as second growth, and most hardwood forest types developed after establishment of the reservoirs. Pine plantations were planted to eastern white pine, Virginia pine, and loblolly pine (Northrop 2001).

The State of Maryland contains 5 of the USDA Plant Hardiness Zones, with the average annual minimum temperatures varying across the state by as much as -15 F⁰ in the Allegheny Mountains to +10 F⁰ in the coastal regions. This variation in temperature affects the frost free seasonal averages (length of growing season) across the state (msa.maryland.gov/msa/mdmanual 2014). The frost free seasonal averages for the reservoir forests are 169 days reported at Parkton, MD, located near Pretty Boy Reservoir, and 183 days reported at Towson, MD, located near Loch Raven and Liberty Reservoirs (USDA SCS 1976). The average annual temperatures are Parkton 51.90° F and Towson 55.65° F. For both locations, the coldest month annually is January, and the warmest July. The average annual precipitation is Parkton 46.74 in. and Towson 51.59 in. (US Climate Data 2017). The monthly distribution of precipitation is fairly uniform throughout the year. Drought can occur in any month or season, but is more likely to occur during the summer season because of unequal distribution of precipitation from summer showers. Generally, stored soil moisture is adequate to reduce the effects of occasional dry periods (USDA SCS 1976).

Deer Population

The Baltimore County Department of the Environment has expressed concern for environmental impacts from the apparent over population of deer in the county. Environmental impacts include the destruction of vegetation and the threat to forest regeneration (Gilgenast et al. 2009). In the mid-1990s and 2008, the Maryland DNR Wildlife Division, and the Baltimore County Department of Environmental Protection and Resource Management conducted Forward-Looking Infrared (FLIR) surveys to estimate deer density in Baltimore County and the Baltimore Reservoir Forests. Deer density was estimated to be 81deer/mi² (31.27 deer/km²). (Gilgenast et al. 2009, Peditto 1999). A 2009 Towson University study of deer density using deer pellet group counts at Loch Raven and Liberty Reservoir Forests, and Baltimore County roads Deer-Vehicle-Collision-Data, concluded that the estimated deer density in the county was 94.85 deer/mi² (36.62 deer/km²), (Gilgenast et al. 2009). Maryland DNR deer hunting harvest data for both antlered and antlerless deer at the three reservoir forests (Liberty and Pretty Boy 1994-2013, Loch Raven 2008-2013), supported the deer density estimates from the LIDR surveys and the Towson University study (Eyler 2013).

Forest Conservation Plan

In April 1999, the Maryland Department of Natural Resources (MD-DNR) Forest Service entered into an agreement with the City of Baltimore to develop a comprehensive forest resource conservation plan for the Loch Raven, Pretty Boy and Liberty Reservoir Forests (Northrop 2001). The plan was part of a series of investigations into the role that forests and forest management play in source water protection at the three reservoirs. As part of the city's goal in protection and enhancement of water quality, the forest conservation plan outlined the

operational goal of maintaining a vigorous and diverse forest by assuring sustained natural regeneration of tree seedlings. A healthy watershed forest provides filtration and assimilation of sediment, soil nutrients, and pollutants (Northrop 2001).

According to Northrop (2001), the plan called for conducting an inventory of the three reservoir forest stands, to determine the health of the forests, and make management recommendations. Forest types and size classes were used to stratify and map the forest stands. A total of 2500 understory and 1500 overstory sampling units were established, and data collected to analyze stand conditions. Stands were sampled using line-transect and nested plot sampling methods.

Stand level data included year of stand origin, year of last treatment, site index species, site index, rings per inch, elevation, aspect, slope, topographic position, and height to base of canopy.

Understory nested sampling units consisted of milacre plots which evaluated ground and herbaceous cover (0-2 feet), and 0.05 acre plots which evaluated shrub cover (2-10 feet). The data types collected included sprout regeneration, ground and shrub cover species observed, and per cent cover by each species. Uncommon and invasive species were also recorded.

Overstory units evaluated the percent cover of the midstory (10-30 feet height), and the overstory (>30 feet height). Canopy closure was determined by use of an ocular tube. Ten readings were taken for both the midstory and overstory, within a 12 foot radius of each sampling unit. Other overstory data collected included tree species and dbh, living or dead, timber quality, saw log height, crown class and condition, and presence of tree cavities.

Between sampling units, data was collected along transects on diameter, and condition of dead and down course woody debris (Northrop 2001).

According to Northrop (2001), 0.01 acre forest regeneration plots were established as a follow up to the initial forest inventory. These regeneration plots considered stump sprout production as well as seedling regeneration. Advanced regeneration was evaluated according to a weighted point system which considered height and dbh.

Through a cooperative agreement with the U.S. Forest Service, NED-1 Decision Support Software was used for the analysis of inventory data. Northrop (2001) proposed that the 2001 inventory data should be used as a baseline for a long-term monitoring program to effectively evaluate future forest conservation practices. Although the forest conservation plan goals and management recommendations were published, plot data and analysis were not available for this thesis study.

Tree Regeneration

Based on the 2001 forest inventory, the forest is even-aged, with trees of the same size class predominating. This lack of diversity for various ages and size classes does not provide assurance for a renewable forest in the future (Northrop 2001). The upper level forest canopy was well represented; however, vertical layering of vegetation was lacking for understory and mid-story trees, shrubs, and herbs. Young seedlings and saplings were found on only 25% of the understory plots. No seedling regeneration was found in the majority of understory plots. Regeneration was absent at Pretty Boy 84%, Liberty 74%, and Loch Raven 63%. (Northrop 2001). The forest conservation plan concluded that the reservoir forests exhibited an extensive and intensive lack of natural tree regeneration (Fig. 6, Table 1). The lack of multi-layered vegetation and tree regeneration brought into question the sustainability of the reservoir forests (Northrop 2001).

Fig. 6 and Table 1: Baltimore City Reservoir Forests – Inventory Findings (Northrop 2001).

The forest conservation plan recommended uneven-aged management to initiate development of advanced regeneration. The group selection method was suggested, to convert the even-aged forest to an uneven-aged condition with greater structural diversity. Group selection creates small canopy gaps allowing sunlight to reach the forest floor to stimulate regeneration of desired tree seedlings. Selective harvesting is used to release desired tree species

and stimulate seed production. The plan called for an initial reduction in density of dominant trees to 50-70%. Once adequate advanced regeneration was established, a second cut would be recommended, reducing relative density to 25%. Typical stands were projected to grow out to 100-130 years, with reserve trees reaching 200 years (Northrop 2001).

Northrop (2001) concluded that the principle cause for the lack of suitable tree regeneration was the extremely high deer population in the reservoir forests. Without effective measures to reduce deer numbers, the goals of silvicultural management were threatened. The plan called for an effective deer control policy, and was considered essential for the long-term sustainability of the watershed forests. The plan also listed invasive species as a potential risk to forest health, and recommended management to protect the forests from this threat. Invasive species, as a percentage of total species represented in the reservoir forests were recorded as follows: Loch Raven 5%, Liberty 5%, and Pretty Boy 2%. Northrop (2001) noted the close proximity of the reservoir forests to the port of Baltimore, where the intentional and accidental importation of exotic species is common. Invasive species compete with and threaten native forest species, altering community structure and ecosystem functions (Northrop 2001).

Deer may be the most widespread barrier to oak regeneration in eastern hardwood forests (Nowacki and Abrams 2008, McWilliams 1995, Marquis 1981). Abrams and Johnson (2012), in one of the longest running deer exclosure studies in Pennsylvania, suggest that without significant forest management interventions to control intense deer herbivory and the spread of invasive species, the loss of oak species will be a primary consequence. The absence of oak species regeneration in many eastern hardwood forests presents one of the greatest challenges to forest managers in the region. Overabundant deer, the spread of invasive species, and the lack of surface-level fire disturbance have all contributed to the absence of oak regeneration.

Deer Exclosure Study

In order to evaluate the impact of deer on tree regeneration at the Baltimore Reservoir Forests, a deer exclosure study was initiated as a follow up to the 2001 forest inventory (Northrop 2001). According to the Baltimore Reservoir Forests Conservation Plan, 20 study sites were selected across the three reservoir forests (Fig. 7, 8, 9). The sites were assigned identification numbers corresponding to the stands in the forest conservation plan. Several factors were considered in site selection. The sites represented the variety of vegetative communities, soil types, stand ages, and deer browse levels, at the reservoir forests. Each study site contained two plots which were located on the same soil type in order to study the same vegetative communities (Northrop 2001). In the 2001 City of Baltimore Municipal Watershed Deer Browse Damage Study introduction, Northrop provides a stand description for each study site (Tables 2, 3, 4).

Each study site contained a fenced exclosure plot which excluded deer, and an adjacent un-fenced reference control plot in which deer had free access. Exclosure plots measured 8x8 ft., with green painted steel tee-posts placed in the ground at each of the 4 corners. Galvanized wire mesh fence material (2 in. x 4 in., 7 ft. height) was placed around and wired to the 4 posts, which excluded deer from the exclosure plots (Figs.10a, 10b). The top of the fenced exclosures were not covered with the wire mesh fence material. One unfenced control plot was associated with each fenced exclosure plot and placed within 20 ft. of the fenced exclosure. The unfenced control plot measured 8x8 ft., with the four corners identified with steel rebar placed in the ground. Approximately 1 ft. of the rebar was left above ground and painted orange.

Fig. 7: Liberty Reservoir Forest (Feldt 2010).

Study Sites	Stand Age Years	Forest Cover Type	Understory	Soil Series	Deer Browse
L28F	30-40	Yellow-Poplar/ Red Pine	Multiflora Rose Christmas Fern Honeysuckle		Heavy
L1C	70-80	Chestnut Oak/ Northern Red Oak	Chestnut Oak	Chrome	Intermediate
L8C	30-40	White Pine	Thimbleberry Wild Strawberry Spicebush	Manor channery	Heavy
L15A	7-10	Mixed Hardwoods	Red Maple Northern Red Oak Yellow-Poplar Multiflora Rose		Heavy
L251	35-40	Loblolly Pine	Raspberry Thimbleberry Honeysuckle Christmas Fern Multiflora Rose		Intermediate
L1A	100-110	Mixed Oak	Multiflora Rose Wild Strawberry Red Maple	Legore	Light
L18E	25-30	Red Maple/ Northern Red Oak	Mountain Laurel Maple-leaf Vib. Red Maple		Light

Table 2: Liberty Reservoir Forest - Deer Study Sites (Northrop 2001).

Fig. 8: Loch Raven Reservoir Forest (Feldt 2010).

Study Sites	Stand Age Years	Forest Cover Type	Understory	Soil Series	Deer Browse
LR 27B	40-50	Yellow-Poplar	Multiflora Rose Honeysuckle	Hollinger & Conestoga	Heavy
LR 25D	60-70	Yellow-Poplar	Spicebush Multiflora Rose Greenbrier	Manor & Brandywine	Intermediate
LR 23D	100-110	Yellow-Poplar/ Eastern White Pine	Spicebush Multiflora Rose American Beech Honeysuckle Wild Strawberry Thimbleberry	Manor channery	Intermediate
LR20A	60-70	Eastern White Pine	Spicebush	Captina	Intermediate
LR16A	30-40	Eastern Red Cedar/ Virginia Pine	Common Privet Honeysuckle	Hollinger & Conestoga	Heavy
LR5A	20-30	Silver Maple/ Black Cherry	American Holly Common Privet Wild Strawberry Honeysuckle	Baltimore	Light
LR34A	20-30	Virginia Pine/ Yellow-Poplar/ Green Ash	Honeysuckle Violet Multiflora Rose Black Cherry Box Elder American Beech	Baltimore	Heavy

Table 3: Loch Raven Reservoir Forest - Deer Study Sites (Northrop 2001).

Fig. 9: Prettyboy Reservoir Forest (Feldt 2010).

Study Sites	Stand Age Years	Forest Cover Type	Understory	Soil Series	Deer Browse
PB31A	20-30	Virginia Pine	Red Maple Low-Bush Blueberry American Holly Honeysuckle Eastern Hophornbeam	Mount Airy	Heavy
PB22A		Yellow-Poplar	Black Cherry Red Maple Raspberry Blueberry Multiflora Rose		
PB37B	40-50	Black Oak/ Chestnut Oak	Mountain Laurel Red Maple	Mount Airy	Light
PB11A	30-40	Shagbark Hickory/ Northern Red Oak	Thimbleberry Honeysuckle Red Maple Maple-Leaf Vib	Manor & Brandywine	Heavy
PB16A		Northern Red Oak/ White Oak	Chestnut Oak Blueberry Mountain Laurel		
PB2C2	20	Pitch Pine	Greenbrier Spicebush Honeysuckle	Manor channery	Light

Table 4: Prettyboy Reservoir Forest - Deer Study Sites (Northrop 2001)

Fig.10a: Loch Raven Reservoir Forest deer exclosure plot LR 16A (Strang 2011).
Note invasive species honeysuckle and oriental bitter sweet inside exclosure, and Japanese stiltgrass outside fence.

Fig.10b: Liberty Reservoir Forest deer exclosure plot L 15A 2010.

Vegetation Data Collection

From 2001 to 2010, each deer study site was visited bi-annually or annually (in the spring or summer, and the fall), to collect data on vegetation in each exclosure and control plot (Figs.10a, 10b). In 2002, 2004, 2005, and 2010, the data was collected once annually at the study sites. Baltimore City Department of Public Works employees were responsible for collection of field data, usually in a team of two people. Data collected consisted of live stem counts of woody vegetation for tree seedlings and saplings, and shrubs. Species were identified and recorded according to size classes: 1.) under 1ft. height, 2.) 1ft. to 2.9 ft. height, 3.) 3 ft. and higher. Any seed dispersing trees within 100 ft. of the plots were identified and recorded. Invasive weed species growing in the plots were identified, and a visual estimation of the percentage ground covered by the weeds was recorded.

Statistical Analyses

This thesis study examines the woody stem count data collected over the 10-year deer exclosure period, to explore differences in seedling densities related to deer herbivory. Given the small sample size of the monitoring plots set out by the Maryland DNR Foresters, observations from the 10 years were treated as replications at the plot level.

Linear regression was used to assess differences between seedling counts in the fenced exclosure plots and in the adjacent unfenced control plots. The dependent variable of interest is Y_{ij} , the number of seedlings in the i th treatment and the j th reservoir. The fenced and unfenced plot treatments were set out in each of the three separate reservoir forest watersheds.

The regression model is of the form:

$$Y_i = \beta_0 + \beta_1 * \text{Reservoir} + \beta_2 * \text{Treatment} + \varepsilon,$$

where Y_i is as stated above, Reservoir is a blocking variable accounting for variation due to unmeasured geographic factors, Treatment has two levels consisting of fenced versus unfenced plots, ε is the unexplained error, and β_0 , β_1 , and β_2 are model parameters.

The PROC REG in version 9.4 of Statistical Analysis System (SAS) was used to fit (SAS Institute 1999) the model parameters. A significance level of $\alpha = 0.05$ was used as criteria of statistical significance for all tests.

CHAPTER 3: RESULTS

Diversity of Tree Species

Across all three Baltimore City Reservoir Forests, from 2001 through 2010, 43 tree and shrub species were recorded in the 20 fenced exclosure plots. The 20 unfenced control plots contained 33 species. This represents a 26% difference in tree and shrub species recorded, between the fenced exclosure plots and unfenced control plots.

A total of 7350 live woody stems were recorded in the fenced exclosure plots over the ten year period. Over the same time period, 5560 live woody stems were recorded in the unfenced control plots. This represents a 28% difference in richness ($p = 0.001$) between exclosure and control plots (Fig. 11).

Dominant Species

Six tree species accounted for 44% of all live woody stems recorded in the fenced exclosure plots, and 50% in the unfenced control plots. The six tree species included oaks (*Quercus spp.*), hickories (*Carya spp.*), ash (*Fraxinus spp.*), yellow-poplar (*Liriodendron tulipifera*), red maple (*Acer rubrum*) and black cherry (*Prunus serotina*).

Shrub species accounted for 42% of all live woody stems recorded in the fenced exclosure plots, and 39% in the unfenced control plots. The shrub species recorded included common serviceberry (*Amelanchier arborea*), barberry (*Berberis thunbergii*), blackhaw (*Viburnum prunifolium*), black hawthorn (*Crataegus spp.*), autumn olive (*Elaeagnus umbellata*), witch-hazel (*Hamamelis virginiana*), mountain laurel (*Kalmia latifolia*), spicebush (*Lindera benzoin*), common privet (*Ligustrum vulgare*), multiflora rose (*Rosa multiflora*), blueberry (*Vaccinium*), and (*Viburnum spp.*).

Species - All Reservoirs - 2001 to 2010

Fig. 11: Species abundance in fenced exclosure plots and unfenced control plots, 2001-2010.

Table 5. Species abundance in fenced exclosure plots and unfenced control plots, 2001-2010. Oaks, Hickories, Oaks & Hickories, All Stems, Shrubs, All Trees, Invasive Shrubs, Invasive Trees.

Species	Total Stems	Unfenced Control	Fenced Exclosure	Difference	% Difference
Oaks	383	117	266	149	78
Hickories	325	91	234	143	88
Oaks & Hickories	708	208	500	292	82
All Stems (Trees & Shrubs)	12,190	5,560	7,350	1790	28
Shrubs	5,299	2,181	3,118	937	35
All Trees	7,611	3,379	4,232	853	22
Invasive Shrubs	879	235	644	409	93
Invasive Trees	40	16	24	8	40

Treatment Response

The effect of the fenced exclosure treatment was significant for oaks ($p = 0.001$), and hickories ($p = 0.001$). For oak and hickory stems combined, the fenced treatment effect was significant ($p = 0.0001$), (Table 6, Fig. 12). Seedling and sapling density for these two tree species was significantly greater in the fenced exclosure plots compared to the unfenced control plots. Seedling and sapling density was greater in the fenced exclosure plots compared to unfenced control plots for most of the other tree and shrub species counted (Table 5); however, the difference was significant for the shrub species ($p = 0.037$) but not for tree species ($p = 0.149$). For all stems counted, tree and shrub species combined, the difference was significant ($p = 0.030$), (Table 6, Fig. 13).

The density of invasive shrub species was significantly greater in the fenced exclosure plots compared to the unfenced control plots ($p = 0.026$). For invasive trees, the difference was not significant ($p = 0.474$), (Table 6, Fig. 14). There were only 40 invasive tree stems counted in the study (16 unfenced and 24 fenced), and 879 invasive shrubs (235 unfenced and 644 fenced), (Table 5).

The density for oaks was statistically different between reservoir forests ($p = 0.001$), (Table 6). The reason for this difference could not be determined in this study. These differences could be related to management or geographic differences at the reservoirs. Future studies could explore these differences between reservoir forests.

Table 6: Summary of regression estimates for oaks, hickories, oaks and hickories, all stems, shrubs, all trees, invasive shrubs, and invasive trees. Significance level alpha set to 0.05.

Variable	DF	Parameter estimate	Standard Error	t Value	Pr > t
Oaks					
Intercept	1	-0.369	0.356	-1.040	0.301
Reservoir	1	0.494	0.154	3.220	0.001
Treatment	1	0.810	0.242	3.350	0.001
Hickories					
Intercept	1	0.81246	0.349	2.33	0.0205
Reservoir	1	-0.1564	0.15062	-1.04	0.2998
Treatment	1	0.77717	0.23692	3.28	0.0011
Oaks and Hickories					
Intercept	1	0.44358	0.60457	0.73	0.4636
Reservoir	1	0.33792	0.26093	1.3	0.1961
Treatment	1	1.58696	0.41041	3.87	0.0001
All Stems					
Intercept	1	34.218	6.572	5.210	<.0001
Reservoir	1	-1.968	2.836	-0.690	0.488
Treatment	1	9.728	4.461	2.180	0.030
Shrubs					
Intercept	1	7.797	3.576	2.180	0.030
Reservoir	1	1.996	1.543	1.290	0.197
Treatment	1	5.092	2.427	2.100	0.037
All Trees					
Intercept	1	26.421	4.725	5.590	<.0001
Reservoir	1	-3.964	2.039	-1.940	0.053
Treatment	1	4.636	3.207	1.450	0.149
Invasive Shrubs					
Intercept	1	1.74747	1.4661	1.19	0.2341
Reservoir	1	-0.23138	0.63276	-0.37	0.7148
Treatment	1	2.22283	0.99526	2.23	0.0261
Invasive Trees					
Intercept	1	0.27721	0.08933	3.1	0.0021
Reservoir	1	-0.0936	0.03855	-2.43	0.0157
Treatment	1	0.04348	0.06064	0.72	0.4738

Fig. 12: Oaks, hickories, oaks and hickories: Predicted average number of seedlings in fenced and unfenced treatments. Error bars represent the average standard error of the estimated number of stems over all three watersheds.

Fig. 13: All stems, shrubs, all trees: Predicted average number of seedlings in fenced and unfenced treatments. Error bars represent the average standard error of the estimated number of stems over all three watersheds.

Fig. 14: Invasive shrubs, invasive trees: Predicted average number of seedlings in fenced and unfenced treatments. Error bars represent the average standard error of the estimated number of stems over all three watersheds.

Role of Invasive Species

The 2001 City of Baltimore Municipal Watershed Deer Browse Damage Study introduction describes the understory of the 20 deer study sites (Tables 2, 3, 4), (Northrop 2001). Five invasive species were observed: multiflora rose (*Rosa multiflora*), common privet (*Ligustrum vulgare*), honeysuckle (*Lonicera maackii*), garlic mustard (*Alliaria petiolata*), and Christmas fern (*Polystichum acrostichoides*) considered a native invader.

From 2001-2010, invasive species were recorded, with invasive vines observed growing on the exclosure fences (Figs. 15, 16). Japanese stiltgrass (*Microstegium vimineum*) and oriental bittersweet (*Celastrus orbiculatus*) were recorded, in addition to the 5 invasive species reported at the start of the study. Eight study sites (fenced exclosure plots and unfenced reference control plots) were reported to have 50% or greater of the understory composed of invasive species. The eight study sites included the following. Loch Raven had >50% coverage on 5 study sites recorded in 2010. In Loch Raven this included LR16A, LR20A, LR27B, LR25D, and LR34A. The LR34A control plot understory was reported to be 100% Japanese stiltgrass. In Prettyboy, exclosure plot PB16A was 99% ferns and control plot 75% ferns. In Liberty, exclosure plot L15A was 99% multiflora rose and control plot 80% multiflora rose, and L28F exclosure plot and control plot were each 100% multiflora rose and oriental bittersweet.

In 1960, Reigner and Sushko noted that plantation plantings of loblolly pine and eastern white pine in the reservoir forests were inhibited by invasive honeysuckle. Research on herbicide control of honeysuckle was conducted at this time by the USFS Northeastern Forest Experiment Station, and Maryland Department of Forests and Parks (Reigner and Sushko 1960).

Fig. 15: Liberty exclosure plot L28F.

Fig. 16: Loch Raven exclosure plot LR34A.

CHAPTER 4: DISCUSSION

Deer Browsing

The findings from the Baltimore City Reservoir Watershed Forests Deer Exclosure Study, suggest that deer browsing affected seedling and sapling density of oak and hickory species. Seedling and sapling density for these two tree species were significantly greater in the fenced exclosure plots where deer were excluded. Although not statistically significant, seedling and sapling density for most other tree species were greater in the fenced exclosures where deer were excluded. The seedling density of shrub species was significantly greater in the fenced exclosure plots.

The findings for oaks and hickories are consistent with other deer exclosure studies which found that deer selectively browse tree species, resulting in lower seedling and sapling densities for preferred browse species (Abrams and Johnson 2012, Rossell et al. 2007, Rooney and Waller 2003, Waller and Mass 2013). Researchers have concluded that deer selectively browse tree seedlings and saplings of species which are most palatable to them (Bugalho et al. 2013, Russell et al. 2001, Horsley and Marquis 1983). Palatability is determined by nutritional quality which is a function of intrinsic bio-chemical properties of the plant, including plant cell contents (e.g. nitrogen and lignin) and the presence of chemical defenses (e.g. secondary phenolic compounds). Soil nutrient content (minerals specific to growing sites) contributes to bio-chemical properties of the plant. Nutritional quality varies with stage of plant growth. As juvenile trees mature (seedling to sapling), chemical and structural defenses (e.g. spines and trichomes) develop which affect nutrient quality and palatability (Bugalho et al. 2013, Boege and Marquis 2005). Palatability has been found to be specific to tree species. *Quercus*, *Carya*, and *Fraxinus* are highly preferred browse genera. *A. rubrum*, *L. tulipifera*, and *P. serotina* are

less preferred (Abrams and Johnson 2012, Horsley et al. 2003, Cote et al. 2004, Abrams 1998, Hicks 1998).

Seedling Density Variation

Deer feeding selectivity can be influenced by the availability of tree seedlings. In any given forest type, the density of tree seedlings vary with forest disturbance history or legacy effects which have restricted regeneration and recruitment of species (Bugalho et al. 2013, Royo et al. 2010b). Some tree species have evolved and adapted to survive and regenerate in specific disturbance conditions (e.g. oaks with fire disturbance). The disturbance history of the Baltimore Reservoir Forests includes clearing of forests for agriculture starting in colonial times, reforestation, repeated forest fires, and the elimination of fire at the end of the twentieth century. The type of tree species present and their seedling abundance available in a stand for deer to browse, are influenced by this disturbance dynamic history.

Density of tree seedlings is also subject to inter-annual variation in regeneration and recruitment. The majority of tree seedlings regenerating under a closed canopy fail to reach the overstory as a result of insufficient light, water, and nutrients (McGarvey et al. 2013). Competition for light and water are primary factors influencing tree seedling regeneration and performance (Aronson and Handel 2011, Flory et al. 2015). Year-to-year variation in tree seedling regeneration is influenced by annual precipitation. Periods of extreme drought and high rainfall can increase mortality of tree seedlings. Extremes in precipitation levels can also affect tree seed production (Bugalho et al. 2013, Ibanez et al. 2007). Variation in annual precipitation was observed in central Maryland over the ten year period of the Baltimore Deer Exclosure Study. The normal average annual precipitation for central

Maryland is 41 inches. Central Maryland experienced drought in 2001 with 33 inches of precipitation recorded at the Maryland Science Center in Baltimore City. Higher than normal precipitation was recorded in 2003 at 57 inches, and 2009 at 53 inches. Other precipitation measuring sites in the Baltimore area reported > 60 inches precipitation in 2003 (Maryland State Climatologist 2017). Although previous studies have found that annual precipitation levels can influence tree seedling regeneration (Aronson and Handel 2011, Bugalho et al. 2013), there was no correlation between annual precipitation and tree seedling regeneration in the Baltimore Deer Exclosure Study.

In the event small tree seedlings (<1ft.) die off within a year because of drought or shade, that portion could be masking a deer browse-based trend which affects only the seedlings surviving through the summer and are browsed in winter, e.g. the larger seedlings (>1 ft.). This effect could not be determined in the Baltimore Deer Exclosure Study, without tagging individual tree stems and tracking survival over the entire time period of the deer exclosure study. Shrubs compared to trees, are generally more resilient and better adapted to survive shade and drought. Many shrub species are shade tolerant and exhibit sprouting.

Direct and Indirect Effects of Deer Browsing

Deer browsing directly affects the survival of tree seedlings. Deer exclosure studies reveal that tree seedling survival is reduced by intensive foliar browsing of favored species (Abrams and Johnson 2012, Bugalho et al. 2013, Tilghman 1989). Deer have a much larger effect on the survival of seedlings and saplings than on the rate at which seeds, including acorns, become seedlings (germination rate), (Russell et al. 2001). Reduction of photosynthetic capability of seedlings and saplings, as a result of deer herbivory, increases mortality risk and

inhibits vertical recruitment (McGarvey et al. 2013). The most common effect of deer browse reported is a change in plant morphology following removal of the terminal meristem. The embryonic tissues contained in the terminal meristem are critical for production of plant tissues and structures (Russell et al. 2001). Consumption of the whole plant or plant parts diminishes the competitive capacity of both seedlings and saplings, and their ability to persist in the forest understory (Hulme 1996). Herbivory can reduce growth rates of both tree seedlings and saplings (Russell et al. 2001, Alverson and Waller 1997). Susceptibility to herbivory however, can vary between seedling and sapling stages, and within species (Bugalho et al. 2013, Boege and Marquis 2005).

Survival of tree seedlings can be affected indirectly through changes in competitive interactions between plants, induced by selective browsing which favors the survival of unpalatable tree species and shrubs (Bugalho et al. 2013). Herbivory can reduce competition from herbaceous cover, indirectly mediating the survival and establishment of tree seedlings (Bugalho et al. 2013, Horsley and Marquis 1983). This indirect effect may explain the greater abundance of red maple and yellow-poplar seedlings and saplings in the unfenced control plots of the Baltimore Deer Exclosure Study. Although this difference was not statistically significant, deer herbivory could remove plants competing for growing space and resources, releasing the two tree species.

The effects of herbivory are cumulative and variable in both time and space (Russell et al. 2001). Inouye et al. (1994) found that deer significantly reduced growth of red oak and white pine seedlings in only the 2nd and 4th years of a 9 year study. The significant negative effects observed in years 2 and 4 however, caused a significant over-all negative effect on growth of both tree species over the 9 year study. Indirect effects may account for significant changes in

community structure and composition (Rooney and Waller 2003). Deer herbivory potentially influences long-term successional dynamics by limiting seedling survival and sapling growth (McGarvey et al. 2013). Studies suggest that the effects of deer accumulate over time (Horsley et al. 2003). Deer can indirectly affect specific vegetation outcomes over time by facilitating the dominance of unpalatable or browse-resilient tree and shrub species, such as red maple, black cherry, and spice bush (Bugalho et al. 2013, Horsley et al. 2003). When these species become established in forest communities, competition for resources can make re-establishment of preferred and less browse-resilient species difficult (e.g. oaks, hickories), (Horsley et al. 2003). Black cherry, and shade tolerant red maple and spice bush were abundant in the exclosure and control plots at the Baltimore Reservoir Forests.

Deer effects are not only accumulative but also interactive and re-enforcing (Strange 2011). Paine (1995), Rooney and Waller (2003) describe deer as strong interactors that can generate indirect effects in structuring forest communities. As keystone herbivores in eastern hardwood forests, deer interact strongly with plants, greatly affecting their distribution and abundance, restructuring whole ecological communities (Waller and Alverson 1997, Paine 1995, Rooney and Waller 2003). In addition to browsing effects, deer disperse seeds (native and invasive), and create concentrated patches of nutrients through urination and defecation (Rooney and Waller 2003). Studies suggest that deer herbivory creates and sustains conditions for invasive species to dominate understory forest communities (Rossell, Jr. et al. 2007). Exclosure studies document significant deer x invasive plant species interactions accounting for reduced woody species abundance and native plant diversity (Waller and Mass 2013, Duquay and Farfaras 2011). Waller and Mass (2013) found invasive garlic mustard reduced growth of oak seedlings significantly more in the absence of deer, suggesting an interactive effect. Duquay and

Fararfas (2011) found unfenced control plots had more Japanese stiltgrass compared to fenced exclosures, and was the most abundant species in the control plots. They concluded that the combination of deer herbivory on native plants and the competition from Japanese stiltgrass, accounted for lower woody species abundance and native plant diversity in the unfenced control plots.

Restoration efforts can be particularly problematic with stands invaded by Japanese stiltgrass and ferns. These browse-resilient invaders share characteristics that provide a competitive edge over native tree species. Both shade tolerant invasive species possess allelopathic defenses, and interfere with native tree establishment primarily through reduction of light. During the Baltimore Deer Exclosure Study, we found several exclosure plot fences overgrown with the invasive vines honeysuckle and oriental bittersweet which cast shade on the plots (Fig 15, 16). Once invasive species become established in forest communities, tree species regeneration and restoration of diversity become difficult. Forest stands dominated by understory invasive species may in some cases represent an alternate stable state, which may persist even after removal of the original cause, high deer density (Horsley et al. 2003, Abrams and Johnson 2012). Invasive species observed in the Baltimore Deer Exclosure Study plots present a challenge for future forest restoration efforts.

Oaks

The unmanaged oak-hickory dominated forests of the Eastern United States, with high deer densities, are not regenerating oaks and other favored browse tree species. Studies indicate that the understories of these forests are no longer dominated by oaks (Abrams and Johnson 2012). The results of the Baltimore Deer Exclosure Study are consistent with the findings of

these studies, and confirm the conclusion of the Baltimore City Reservoir Forests Conservation Plan, that the watershed forest is no longer regenerating oak species, and intensive deer herbivory appears to be a major contributing factor (Northrop 2001).

Like other eastern hardwood forests threatened by over-abundant deer populations, the successional status of the Baltimore Reservoir Forests is changing to tree species not favored by deer, including shade tolerant tree species and invasive species. Intense browsing of seedlings and small saplings also appears to be changing stand structure to one where large saplings and mature trees are disproportionately represented in greater numbers (Northrop 2001, McGarvey et al. 2013, Côté et al. 2004, Tilghman 1989). Successional dynamics have been influenced by selective browsing of palatable tree seedlings, altering the composition, density, and diversity of the forest understory layer (McGarvey et al. 2013, Horsley et al. 2003, Rooney and Waller 2003,). The loss of oak seedlings from the understory layer in oak-dominated forests could lead to the elimination of oaks from the overstory (McGarvey et al. 2013). Even with the removal of deer and intensive browsing, less favored and resilient browse species, including shade tolerant tree species and invasive species, could continue to increase while oaks decline (Abrams and Johnson 2012).

Deer Density

Intensive herbivory resulting from high deer populations is clearly a limiting factor for oak regeneration and other preferred browse species in some eastern hardwood forests (Hicks 1998, Lorimer 1993). The threshold for deer population density necessary for deer-induced failure of tree regeneration and recruitment is difficult to determine. Deer populations in the Eastern U.S., prior to European settlement, were estimated to have been 4 deer/km² (Abrams and

Johnson 2012). Waller and Alverson (1997) suggest that deer density $> 4/\text{km}^2$ could cause detrimental impacts to browse-sensitive tree seedlings. Russell et al. (2017) suggest that less than 40% of northern U.S. forests may have deer densities below this level. Some studies estimate current deer density to be 2-4 times greater (Russell et al. 2001). Surveys estimate deer density at the Baltimore Reservoir Forests to be between 31.27- 36.62 deer/ km^2 (Gilgenast et al. 2009, Maryland DNR 1998, Eyler 2013). Russell et al. (2001) found that all studies which documented deer-induced failure of tree recruitment were conducted in stands where deer densities exceeded 8.5 deer/ km^2 . Results from a Pennsylvania deer exclosure study, in large blocks of contiguous forest under a 100-year rotation, suggest that many tree species will decrease at deer densities > 8 deer/ km^2 (Horsley et al. 2013). Tilghman (1989) recommends a target deer density of < 7 deer/ km^2 in managed eastern hardwood forests.

Forest deer carrying capacities vary spatially and temporally; because, food is more abundant and available in some areas than in others, and in some years and seasons (Russell et al. 2001). Local deer census counts from state game agencies along with an accurate assessment on the abundance of preferred browse species (inventory), can give an indication as to the potential effects of deer on tree regeneration in a stand (Hicks 1998). In early successional forest habitat, including clearcut and heavily thinned stands, local deer density can determine the magnitude of the effects of herbivory on the rate and direction of forest succession. The magnitude of deer effects may be diminished in larger early successional areas, because deer browsing is less concentrated (Tilghman 1989, Russell et al. 2001). In large canopy thinned treatments, herbivore consumption can become saturated when plant regeneration becomes extremely abundant; while, in stands with a low density of regeneration, the same number of deer can exert greater impact on the tree seedlings present (Fig. 17), (Hicks 1998, Marquis et al.

1992, Tilghman 1989). Future timber harvests and treatments planned for the Baltimore Reservoir Forests should consider the size of harvested areas and the potential deer impacts which may result.

Fig. 17: Deer impact index (Hicks 1998, from Marquis et al. 1992).

The magnitude of deer effects on plant survival and fecundity is affected by the timing of herbivory. Stem clipping studies simulating deer herbivory found increased mortality and reduced fecundity during late growing season; while, winter clipping had little or no effect upon plant mortality (Russell et al. 2001). Deer can congregate in geographic areas as a result of limited movement or migration, leading to year-round browsing pressure. Constant browsing pressure across all seasons can result in greater tree seedling mortality and reduced growth, in comparison to either summer or winter browsing. During winter, deciduous foliage is reduced, and browsing can shift to less palatable green conifers if available (Augustine 1997). Deer impacts should be considered in any future plans for planting and managing pine plantations in the Baltimore Reservoir Forests.

Exclosure Study Limitations

Exclosure studies provide evidence that deer can have substantial impacts on tree seedling and sapling growth and survival, altering forest structure and composition. Russell et al. (2001) caution however, that researchers should be careful in concluding that such effects are always widespread and common place. The local density of deer, and the availability and abundance of plants vary temporally and spatially, contributing to variation in deer effects on forest communities (Russell et al. 2001). It is difficult to interpret the long-term effects of deer on vegetation because of changes in ambient deer density and food supply, as deer move through a forest matrix with patches of different disturbance levels (Horsley et al. 2003, McGarvey et al. 2013).

Rooney and Waller (2003) suggest that deer exclosure study findings may be confusing and challenging to interpret. The exclusion of deer in study plots creates conditions that exist

outside the natural range of variation for deer densities in forest communities (Rooney and Waller 2003). The Baltimore Deer Exclosure Study, like most exclosure studies conducted in eastern forests, compared the effects of zero deer density inside the fenced plots with ambient deer density outside the fence, and within a single disturbance level (undisturbed). Horsley et al. (2003) suggest that some mechanisms of deer-plant interaction may be nonlinear, with gradients of deer density. Because deer exclosure studies like the Baltimore study provide only two points of reference for density, nonlinear effects are difficult to observe (Horsley et al. 2003). Although the results may be limited by failing to account for possible effects of browsing gradients, deer exclosure studies can nevertheless provide useful insights into the effects of deer on forest dynamics and possible management solutions (Bugalho et al. 2013).

Interpreting deer exclosure study results and determining significance, is complicated by the myriad of variables that influence tree regeneration and recruitment. Disturbance history can have a particularly strong influence (McGarvey et al. 2013). Russell et al. (2001) note that deer exclosure studies are prevalent since 1970, and much of the literature relevant to deer effects on plants has been published in the last 35 years, yet most dramatic forest disturbances have happened in the past, so present forest vegetation has already undergone most changes that deer can cause. Deer effects on plants can be missed because there is no baseline to serve as a reference. Tree regeneration of preferred browse species may now be so rare or absent from some eastern hardwood forest understories that the effects of deer can no longer be detected (Russell et al. 2001). Earlier years of chronic deer browsing of preferred tree species can result in stands with low tree regeneration potential. Changes in deer exclosure plots can be strongly influenced by local tree species pools and seed banks, which may have already been depleted

from chronic browsing before the fencing of exclosure plots (Russell et al. 2001, Rooney and Waller 2003).

Rather than fenced deer exclosure plots creating conditions that would occur without browsing, exclosures can illustrate the recovery potential of plots in the absence of deer (Rooney and Waller 2003). These scenarios could represent the forest dynamics of the Baltimore Reservoir Forests. The Baltimore City Reservoir Forests Conservation Plan noted that tree regeneration was conspicuously absent in the forest understory (Northrop 2001). We know that extensive disturbance occurred in this forest watershed prior to this study and organization of the Baltimore Reservoirs. The effects of the growing deer population in Baltimore County and the reservoir watershed forests have also been reported prior to this study (Maryland DNR 1996, Maryland DNR 1998).

Research has shown that under a closed forest canopy, the vast majority of regenerating tree stems fail to reach the overstory as a result of insufficient light, water, and nutrients (McGarvey et al. 2013, Aronson and Handel 2011). In a closed canopy forest, natural delays in mature tree recruitment may also mask the full impact of deer herbivory for decades (McGarvey et al. 2013).

Future Study Recommendations

Future studies examining the effects of deer at the Baltimore Reservoir Forests should consider several modifications to methods for data collection and analysis. First, the size of the study site plots should be increased as well as the number of sites, to add power to statistical analysis. Results from deer exclosure studies are usually limited by the size of fenced plots (Bugalho et al. 2013). Larger plots allow for collecting a larger pool of data for evaluation.

With competing plant species confined to the small area of fenced plots, like the 8x8 ft. plots in the Baltimore study, light levels are limited on the forest floor (Abrams and Johnson 2012).

Abrams and Johnson (2012) also suggest that deer enclosure fences provide perches for birds who serve as vectors for high seed inputs of plant species including invasive species. The fences in the Baltimore Deer Exclosure Study plots appeared to also serve as a structure for invasive vines to become established, e.g. Japanese honey suckle, oriental bittersweet, and English ivy (Figs. 15, 16).

The second recommendation would be for all tree seedlings and saplings identified to be individually tagged, measured, and tracked over the entire time period of the study. This method of repeatedly censusing individual tree seedlings would allow for assessing survival rates over time (Russell et al. 2001). Thirdly, total vegetation ground cover (including invasive herbs and vines) should be measured and recorded by plot.

Implementation of these recommendations would require substantial investments in manpower and time to be successful. Experimental study success is also dependent upon consistent data collection, measurements, and recordation.

Management Recommendations Discussion

The forest inventory conducted for the Baltimore City Reservoir Forests Conservation Plan found that the reservoir forests exhibited an extensive and intensive lack of natural tree regeneration. The plan suggested that the extremely high deer population was the principle cause for the lack of suitable advanced tree regeneration (Northrop 2001). The results from the follow-up deer exclosure study suggest that deer herbivory is an important contributing factor for the lack of tree seedlings and saplings in the reservoir forests, particularly for oak and hickory

species. The scarcity of oak seedlings and saplings in the Baltimore Reservoir Forests is typical of many eastern hardwood forests with high deer densities (Abrams and Johnson 2012, Abrams 1992). In addition to deer herbivory however, other factors have contributed to the virtual cessation of oak species recruitment which include lack of disturbance, particularly fire, and an increase in shade tolerant tree species and invasive species (Abrams and Johnson 2012, Abrams 1992, 1998, Cote et al. 2004). Forest management for the restoration of oak species requires that all these factors be addressed.

Restoring advanced tree regeneration begins with reducing deer herbivory. Hunting female deer (does) is the only effective method to reduce herd size (Hicks 1998). Deer hunting with bow has been permitted at Prettyboy and Liberty Reservoir Forests for over 40 years however, not at the Loch Raven Forest until 2008 (Strang 2011, Baltimore DPW 2017). In addition to hunting, Hicks (1998) describes four approaches to managing forests with high deer populations. First is exclusion/protection by utilizing fences and tree shelters, an option which is expensive and impractical for large stands. Second is inhibition by scattering or piling stand harvest slash, creating an impediment to the movement of deer and allowing tree seedlings to escape browsing. Third is satiation, a technique used in even-aged management methods, e.g. clearcutting, seed-tree, and shelterwood. These methods can create an abundance of regeneration and overwhelm the local deer herd with food (Fig. 17), (Marquis 1992). Large cutting blocks have a greater ratio of interior to perimeter, with a total biomass of regeneration large enough to satiate the deer population. Square and circular harvest site openings also have perimeters which are less exposed to browsing, compared with long and narrow openings. The fourth approach described by Hicks (1998) is the use of commercial repellents, which are expensive and impractical for large-scale operations. Future timber harvests and treatments at

the Baltimore Reservoir Forests should consider the satiation technique, size of cutting blocks, and shape of harvested areas.

When deer densities are reduced to appropriate levels (< 7 deer/km²), (Tilghman 1989), it is not clear how quickly restoration of forest structure and function, and species diversity can be achieved (Lantham 2005, Horsley et al. 2003). Studies suggest that the regrowth of forest understories and tree regeneration can occur in a few years following the reduction or exclusion of deer; however, full recovery of the structure and function of forest ecosystems will likely take decades, and may require active and expensive interventions (e.g. silvicultural treatments, prescribed fire, and planting of tree seedlings) beyond the reduction of deer numbers. Over time, the overbrowsing-induced dominance of unpalatable and browse-resilient species interferes with the re-establishment of tree species lost to browsing, even if overbrowsing stops. As a result, overbrowsing can cause a persistent change in the trajectory of vegetation and forest succession. The longer overbrowsing persists, the more difficult it becomes to restore the original native tree species, in part because seed and other propagule supplies have been greatly reduced or eliminated (Lantham 2005).

In oak-hickory stands with depleted advanced regeneration, such as the Baltimore Reservoir Forests, researchers recommend several management strategies for restoration of oak species. Whether on productive mesic sites or less productive xeric sites, light is the primary limiting factor for successful regeneration and recruitment of oaks. Understory light levels are critical for survival and growth of all oak species (Rentch et al. 2003, Carvell and Tryon 1961), and dense shade hinders oak regeneration development (Brose and Van Lear 1997, Lorimer 1993). Under a closed canopy, oak advance regeneration rarely grows into the overstory because of its relative intolerance to shade. In most instances, the density of the canopy must be reduced

to introduce light and open growing space for regeneration, and allow recruitment of oaks into the overstory (Larsen and Johnson 1998).

Even-aged management is the most common silvicultural prescription for oak forests, reducing overstory densities and increasing understory light levels. The preference for even-aged systems is due in part to the even-aged condition of most second-growth forests like the Baltimore Reservoir Forests (Rentch et al. 2003). In eastern hardwood forests, clearcutting has been a common, successful and reliable even-aged method. It has become less used because of objectives other than timber management, e.g. aesthetics, wildlife, biodiversity, and recreation. Shelterwood is frequently used and allows manipulation of overstory density and understory light levels, crucial in the restoration of older oak-hickory stands (Rentch et al. 2003). Larsen and Johnson (1998) recommend that the overstory be removed within a decade of a shelterwood treatment or oak reproduction may not be recruited into the overstory.

The initial cut in a shelterwood treatment can stimulate regeneration of fast-growing shade intolerant tree species, release of existing shade tolerant tree regeneration, and encroachment of invasive species. Reducing and inhibiting this competition by understory treatment is essential for developing oak stands (Brose and Van Lear 1997, Loftis 2004). Basal herbicide treatment can be effective for controlling competing trees. Broadcast herbicide treatment can be effective in controlling grasses and ferns (Gould 2005), but the possibility for contamination of drinking water supplies may restrict their use in the Baltimore Reservoir Forests (Brose and Van Lear 1997, de la Cretaz and Kelty 2002). Mechanical treatment (mowing) can be used as an alternative for controlling understory competition (de la Cretaz and Kelty 2002). Mowing and herbicide treatments are expensive and may not be practical in large stands. Prescribed fire is recommended, combined with shelterwood treatment, to control

competition while improving oak stem form and stimulating height growth of oak regeneration (Flory et al. 2015, Brose and Van Lear 1997).

The combination of prescribed fire and shelterwood treatment can return a natural disturbance regime, and restore oak regeneration to eastern hardwood forests, particularly on productive sites, including the Baltimore Reservoir Forests (Brose and Van Lear 1997, Rentch et al. 2003). For prescribed fire to be successful, three factors are crucial (Brose and Van Lear 1997). First, an interval of several years between harvest and burning is required for oak seedlings to develop large root systems which are less vulnerable to fire (Johnson 1974). Second, spring is recommended as the best season for burning, reducing density of competition, improving oak stem form, and stimulating height growth. Third, medium to high intensity fire is best for reducing density of competition, with minimal losses of oak species (Fig.18). The combination of prescribed fire and shelterwood treatment for oak restoration may require multiple fires, depending on development of oak regeneration during the stand initiation phase (Brose and Van Lear 1997).

High deer populations and invasive species may present the greatest challenge to forest managers in restoring oak species in eastern hardwood forests. Abrams and Johnson (2012), in one of the longest running deer exclosure studies in oak dominated eastern forests, at Valley Forge National Park in Pennsylvania, suggest that without significant forest management interventions to control deer herbivory and the spread of invasive species, the loss of oak species will be a primary consequence. Eschtruth and Battles (2008) found that the spread of invasive species can be accelerated by deer, and that canopy disturbance may magnify the impact. Waller and Maas (2013) suggest that forest managers interested in sustaining hardwood species sensitive to deer herbivory, must first reduce deer densities before addressing the control of invasive

species. For the Baltimore Reservoir Forests, deer hunting is recommended as the preferred method to reduce deer densities.

Fig. 18: Mortality (%) of oak, hickory, red maple, and yellow-poplar advance regeneration as fire intensity increases within spring prescribed burns conducted in shelterwood stands (Brose and Van Lear 1997).

Beasley and McCarthy (2011) recommend several management techniques to protect and restore eastern hardwood forest communities from the impacts of invasive species. First, monitor the forest understory area and prevent the rapid expansion of invasive species by immediate implementation of mechanical removal or treatment with plant-specific post-emergent herbicides. The second recommendation by the researchers is forest restoration of hardwood species through artificial regeneration, with direct planting of seedlings. Johnson et al. (2015) suggest forest restoration may be achieved by planting tree seedlings sufficiently large to escape competition with invasive species.

Beasley and McCarthy (2011) reported that planted two-year-old hardwood seedlings were not affected by the presence of Japanese stiltgrass under a closed forest canopy. Japanese stiltgrass presents a special challenge for oak restoration in a disturbance regime utilizing shelterwood and prescribed fire. Flory et al. (2015) found that oak restoration methods using prescribed fire will likely fail in stands invaded by Japanese stiltgrass because the temperature of fires and their duration can increase to the point where survival of oaks is significantly reduced. These results suggest a fire-invasive interaction that inhibits oak seedling establishment in invaded stands (Flory et al. 2015).

Browsing can create understories dominated by unpalatable or browse-tolerant species, e.g. Japanese stiltgrass, which can change the expected impacts of prescribed fire and large canopy gaps in shelterwood treatments (Thomas-Van-Gundy et al. 2014, Nuttle et al. 2013). Browse tolerance may be more important than shade tolerance in determining the composition of the advance tree regeneration layer (Thomas-Van-Gundy et al. 2014, Long et al. 2007, Kreuger et al. 2009, Nuttle et al. 2013). Brewer et al. (2015) recommend that oak stands heavily infested with Japanese stiltgrass be given lowest priority for restoration considering the costs involved;

however, in undisturbed stands without the invasive, selective canopy reduction with prescribed fire can be effective in restoring tree species composition. Japanese stiltgrass was observed to be a growing presence in the Baltimore Reservoir Forests from 2001-2010, and represents a serious challenge for future forest restoration (e.g. Loch Raven Reservoir Forest in 2008, plot LR 34A was covered 100% with Japanese stiltgrass).

Recommendations Summary

The city of Baltimore depends on forest cover to provide watershed protection for its three reservoirs (Reigner and Sushko 1960). For watershed management, tree regeneration is crucial in stabilizing the forest, providing soil-stabilization and protection from water pollutants. Regeneration is the foundation for species composition and forest structure. It provides a level of resistance and recovery from major disturbances such as hurricanes, ice storms, and insect outbreaks (de la Cretaz and Kelty 2002). In the Baltimore Reservoir Forests, high deer populations and invasive species may represent the greatest threats to tree species regeneration, forest resilience, and recovery from potential major disturbances. Minimizing the impacts of deer and invasive species on the reservoir forests is crucial to ensuring the quality of water resources for Baltimore City in the future.

Even-aged management is recommended to increase tree regeneration and survival, considering the strong effect of greater light levels. Methods that take into account other goals such as stand age diversity or wildlife habitat include variable density retention, shelterwood, or seed-tree with reserves.

The use of prescribed fire could be considered as a management tool for stimulating oak regeneration in the Pretty Boy and Liberty Reservoir Forests. Implementing prescribed fire at

the Loch Raven Reservoir Forest would be a greater challenge, considering the close proximity of Baltimore and suburban population surrounding the forest.

For even-aged management and prescribed fire to be effective, the problems of high deer populations and encroachment of invasive species must be addressed first. This strategy will take considerable time, before the benefits of increased oak and hickory tree regeneration are realized (Hutchinson T.F. 2012).

Fig. 19: Loch Raven Reservoir Forest, deer hunter walking through Japanese stiltgrass (Smith 2008).

LITERATURE CITED

- Abrams, M.D. 1990. Adaptations and responses to drought in *Quercus species* of North America. *Tree Physiology*. 7(1-4): 227-238.
- Abrams, M.D. 1992. Fire and the development of oak forests. *BioScience*. 42: 346-353.
- Abrams, M.D. 1996. Distribution, historical development, and ecophysiological attributes of oak species in the eastern United States. *Ann. Sci. For.* 53: 487-512.
- Abrams, M.D. 1998. The red maple paradox: What explains the widespread expansion of red maple in eastern forests? *BioScience*. 48 (5): 355-364.
- Abrams, M.D. 2002. The postglacial history of oak forests in eastern North America, p. 34-35. in W. J. McShea and W.M. Healy (eds.), *Oak forest ecosystems*. The Johns Hopkins University Press, Baltimore, MD.
- Abrams, M. D. 2003. Where has all the white oak gone? *BioScience*. 53 (10): 972-939.
- Abrams, M.D. and J.A. Downs. 1990. Successional replacement of old-growth white oak by mixed-mesophytic hardwood species in southeastern Pennsylvania. *Canada Journal Forest Resources*. 20: 1864-1870.
- Abrams, M.D., D.A. Orwig and T.E. DeMeo 1995. Dendrological analysis of successional dynamics for a pre-settlement white pine-mixed oak forest in the southern Appalachians, *USA Journal of Ecology*. 83: 123-133.
- Abrams, M.D. and S.E. Johnson. 2012. Long-term impacts of deer exclosures on mixed- oak forest composition at the Valley Forge National Historical Park, Pennsylvannia, USA. *Journal of the Torrey Botanical Society*. 139(2): 167-180.
- Abrams, M.D. and G.J. Nowacki. 2008. Native Americans as active and passive promoters of mast and fruit trees in the eastern USA. *Holocene*. 18: 1123-1137.
- Anagnostakis, S.L. 2002. The effect of multiple importations of pests and pathogens on a native tree. *Biological Invasions*. 3: 245-254.
- Aronson, M. F.J. and Handel. 2011. Deer and invasive plant species suppress forest herbaceous communities and canopy tree regeneration. *National Areas Journal*. 31 (4) 400-407.
- Augustine, D.J. 1997. Grazing patterns and impacts of white-tailed deer in a fragmented forest ecosystem. M.S. thesis. University of Minnesota, St. Paul. 3-5 pp.

- Averill, K.M., D.M. Mortensen, E.A.H. Smithwick and E. Post. 2016. Deer feeding selectivity for invasive plants. *Biological Invasions*. 18 (5): 1247-1263.
- Baltimore City Department of Public Works (DPW). 2017. publicworks.baltimorecity.gov
- Beasley, R.R. and B. McCarthy. 2011. Effects of *Microstegium vimineum* (Japanese stiltgrass) on native hardwood survival and growth: implications for restoration. *Natural Areas Journal*. 31 (3): 246-255.
- Beisner, B.E, D.T. Haydon. and K. Cudington. 2003. Alternate stable states in ecology. *Frontiers in Ecology and the Environment*. 1: 376-382.
- Besley, F.W. 1929. Maryland Geological Survey. In Northrop, R. 2001. A comprehensive forest conservation plan for long-term watershed protection on the City of Baltimore Reservoirs. Maryland Department of Natural Resources ForestService. North East, Maryland. 41p.
- Boege, K. and R.J. Marquis. 2005. Facing herbivory as you grow up: the ontogeny of resistance in plants. *Trends Ecology Evolution*. 20: 441-448.
- Boerner, R.E.J. and J.A. Brinkman. 1996. Ten years of tree seedling establishment and mortality. in an Ohio deciduous forest complex. *Torrey Botany Club*. 123: 309-320.
- Braun, E.L. 1950. Deciduous forests of eastern North America. New York: Hafner. 596 p.
- Brewer, J.S., M.J. Abbott and S.A. Moyer. 2015. Effects of oak-hickory restoration treatments On native groundcover vegetation and the invasive grass, *Microstegium vimineum*. *Ecological Restoration*. 33 (3):256-265.
- Brose, P.H. and D.H. Van Lear. 1998. Responses of hardwood advance regeneration to seasonal prescribed fires in oak-dominated shelterwood stands. *Canadian Journal of Forest Research*. 28: 331-339.
- Brush, G.S., C. Link and J. Smith. 1977. The natural forests of Maryland: an explanation of the vegetative map of Maryland. Department of Geography and Environmental Engineering. Baltimore: Johns Hopkins University. 1-2 p.
- Bugalho, M.N., I. Ibanez and J.S. Clark. 2013. The effects of deer herbivory and forest type on Tree plant growth stage. *Forest Ecology and Management*. 308: 90-100.
- Buttrick, P.L., 1915. Commercial uses of chestnut. *American Forestry*. 21: 960-968.
- Campbell, T.A., B.R. Laseter, W.M. Ford, R.H. Odom and K.V. Miller. 2006. Abiotic factors influencing deer browsing in West Virginia. *Northern Journal of Applied Forestry*. 23 (1): 20-26.

- Carvell, K.L. and E.H. Tyron. 1961. The effect of environmental factors on the abundance of oak regeneration beneath mature oak stands. *Forest Science*. 7: 98-105.
- Chadwell, L.S. and D.S. Buckley. 2003. Site and canopy characteristics associated with oak advance reproduction in mature oak- hickory forests in the Ridge and Valley Province in Tennessee. USDA Forest Service General Technical Report NC. 234: 228-236.
- Cipollini, K., E. Ames and D. Cipollini. 2009. Amur honeysuckle (*Lonicera maackii*) management method impacts restoration of understory plants in the presence of white-tailed deer (*Odocoileus virginiana*). *Invasive Plant Science and Management*. 2: 45-54.
- City of Baltimore Department of Public Works Bureau of Water and Waste Water. 1981. The story of Baltimore's water supply. 1-34 pp.
- Clark, F.B. 1968. The silviculture of oak and associated species. USDA Forest Service. Res. Pap. NE-144: 1-16.
- Coté, S.D., T.P. Rooney, J.P. Tremblay, C. Dussault, D.M. Waller. 2004. Ecological impacts of deer overabundance. *Annu. Rev. Ecol. Syst.* 35: 113-147.
- Crow, T.R. 1988. Reproductive mode and mechanisms for self-replacement of northern red oak (*Quercus rubra*) - a review. *Forest Science*. 34 (1): 19-40.
- Davis, M.B. 1983. Quaternary history of deciduous forests of eastern North America and Europe. *Annals of the Missouri Botanical Garden*. 70 (3): 550-563.
- de la Cretaz, A.L. and M.J. Kelty. 2002. Development of tree regeneration in fern-dominated forest understories after reduction of deer browsing. *Restoration Ecology*. 10(2):416-426.
- Duguay, J.P. and C. Farfaras. 2011. Overabundant suburban deer, invertebrates, and the spread of an invasive exotic plant. *Wildlife Society Bulletin* 35(3): 243-251.
- Emerson, G.B. 1846. Report on the trees and shrubs growing naturally in the forests of Massachusetts. Boston: 574 p.
- Eschtruth, A.K. and J.J. Battles. 2008. Acceleration of exotic plant invasion in a forested ecosystem by a generalist herbivore. *Conservation Biology*. 10: 1523-1739.
- Eyler, B. 2013. White-tailed deer harvest surveys at Baltimore Reservoir Forests. Maryland Department of Natural Resources.
- Feldt, R. 2010. Baltimore Reservoir Forests location maps, in Baltimore City Watershed Forests Deer Exclosure Study 2017. West Virginia University. 1: 28, 36-38. MD DNR FS.
- Foster, D.R., G. Motzkin and B. Slater. 1998. Land-use history as long-term broad-scale disturbance: Regional forest dynamics in central New England. *Ecosystems*. 1: 96-119.

- Flory, S.L., K. Clay, S.M. Emery, J.R. Robb and B. Winters. 2015. Fire and non-native grass invasion interact to suppress tree regeneration in temperate deciduous forests. *Journal of Applied Ecology*. 52: 992-1000.
- Freinkel, S. 2008. Blighted Hopes: American chestnut: The life, death and rebirth of a perfect tree. *American Scientist*. 96 (4): 345-346.
- Ganoe, J.T. 1931. The origin of a National Reclamation Policy. *The Mississippi Valley Historic Review*. 18(1): 34-52.
- Gilgenast, K., J. Graf, X. Li, D. Morgan, J. Ryon and M. Singh. 2009. A study of the deer population in Baltimore County interim report. Towson University, Maryland. 4-23 pp.
- Gould, P.J. 2005. Regenerating oak dominated stands: descriptions, predictive models, and guidelines. Pennsylvania State University. Thesis. 100-119 pp.
- Hicks Jr., R.R. 1998. Ecology and management of the central hardwood forests. West Virginia University. 1-287 pp.
- Horsley, S. B. and D.A. Marquis. 1983. Interference by weeds and deer with Allegheny hardwood reproduction. *Canadian Journal of Forest Res.* 13: 61-69.
- Horsley, S.B., S.L. Stout and D.S. DeCalesta. 2003. White-tailed deer impact on the vegetation dynamics of a northern hardwood forest. *Ecological Applications*. 13(1): 98-118.
- Hulme, P.E. 1996. Herbivory, plant regeneration, and species co-existence. *Journal Ecology*. 84:609-615.
- Hutchinson, T.F., R.P. Long, J. Rebeck, E. K. Sutherland and D.A. Yaussy. 2012. Repeated prescribed fires alter gap-phase regeneration in mixed-oak forests. *Ca. J. For. Res.* 42: 312.
- Ibanez, I., J.S. Clark, S. LaDeau and J.H.R. Lambers. 2007. Exploiting temporal variability to understand tree recruitment response to climate change. 77(2): 163.
- Inouye, R.S., T.D. Allison and N.C. Johnson. 1994. Old field succession on a Minnesota sand plain: effects of deer and other factors on invasion by trees. *Tor. Bot. Club*. 121: 266-276.
- Janzen, D.H. 1971. Seed predation by animals. *Ann. Rev. Ecol. Syst.* 2: 465-492.
- Johnson, D.J., S.L. Flory, A. Shelton, C. Huebner and K. Clay. 2015. Interactive effects of a non-native grass (*Microstegium vimineum*) and herbivore exclusion on experimental tree regeneration under differing forest management. *Journal Applied Ecology*. 52: 210-219.

- Johnson, P.S. 1974. Survival and growth of northern red oak seedlings following a prescribed burn. USDA Forest Service Res. Note NC-177: 1-3.
- Keever, C. 1973. Distribution of major forest species in southeastern Pennsylvania. *Ecology monographs*. 43: 303-327.
- Knight, T.M., J.L. Dunn, L.A. Smith, J. Davis, and S. Kalisz. 2009. Deer facilitate invasive plant success in a Pennsylvania forest understory. *Natural Areas Journal*. 29(2): 110-116.
- Kraft, J.C. and G.S. Brush. 1981. A geological-paleoenvironmental analysis of sediments in St. John's Pond and the nearshore zone near Howard's Wharf at St. Mary's City. In Northrop, R. 2001. A comprehensive forest conservation plan for long-term watershed protection on the City of Baltimore's reservoirs. Maryland Department of Natural Resources Forest Service. North East, Maryland. 45p.
- Krueger, L.M., C.J. Peterson, A. Royo and W.P. Carson. 2009. Evaluating relationships among tree growth rate, shade tolerance, and browse tolerance following disturbance in an eastern deciduous forest. *Canadian Journal of Forest Research*. 39(12): 2460-2469.
- Lantham, R.E. 2005. Managing white-tailed deer in forest habitat from an ecosystem perspective Pennsylvania case study. Report of the deer management forum for Audubon Pennsylvania. 100-145 pp.
- Larsen, D.R. and P.S. Johnson. 1998. Linking the ecology of natural oak regeneration to silviculture. *Forest Ecology Management*. 106: 1-7.
- Loftis, D. and C.E. McGee. 1993. Oak regeneration: serious problems, practical recommendations . USDA Forest Service. Gen. Tech. Rep. SE-84: 34.
- Loftis, D.L. 2004. Upland oak regeneration and management. USDA Forest Service. Gen.Tech. Rep. SRS-73: 163-167.
- Long, Z.T., T.H. Pendergast IV, W.P. Carson. 2007. The impact of deer on relationships between tree growth and mortality in an old-growth beech-maple forest. *Forest Ecology Management*. 252: 230-238.
- Lorimer, C.G. 1985. The role of fire in the perpetuation of oak forests. In *Challenges in oak management and utilization*. J. E. Johnson. Cooperative Ext. Ser. Univ. Wisconsin Madison. 8-25 pp.
- Lorimer, C.G. 1993. Causes of the oak regeneration problem. In: Loftis, C.G. and C.E. McGee (Eds.), *Oak regeneration : serious problems, practical recommendations*. USDA Forest Service. Gen. Tech. Rep. SE-84: 14-39.
- MacCleery, D.W. 1992. American forests: a history of resiliency and recovery. USDA Forest Service. FS-540: 59.

- Marquis, D.A. 1981. Effect of deer browsing on timber production in Allegheny hardwood Forests of northwestern Pennsylvania. USDA Forest Service. Res. Pap. NE-475: 10.
- Marquis, D.A., R.L. Ernst and S.L. Stout. 1992. Prescribing silvicultural treatments in hardwood stands of the Alleghenies (revised). USDA Forest Service. Gen. Tech. Rep. NE-96: 101.
- Maryland Department of the Environment (MDE), Water Protection Division. 2014. Watershed report for biological impairment of the Loch Raven Reservoir, biological stressor identification analysis results and interpretation. BSID Doc. Ver. January 2014. 12 p.
- Maryland Department of Natural Resources. 1998. Charting the course for deer management in Maryland. Maryland Department of Natural Resources Technical Report, Annapolis, USA. 8-65 pp.
- Maryland State Climatologist. 2017. Dept. of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland. www.atmos.umd.edu/~climate.
- Maslen, S.P. 1991, 2010. Personal communication records and conversation. Former Watershed Forester, City of Baltimore Department of Public Works.
- McGarvey, J.C., N.A. Bourg, J.R. Thompson, W.J. McShea and X. Shen. 2013. Effects of twenty years of deer exclusion on woody vegetation at three life-history stages in a Mid-Atlantic temperate deciduous forest. *Northeastern Naturalist*. 20(3): 451-468.
- McGee, C.E. 1984. Loss of *Quercus* spp. Dominance in an undisturbed old-growth forest. *J. Elisha Mitchell Sci. Soc.* 102: 10-15.
- McShea, W.J., W.M. Healy, P. Devers, T. Fearer, F.H. Koch, D. Stauffer, J. Waldon. 2006. Forestry matters: decline of oaks will impact wildlife in hardwood forests. *Journal of Wildlife Management*. 71(5): 1726.
- McWilliams, W.H. 1995. Adequacy of advance tree-seedling regeneration in Pennsylvania's forests. *Northern Journal Applied Forestry*. 12(4): 187-191.
- Mid-Atlantic Hiking Group. 2016. Loch Raven Reservoir, Merryman Pt. Photo. Baltimore, MD.
- Mikan, C.J., D.A. Orwig and M.D. Abrams. 1994. Age structure and successional dynamics of a presettlement-origin chestnut oak forest in the Pennsylvania Piedmont. *Torrey Botanical Club*. 121: 13-32.
- MSA.maryland.gov/msa/mdmanual. 2014. Frost free seasonal averages in Maryland.
- Nauertz, E.A., T.R. Crow, J.C. Zasada and R.M. Teclaw. 2004. Microclimatic variation between managed and unmanaged northern hardwood forests in upper Michigan USA. USDA Forest Service. Gen. Tech. Rep. NC-236: 1-27.

- Northrop, R. 2001. A comprehensive forest conservation plan for long-term watershed protection on the City of Baltimore Reservoirs. Maryland Department of Natural Resources Forest Service. North East, Maryland. 1-266 pp.
- Nowacki, G.J. and M.D. Abrams. 2008. Demise of fire and mesophication of eastern U.S. forests. *BioScience*. 58: 123-138.
- Nuttle, T., A.A. Royo, M.B. Adams, and W.P. Carson. 2013. Historic disturbance regimes promote tree diversity only under low browsing regimes in eastern deciduous forest. *Ecol. Monogr.* 83(1): 3-17.
- Olden, J.D. 2006. Biotic homogenization: a new research agenda for conservation biogeography. *Journal of Biogeography*. 33: 2027-2039.
- Paillet F.L. 2002. Chestnut: history and ecology of a transformed species. *Journal of Biogeography*. 29: 1517-1530.
- Paine, R.T. 1995. A conversation on refining the concept of keystone species. *Conservation Biology*. 9: 962-964.
- Peditto, P.A. 1999. White-tailed deer forward looking infrared survey Loch Raven Reservoir. Maryland Department of Natural Resources. Annapolis, Maryland. 1-6 pp.
- Qian, H. and R.E. Richlefs. 2006. The role of exotic species in homogenizing North American flora. *Ecology Letters*. 2006. 9: 1293-1298.
- Rawinski, T.J. 2014. White-tailed deer in northeastern forests: understanding and assessing impacts. USDA Forest Service. NA-IN-02-14: 1-22.
- Redman, D.E. 2004. The vascular flora of the Loch Raven Watershed, Baltimore County, Maryland. City of Baltimore Department of Public Works Bureau of Water and Wastewater Environmental Services Division, Reservoir Natural Resources Section. Report Number: RNRS-2004-01: 1-12.
- Reigner, I.C. and L.G. Ningard 1967. Baltimore's watersheds: an example of integrated land use. *Journal (American water works association)*. 59(11): 1469-1477.
- Reigner, I.C. and W.C. Sushko. 1960. The Baltimore watershed: an example of good management. *Public Works Magazine*. April 1960. 85-88 pp.
- Rentch, J.S., M.A. Fajvan and R.R. Hicks. 2003. Oak establishment and canopy accession strategies in five old-growth stands in the central hardwood forest region. *Forest Ecology and Management*. 184: 285-297.

- Rooney, T.P. and D.M. Waller. 2003. Direct and indirect effects of white-tailed deer in forest ecosystems. *Forest Ecology and Management*. 181:165-176.
- Rose, A.K. 2008. The status of oak and hickory regeneration in forests of Virginia. *Proceedings of the 16th Central Hardwoods Forest Conference*. GTR-NRS-P-24. 70-79 pp.
- Rossell Jr., C.R., S. Patch and S. Salmons. 2007. Effects of deer browsing on native and non-native vegetation in a mixed oak-beech forest on the Atlantic coastal plain. *Northeastern Naturalist*. 14 (1): 66-72.
- Royo, A.A., S.L. Stout, D.S. deCalesta and T.G. Pierson. 2010b. Restoring forest herb communities through landscape-level deer herd reductions: is recovery limited by legacy effects. *Biology Conservation*. 143: 2425-2434.
- Russell, E.W.B. 1987. Pre-blight distribution of *Castanea dentate*. *Torrey Botanical Club*. 114: 183-190.
- Russell, F.L., D.B. Zippen and N.L. Fowler. 2001. Effects of white-tailed deer (*Odocoileus virginianus*) on plants, plant populations and communities. *The American Midland Naturalist*. 146: 1-26.
- Russell, M.B., C.W. Woodall, K.M. Potter, B.F. Walters, G.M. Domke, C.M. Oswalt. 2017. Interactions between white-tailed deer density and the composition of forest understories in the northern United States. *Forest Ecology and Management*. 383: 31-32.
- Sander, I.L., P.S. Johnson and R.F. Watt. 1976. A guide for evaluating the adequacy of oak advance reproduction. *USDA Forest Service. Gen. Tech Rep. NC-23*: 7.
- SAS Institute Inc. 1999. *SAS/STAT users guide, version 8*, Cary, NC. ISBN 1-58025-494-2.
- Shumway, D.L., M.D. Abrams and C.M. Ruffner. 2001. A 400-year history of fire and oak recruitment in an old-growth forest in western Maryland, U.S.A. *Canadian Journal of Forest Research*. 31: 1437-1444.
- Smith, P. 2008. patricksmithphotos.com/2008. Loch Raven Reservoir. Baltimore, Maryland.
- Steiner, K.C., J.C. Finley, P.J. Gould, S. Fei and M. McGill. 2008. Oak regeneration guidelines for the central Appalachians. *Northern Journal Applied Forestry*. 25 (1): 5-16.
- Stephenson, S.L. H.S. Adams and M.L. Lipford. 1991. The present distribution of chestnut in the upland forest communities of Virginia. *Torrey Botanical Club*. 118: 24-32.
- Strang, A.H. 2011. Impact of deer management inaction on natural ecosystems. Maryland Department of Natural Resources Forest Service. Annapolis, Maryland. 1-18 pp.

- Ten Thirty One Aerial Photography. 2016. tenthirty.one. Liberty Reservoir. Baltimore, MD.
- Thomas-Van-Gundy, M., J. Rentch, M.B. Adams and W. Carson. 2014. Reversing legacy effects in the understory of an oak-dominated forest. *Canadian Journal of Forest Research*. 44: 350-351.
- Tilghman, N.G. 1989. Impacts of white-tailed deer on forest regeneration in northwestern Pennsylvania. *Journal of Wildlife Management*. 53: 524-532.
- USDA. Soil Conservation Service. 1976. Baltimore Soil Conservation District. Baltimore County Maryland Soil Survey. 1-40 pp.
- USGS 24K Map: Towson, Maryland. 2013.
- Vandermaast, D.B. and D.H. Van Lear. 2002. Riparian vegetation in the southern Appalachian mountains (USA) following chestnut blight. *Forest Ecology and Management*. 155: 97-106.
- Van Lear, D.H., and T.A. Waldrop. 1989. History, uses and effects of fire in the Appalachians. USDA Forest Service Gen. Tech. Rep. SE-54:1-15.
- Waller, D.M. and W.S. Alverson. 1997. The white-tailed deer: a keystone herbivore. *Wildlife Society Bulletin*. 25: 217-226.
- Waller, D.M. and L.I. Mass. 2013. Do white-tailed deer and exotic plant garlic mustard interact to affect the growth and persistence of native forest plants? *Forest Ecology and Management*. 304: 296-302.
- Wang, G.G., B.O. Knapp, S.L. Clark and B.T. Mudder. 2013. The silvics of *Castanea dentata*, American chestnut. USDA Forest Service. Technical Report SRS-173: 2-18.
- Williams, S.C. and J.S. Ward. 2006. Exotic seed dispersal by white-tailed deer in southern Connecticut. *Natural Areas Journal*. 26(4): 383-390.
- Zeigler, E.A. 1920. Problems arising from the loss of our chestnut. *Forest Leaves*. 17: 152-155.

Fig. 20: Liberty Reservoir (Ten Thirty One Aerial Photography 2016).

Fig. 21: Loch Raven Reservoir Forest, Merryman Point Area (Mid-Atlantic Hiking Group 2016).

Fig. 22: Prettyboy Reservoir Forest. View from Prettyboy Dam looking down Gunpowder River (Buck 2010).

Walter Buck and Len Wrabel conducting forest inventory for Baltimore County Forest Health Assessment at Pottery Farm Park near Loch Raven Reservoir, spring 2010.