

**SPATIAL PATTERNS OF POTENTIAL FOREST
PRODUCTIVITY IN MARYLAND: EXPLORING
LANDSCAPE PLANNING FOR FOREST CARBON
SEQUESTRATION AND FRAGMENTATION
REDUCTION**

Submitted to the Harry R. Hughes Center for Agro-Ecology, Inc.

December 2008

Steven W. Seagle

**Department of Biology
Appalachian state University
Boone, NC 28608**

ACKNOWLEDGMENTS

Funding for this project was provided through the Harry R. Hughes Center for Agro-Ecology, Inc., a 501 (c) (3) affiliate of the University of Maryland. Advice and guidance in project preparation and finalization were provided by Dr. Russ Brinsfield and Dr. Sarah Taylor-Rogers of the Center. Mr. Dave Helmers assembled the natural vegetation maps of Maryland, assisted in reducing the number of forest type classifications, and implemented the forest model (PnET-CN GIS) to simulate forest productivity in Maryland. Land use and land cover map layers were provided by Mr. J.B. Churchill of the Appalachian Laboratory, University of Maryland Center for Environmental Science. Mr. Greg Dobson, now with the National Environmental Modeling and Analysis Center (NEMAC) at the University of North Carolina – Asheville, developed formats for mapping of simulation model output. Dr. Rene Salinas of the Department of Mathematical Sciences at Appalachian State University assisted in implementation of optimization algorithms. A portion of the literature survey and assembly of an extended annotated bibliography were carried out by Ms. Debra Fischer. Al Todd, Rich Birdsey, and Don Strebel provided valuable comments on a draft of the report.

TABLE OF CONTENTS

List of Tables	iv
List of Figures	iv
List of Appendices	iv
Executive Summary	v
Introduction And Goals	1
Carbon Trading: Markets And Externalities	1
Problems Associated With Forest Carbon Sequestration	1
Intertwined Ecological And Economic Questions	3
Competing Ecosystem Services	4
The Maryland Forest Carbon Landscape	4
Methods	6
Overview	6
Simulating Forest Productivity	7
Forest Ecosystem Model	7
Forest Types And Land Cover	7
Model Physical Driving Variables	9
Forest Productivity Simulations	9
Analyses Of Forest Productivity And Fragmentation	10
Forest Conservation And Afforestation	10
Quantifying Forest Fragmentation	11
Optimization – The Theoretical Framework	11
County-Level Optimization	12
Results	13
Patterns Of Forest Productivity	13
Forest Conservation And Afforestation	14
Carbon Sequestration Versus Reducing Fragmentation	17
Discussion And Conclusions	24
Summary	29
References	29

LIST OF TABLES

Table 1. County Statistics For Simulated Forest Productivity	15
--	----

LIST OF FIGURES

Figure 1. Maryland Vegetation Maps	8
Figure 2. Simulated Forest Productivity For Maryland	13
Figure 3. County Productivity – Frederick, Prince George’s, Caroline	18
Figure 4. Land Use And Forest Productivity – Frederick County	19
Figure 5. Land Use And Forest Productivity – Prince George’s County	20
Figure 6. Land Use And Forest Productivity – Caroline County	21
Figure 7. County Classification For Optimization	22
Figure 8. Optimization Results For Prince George’s County	25

LIST OF APPENDICES

Appendix A: County Maps Website Description	32
---	----

EXECUTIVE SUMMARY

1. Carbon trading markets are rapidly developing at national and international scales to offset atmospheric CO₂ emissions. However, carbon mitigation projects are generally implemented at local scales where local information must be available to quantify market values. Fairness, both in payments and expectations, in local markets depends on understanding spatial variation in the potential for carbon sequestration.

2. Many carbon trading agreements revolve around forest conservation, forest management strategies, or planting of forest on nonforest land (afforestation). However, physical conditions that determine forest productivity vary widely across Maryland and often within individual Maryland counties. This project simulates and maps (by county) potential forest productivity (gC / m² / yr) at a 250 m resolution for the State of Maryland to visualize and assist in understanding spatial heterogeneity in potential forest productivity.

3. Funds for afforestation, deriving from carbon sequestration projects, represent a new source of funds for enhancing forest ecosystem services. Obviously the goal of these projects is to sequester carbon. However, in some instances, it is both feasible and desirable to orient afforestation projects toward simultaneously increasing carbon storage and providing other ecosystem services, in particular reducing forest fragmentation which may act as an indicator for a broad array of ecological services.

4. Spatial optimization of afforestation strategies for more than one objective (e.g., carbon sequestration and fragmentation reduction) depends on both spatially distributed information and relatively specific objectives regarding carbon storage policies, implementation of those policies, and emphasis on each objective. To narrow the scope of this problem, a strategy was derived to classify each Maryland county regarding the usefulness of spatial optimization analyses when potential carbon storage and reduction in forest fragmentation are equally weighted.

5. Allegany, Baltimore, Carroll, Cecil, Frederick, Garrett, Harford, Howard, Montgomery, Washington, and Worcester Counties are unlikely to benefit from optimization analyses of these objectives at the county-wide level because forest cover is either extensively distributed across the range of potential forest productivity, or because current forests are largely clumped in areas of high potential productivity. Thus carbon storage projects should focus on maximizing afforestation of highly productive sites. Maps of each county point out these appropriate areas. Somerset County, with low spatial variation in potential productivity and almost 50% forest cover, can maximize these ecosystem services by aiming afforestation projects toward reduction of forest fragmentation. Caroline, Dorchester, Kent, Queen Anne's, Talbot, and Wicomico Counties are unlikely to benefit from optimizing either productivity or fragmentation reduction because of relatively low variation in productivity and highly dispersed, sparse

forest cover. No informed recommendation can be made regarding optimal spatial situation of afforestation projects. Anne Arundel, Calvert, Charles, Prince George's, and St. Mary's Counties should benefit from optimization analyses carried out at the county-wide scale because of significant spatial variation in potential productivity and interspersed current land uses. Maps of optimization analyses with differential weightings for productivity and fragmentation production are presented.

6. Lack of information to be gained from county-level optimization analyses does not mean that smaller scale (sub-county) optimizations would be uninformative. Similarly, it must be remembered that if carbon sequestration is sought, any afforestation or intensive forest management project in any location should have some level of success. Results from this project should help guide where that success may be greatest.

INTRODUCTION AND GOALS

With the acceptance that carbon dioxide (CO₂) is a potent greenhouse gas whose buildup in Earth's atmosphere is playing an active role in global warming, scientific and management activities must seek innovative ways to mitigate this impact. From a broad perspective, mitigation can occur through lowering CO₂ emissions or sequestering carbon in excess of that being emitted. Decreasing emissions of CO₂ is dependent on a variety of initiatives: voluntary efforts to conserve energy, policy and regulatory forcing of energy conservation, decreasing human activities that release carbon currently stored in various ecosystem components, greater efficiency in energy generation, and development of energy sources that are not carbon based. Sequestration, in contrast, normally focuses on using biological systems as CO₂ scrubbers to transfer atmospheric carbon to biomass. A coherent and comprehensive carbon management policy, at any biological, technological, social or political scale, will almost certainly involve all of these activities. In support of the overall goal of understanding how to manage carbon, this report seeks to provide insight to spatial patterns of potential carbon sequestration by forests in the State of Maryland. More importantly, because forests provide a wide spectrum of ecosystem services in addition to carbon storage, specific consideration is given to concurrent the potential for simultaneous carbon storage and habitat enhancement.

Carbon Trading: Markets And Externalities

A market for carbon trading has developed globally with an overall aggregated market value greater than U.S. \$10 billion in 2005 (Capoor and Ambrosi 2006). This market has slowly but steadily developed in the United States even though the U.S. has not ratified the Kyoto Protocol, which could set binding targets for greenhouse gas reductions. In the United States, this market is a likely predecessor to a regulatory scenario of "cap and trade", where carbon emissions caps will be established and entities exceeding the cap could pay for emissions reduction credits to offset regulatory penalties. Because CO₂ is now considered a pollutant in the U.S., thus giving the U.S. Environmental Protection Agency mandate to regulate it, formalization of this market seems more likely than ever. Although the basic goal of carbon trading, that industries emitting CO₂ can "pay for" those emissions by funding projects that sequester carbon, is relatively simple, history indicates that implementation will have multiple problems to overcome (McMillan 2002, Bayon 2004). These include degree of government will to develop the program, establishment of legal institutions to oversee the process, definition and enforcement of property rights, equitable involvement of relevant stakeholders, market participant trust, access to market information, and understanding of market externalities. Many of these externalities extend from the use of forest ecosystems to sequester atmospheric carbon and carbon credit trading that invests in the ability of forest to do sequester carbon.

Problems Associated With Forest Carbon Sequestration

Forests play a central role in virtually all discussions of carbon sequestration strategies (Andersson and Richards 2001; Murray et al. 2000; Sedjo et al. 1995; van Kooten et al. 2004). Although clearly part of the solution for reducing atmospheric CO₂, management

of existing forests and afforestation remain contentious in this application. Specifically, problems of cost management for project based approaches, lost opportunity costs, leakage, causes of land use change, permanence of carbon storage (Marland et al. 2001), and estimation of forest/land value all must be solved. Several of these problems are relevant to this project.

Individual project based approaches, where many projects identify specific land areas for carbon sequestration projects, will eventually result in extensive numbers of forest projects that would need to be evaluated for sequestration potential, project implementation, and actual carbon sequestered. Richards and Andersson (2001) concluded that the extent of measurement and accounting on a project by project basis would be so unwieldy as to be impossible. Kennett (2002) further emphasized the need for wide-reaching national policies, and thus national leadership, to offset issues created from project by project carbon management. From a solutions perspective, Andersson and Richards (2001) specifically point out that large scale remote sensing of forest area and productivity should be utilized to assess project and policy implementation and success. While technological hurdles remain, a remote sensing approach for large-scale accounting purposes seems logical. However, remote sensing would not alleviate all site based problems. For example, remote sensing of current forest biomass might identify large standing stocks of carbon that would be valuable to conserve or reforest after harvest, but may not identify nonforest areas having high potential for carbon sequestration through afforestation.

Leakage within a forest carbon trading scheme generally refers to loss of forest land (and thus loss of forest carbon sequestration) despite afforestation/reforestation programs because of other opportunity costs, shifting spatial land use, natural disturbance, etc. (Richards and Andersson 2001). In other words, any current system of forest carbon trading and storage is open to a variety of market and natural forces. Deforestation for development represents a major loss of forest land and potential forest land where demand is high for residential housing, retail space, etc. One leakage scenario would be the conservation of forest within a carbon sequestration project, but losing the potential positive impacts by simply allowing deforestation in another local area that is not part of a sequestration or conservation plan. In some areas, high yield agriculture can be an economic incentive for deforestation that can offset carbon sequestration gains from afforestation. Management of these issues is rooted in local and regional planning and obviously involves ecosystem services other than carbon sequestration. However, spatial understanding of potential forest carbon sequestration can readily be incorporated into planning activities to assist in the placement of forest carbon sequestration projects. An insidious aspect of carbon loss from sequestration programs is disturbance-induced losses. Beshears and Allen (2002) argue that the global extent of forests that are subject to carbon releasing disturbances (such as fire and drought), the unpredictability and magnitude of these disturbances, and the rapidity with which they can occur should be considered in any strategy to use forests for long-term or permanent carbon sequestration. McNulty (2002) more specifically estimated that a single hurricane can convert 10% of the total annual carbon sequestered in forests into dead/downed wood, of which only a small amount is ever salvaged. While such disturbances are seldom predictable,

particularly in a changing climate, their impacts on carbon release from forest can be estimated and used in carbon accounting at both regional and national scales. If desired, such uncertainties can be incorporated into ecosystem models to predict forest carbon sequestration potentials.

Effective forest carbon sequestration projects rely on estimates of site productivity to determine potential carbon storage and place values on land for carbon sequestration. Site based estimates can be derived from interpolation of forest inventory and analysis (FIA) data (e.g., Frieswyk and DiGiovanni 1988), onsite measurements, ecosystem productivity models, or remotely sensed imaging. Remote sensing and onsite measurements of forest growth characteristics require that forest is already the land cover in place and thus are less useful when afforestation is involved. The accuracy of interpolating FIA data depends on the density of existing FIA plots, complexity of topography, spatial heterogeneity of soils, etc. Although not free from problems of data reliability and spatial resolution, ecosystem models do represent a means of continuous estimation of forest productivity regardless of current land cover, and thus a means of comparing locally and regionally the potential productivity of different land parcels.

Intertwined Ecological And Economic Questions

Atmospheric carbon is a global problem and thus large-scale markets to help manage the problem are logical. Thus atmospheric carbon mitigation policies, to the extent they have evolved, exist primarily at international, national or state levels. These policies can leave an organizational gulf between policy and local on-the-ground implementation of carbon sequestration projects which jeopardizes the success of even sound policies. Similarly, even though the basic physical and biological aspects of carbon cycling are reasonably well understood, applications of that knowledge to carbon mitigation are confounded by the fact that most sequestration projects are inherently local in implementation. Thus the positive impacts of specific mitigation projects cannot be maximized without summarizing how local physical driving variables and ecological process rates influence local carbon sequestration and storage. Without a reasonable handle on this uncertainty, it is difficult to understand how land resources can be valued for carbon sequestration or how appropriate compensation for sequestration can be calculated. Without appropriate evaluation and valuation of carbon storage potentials how can local projects provide appropriate feedback to policy implementation? These issues are inherent in the implementation of carbon trading, where two basic questions often remain difficult to answer: How does a market manager or a regulatory agency know that investors are receiving the benefit (carbon sequestered) being paid for? And, what amount of compensation should a public or private land owner receive for participating in a carbon sequestration trade? Answers to these questions require understanding spatial variation in the potential for ecosystem carbon sequestration at as fine a spatial resolution as possible. While confidence in this knowledge is dependent on reliability in environmental driving variables (e.g., weather, pathogens, disturbances, etc.), accuracy of environmental data bases, and on-the-ground management activities, appropriate synthesis tools do exist to lend significant insight to where carbon sequestration would be

most effective. This insight should help bridge the disconnection between carbon trading policies and actual project-based carbon sequestration.

Competing Ecosystem Services

Boyd and Banzhaf (2006) define ecosystem services as “components of nature, directly enjoyed, consumed, or used to yield human well-being”, and point out that in most cases markets for ecosystem services tend to define those services in coarse and incomplete ways. For example, in using forests as units in carbon trading, the units of trade may be “acres of forest”. The acres of forest needed for a carbon transaction could be determined simplistically by multiplying the cost per ton to sequester carbon in a forest (van Kooten et al. 2004) by the tons of carbon that could be sequestered per acre of forest, and then dividing the product into the dollars available for trading. One reason this example is simplistic results from the fact that the unit, acres of forest, is in fact a composite of ecosystem services rather than just a mass of carbon. Each acre of forest is not just capable of sequestering carbon, but also of providing timber/fiber, preventing erosion, supporting biodiversity, cleaning water, removing air pollutants, and providing recreation. Consideration of these externalities will often alter the view of forest carbon dynamics. For example, one debate in forest carbon storage surrounds rotation time between harvests. Whether to harvest and how often to harvest are usually a function of carbon sequestration rate, maximum stored carbon, permanence of products manufactured from harvested trees, harvest debris dynamics, and soil carbon dynamics. For a forested catchment in Australia, Creedy and Wurzbacher (2001) found different optimal solutions for forest management when considering carbon sequestered, timber produced, and water quality simultaneously. Several studies (Matthews et al. 2002; Caparros and Jacquemont 2003; Huston and Marland 2003) have explicitly suggested that biodiversity and its closely associated issue of habitat conservation needs more careful consideration when planning forest carbon sequestration policy and specific projects. Caparros and Jacquemont (2003) and Feng and Kling (2005) further point out that both economic and legal conflicts can occur when existing conservation strategies/programs must mesh with emerging carbon sequestration strategies. Fortunately, quantitative techniques do exist to find and promote optimal spatial management strategies when multiple resources are involved. For example, Bailey et al. (2006) demonstrated the feasibility of using geographic information system technology to identify the most valuable agricultural fields for conversion to woodland in order to maximize carbon sequestration, recreation, biodiversity, and landscape aesthetics. Resolution of these competing interests by determining where different management strategies or different ecosystem services should be emphasized will continue to promote landscape management that serves the broadest public constituency.

The Maryland Forest Carbon Landscape

Eventual formulation of carbon sequestration policy in the United State at various levels of political organization will have the same general goal of mitigating atmospheric CO₂ impacts, but is unlikely to mesh completely in specific goals or implementation plans. Nonetheless, at any scale of implementation, it seems logical that carbon sequestration

policies that involve land use should seek to optimize multiple ecosystem services provided by the different land covers and specific habitat types. For example, if afforestation is a component of policy then afforestation should be carried out to provide other services such as expanding forest interior habitat, decreasing forest fragmentation, increasing riparian buffer area, etc. With strong east-west gradients in topography, rainfall, bedrock geology, growing season length, natural vegetation type, current land use, and development pressure, the State of Maryland likely represents a mosaic of solutions for provision of ecosystem services within a context of carbon sequestration. Essentially, there are likely both strong state-wide and local patterns in potential forest productivity as well as opportunities to use forest conservation or afforestation as tools to enhance delivery of forest ecosystem services.

Consideration of more than one ecosystem service carries significant economic implications in the form of additionalities (Richards and Andersson 2001). In essence, the value of a carbon sequestration project that creates new forests on marginal agricultural land is decreased if that land would have undergone afforestation for other reasons, such as declining agricultural productivity, riparian buffer expansion or habitat creation. Conversely, the value of afforestation from a carbon project would be enhanced if ecosystem services beyond just carbon sequestration would be increased. Although it may be unclear how current or developing carbon trading systems might handle such additionalities or how some ecosystem service values may be computed, the implications for management are multifaceted. For example, the most basic implication is that additionalities might influence whether forest carbon payments should focus on forest conservation or afforestation. With the State of Maryland's widespread participation in forest establishment for water quality management in the Chesapeake Bay watershed, efforts to retain open space and working farms, and orientation toward landscape and forest management through the Maryland Greenways Project, the potential for additional ecosystem services to influence carbon trading economics seems both high and complex.

Forest fragmentation is clearly a detriment to forest animal habitat (Boulinier et al. 2001), a deterrent for movements of some forest animal species (Gardner and Gustafson 2004; Rogers and McCarty 2000), a conduit for invasion of forests by exotic species (Watkins et al. 2003), a factor in controlling landscape processes and a result of landscape processes (Turner et al. 1997), an indicator of biodiversity (Ritters et al. 2003), and an important consideration for wildlife species in human dominated landscapes (Borgmann and Rodewald 2004). Forest fragmentation, particularly in reference to riparian forests, has also been implicated in the ability of forests to serve as nutrient sinks (Collinge 1996). Forest fragmentation is considered a national habitat management issue (Ritters et al. 2002), as well as an issue of high concern in Maryland and the Chesapeake Bay watershed (O'Connell 1998). Thus forest fragmentation has extensive ecological impacts on the ecosystem services provided by forestland and is clearly a possible, far-reaching additivity in carbon trading projects. For example, if carbon trading payments funded afforestation for carbon sequestration, then the ecological value of those payments would be increased if afforestation efforts were also targeted to reduce forest fragmentation. Likewise, if a carbon sequestration project were aimed at conservation of highly productive forests then the additional benefits of maintaining forest energy flows and

food web structure (Seagle and Sturtevant 2005) would be attained. As a single forest and landscape attribute, forest fragmentation may be a strong surrogate for many forest ecosystem services and an excellent candidate for dual consideration in managing forest carbon trading projects.

Use of forest lands as a tool in carbon sequestration policy seems clearly tied to understanding spatial patterns of potential forest productivity relative to current land use and how landscape-scale mixtures of current land use influence the potential for forest management to affect multiple forest ecosystem services. Thus, with focus on the use of forests as a tool in carbon sequestration policy, this project seeks to:

- (1) Model potential forest productivity for all of Maryland;
- (2) Identify at the county level where carbon trading payments might be used most effectively for forest conservation or afforestation;
- (3) Formulate a theoretical approach for simultaneously maximizing carbon storage and fragmentation reduction through afforestation; and
- (4) Determine at the county level when afforestation for carbon sequestration should focus solely on carbon storage or can effectively involve reduced forest fragmentation.

METHODS

Overview

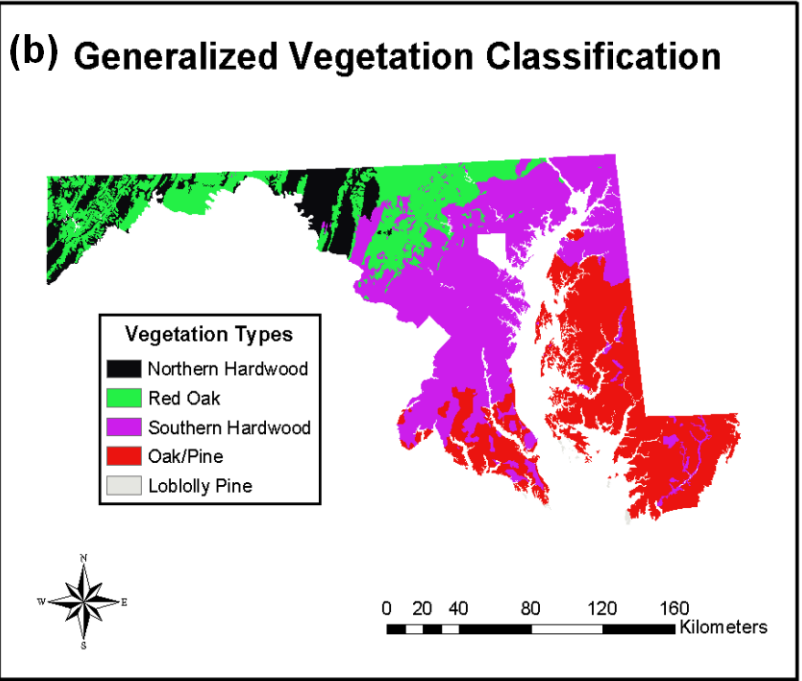
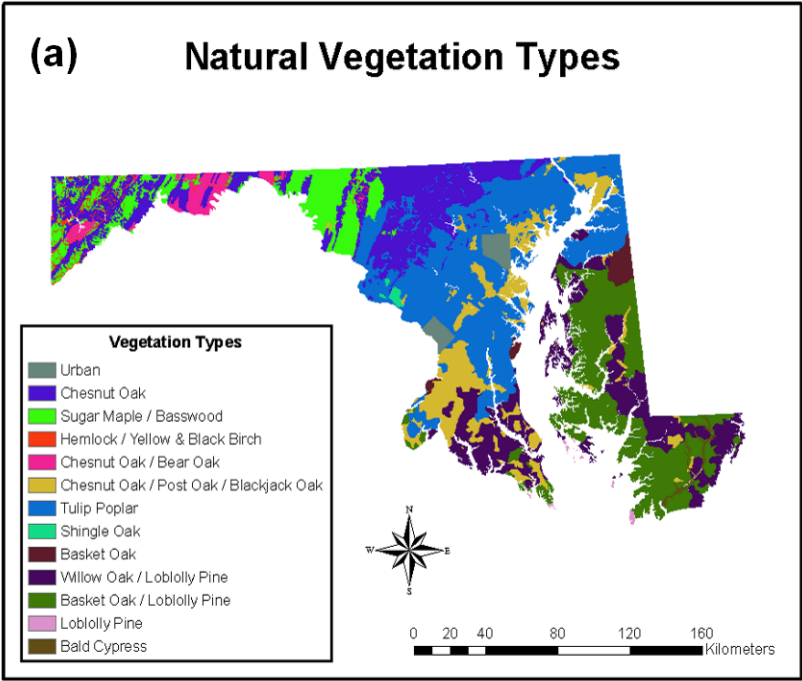
Comparing spatial variation in potential forest carbon sequestration across the State of Maryland requires state-wide application of a single technique to estimate potential forest productivity. Sturtevant and Seagle (2004) and Seagle and Sturtevant (2005) developed statistical models to predict forest productivity from topographic variables for western Maryland. These models were originally proposed for this project before the project scope was increased to the entire State. While these models seemed well-suited to the Ridge-and-Valley and Appalachian Plateau portions of Maryland, the technique is untested for the rest of Maryland and, being based on topographic variation, is likely untenable for much of central and most of eastern Maryland. Thus a forest ecosystem model was applied to estimate potential net primary production for the entire State. The application of this model was dependent on multiple layers of environmental data, the coarsest of which determined the model spatial resolution of 250 m. Model results were subsequently summarized and mapped by county, analyzed by pixel (250 m resolution) to identify areas within each county for forest conservation/reforestation or afforestation efforts that would maximize potential carbon sequestration, and analyzed also at the county level to determine the potential for simultaneously optimizing the ecosystem services of carbon sequestration and reduction of fragmentation.

Simulating Forest Productivity

Forest Ecosystem Model. The model PnET-CN GIS (W.L. Currie, pers. comm.) is a spatially-explicit version of the model PnET-CN (Aber et al. 1996). Thus the area to be simulated is gridded, with each pixel in the grid characterized by the model driving variables (e.g., soil water holding capacity, monthly minimum and maximum temperature, monthly precipitation, and monthly photosynthetically active radiation), forest vegetation type with associated growth parameters, and land cover information if the forest to be simulated is embedded in a multiple-use landscape. Model algorithms use these databases to simulate forest growth, carbon and nitrogen fluxes within each grid cell with a monthly timestep. Each pixel in the simulated area is independent and thus ecosystem processes within a pixel are not influenced by surrounding pixels in the grid. For implementation, the model is inextricably linked to ArcGIS. Coded “macros” provide a user-prompted menu interface that allows a user to select geographic areas to be simulated, resolution of simulated areas, geographic projections for model grids, vegetation data sets, and vegetation parameters. Besides making these inputs available in a spatial format, the GIS linkage allows model output to geographically referenced grids as well. One advantage of this gridded output format is its immediate availability for map production, export to database format, and use in spatial optimization algorithms. Obviously a spatially-explicit model can entail significant runtimes that depend on the extent of the area simulated, the resolution (grid cell size) of the simulated area, and the length of the simulation (number of years). Area simulated is chosen by the user in the user interface menu. The model format allows two resolutions for simulation – 100 m or 250 m. There is a large difference in run times for these two resolutions, yet areas as large as combined Allegany and Garrett Counties (MD) have been run with either resolution. User preference for length of model runs is available, although previous studies using PnET-CN have found that 100-150 yrs is appropriate for model equilibration.

Forest Types and Land Cover. Forest type is an important input variable for PnET-CN. The State of Maryland has multiple natural forest cover types that were mapped by Brush et al. (1980). A geo-referenced digital image of this map was obtained and modified by on-screen digitization to provide a base reference for forest types (Figure 1). Two aspects of this modification process are particularly noteworthy. First, highly dendritic forest types, particularly on Maryland’s Coastal Plain, presented resolution problems in digitizing while accounting for quite small areas of forest cover. These types were subsumed in the matrix of dominate forest types. Second, the number of forest types in Maryland far exceeds the resolution of vegetation growth parameters. In other words, not enough is known about differences in growth parameters to differentiate the numerous forest types identified by Brush et al. (1980). Based on composition of dominant and co-dominant tree species, these multiple forest types were aggregated to achieve five distinct forest types that reflect major differences in growth characteristics and capture most of the spatial variation in vegetation cover (Figure 1). Because many of the forest types that were aggregated had similar tree species composition, the impact of this aggregation on

Figure 1. Maps of the natural vegetation types of Maryland (a) derived from Brush et al. (1980), and a generalized vegetation map (b) that consolidates the vegetation classes of Brush et al. (1980) for forest productivity simulations.



model output is likely low in terms of prediction of productivity for most parts of Maryland. However, where subtle elevation changes along the lower Eastern Shore produce fine-scale juxtaposition of hardwood and softwood forest types, local errors in productivity estimates are possible from both aggregating forest types and from resolution of model input being coarser than vegetation type distribution. The final polygon version of the forest type map was converted to raster and projected to UTM Zone 17, then re-sampled to 100 m and 250 m resolutions.

The USGS National Land Cover Dataset (1992 land cover data) was used to create land cover maps at 100 and 250 m resolutions as well. Five classifications were used in developing the land cover dataset: Forest (deciduous, evergreen and mixed forest); Nonforest (agricultural crops of all types, pasture, and hay land); Developed (low and high intensity residential, commercial/industrial, urban/recreational grasses); Water & Woody Wetlands (open water, woody wetlands, emergent wetlands); and Unforestable (bare rock/sand/clay, quarries/gravel/strip mines). In analyses, nonforest lands were considered to have potential for afforestation. In contrast, unforestable lands were areas where human activities have highly degraded the potential for forest growth or would not naturally be expected to support significant forest growth. The inclusion of strip mines in this category might be questioned because many mines have been revegetated with trees; however, the high variation in reclaimed mine conditions makes it difficult to generalize model driving variables and strip mines are not considered candidates for carbon sequestration in this analysis. The lumping of woody wetlands, open water and emergent wetlands creates some anomalous looking land cover maps in areas with a mix of these land cover types, such as the lower Eastern Shore region. However, these areas are again not considered for possible afforestation efforts.

Model Physical Driving Variables. Driving variables for the model included soil water holding capacity (WHC), monthly minimum temperature, monthly maximum temperature, monthly precipitation, and monthly photosynthetically active radiation (PAR). Soil WHC was obtained from the USDA Natural Resources Conservation Service's STATSGO data base. These data (1 km resolution) were resampled to 100 and 250 m resolutions. Monthly minimum and maximum temperatures and monthly precipitation were obtained from the DAYMET model database (University of Montana). Data files of these variables for each month were projected to UTM Zone 17 and resampled to 100 and 250 m resolutions. Monthly shortwave radiation was also obtained from the DAYMET database, converted to PAR, and projected to appropriate geographic coordinates and resolutions.

Forest Productivity Simulations. PnET-CN was used to simulate forest net primary productivity (NPP; $\text{g C} / \text{m}^2 / \text{yr}$) at a 250 m resolution for 150 years for the entire State of Maryland. Thus NPP at the end of the model run reflects that expected for each pixel under the average environmental conditions presented in the model and establishes the spatial pattern of potential carbon sequestration within the State. Because of computer storage space requirements these simulations were carried out with the State broken into several sections; this procedure had no effect on model output because each modeled pixel is independent of all others. The spatial resolution of 250 m was chosen because of

computational time, inability of subsequent county-level optimization analyses to handle higher resolution data efficiently, and a closer match to the spatial resolution of model driving variables. Notably, these model runs included each pixel of land in the State of Maryland regardless of current land use, thus each pixel is assigned a simulated forest net primary productivity. This type of model output facilitates analysis of carbon mitigation strategies such as afforestation.

Analyses Of Forest Productivity And Fragmentation

With spatially explicit patterns of potential forest productivity established, fundamental analyses ranged from sorting and ranking by productivity and land use/cover (i.e., GIS-based analyses) to more complex optimization problems involving more than one ecosystem service. The former analyses have the potential to rank each pixel (250 m resolution) within a given area in terms of potential to sequester forest carbon. While such rankings are useful, competing land uses and lack of information regarding local land planning make broader spatial identification of areas where forest conservation, forest management, or afforestation would be most conducive to carbon sequestration even more valuable. Once such areas are identified, more intense local planning with further data on land ownership, zoning, land prices, etc. could then be carried out. Simultaneously considering more than one ecosystem service, in this case potential for carbon sequestration and habitat improvement in the form of decreased forest fragmentation, is mathematically tractable but inevitably is susceptible to local details of ownership, land values, etc. as well. Consequently, for this project these analyses focused on the county-level to provide insight to current land use impacts on combined forest carbon sequestration strategies and forest fragmentation reduction. Future analyses that focus on smaller units of land (county or sub-county levels), perhaps identified in this project, and using finer resolution databases in conjunction with detailed local planning and objectives could further assist landscape planning for multiple ecosystem services.

Forest Conservation and Afforestation. Maps of potential forest productivity derived from PnET-CN model runs were overlain with land use/cover maps. Using these two map layers, pixels were initially searched for current forest land cover and ranked by potential forest productivity. Current forest cover that occurs in areas of high potential forest productivity should be of greatest value for carbon sequestration strategies involving conservation of that forest as a carbon stock or application of forest management strategies (e.g., application of optimal harvest rotations) to sequester carbon in forest biomass and forest products. Because a listing of scattered pixels would be difficult to interpret, results of this exercise are presented as land use / land cover maps at the county level, with the top 25% of pixels for forest productivity that are currently forest highlighted. Similarly, nonforest land was searched and ranked by potential forest productivity. The resulting county level maps of pixels (top 25%) that would contribute most to carbon sequestration if converted to forest should provide clear information on where afforestation efforts might be undertaken with the goal of sequestering carbon.

Quantifying Forest Fragmentation. Forest fragmentation was defined at the county level as the density of forest-nonforest edges, with an edge being the interface between two pixels in the land use / land cover map. Specifically, for each county, the total number of pixel edges that were classified as a forest-nonforest interface were enumerated and divided by the total number of edges in the map. All non-forest land uses were considered to contribute to the calculation of forest-nonforest interfaces. Consequently, landscapes where forest pixels are aggregated into clumps would by this definition have a lower edge density, while the other extreme of having many forest pixels isolated in a matrix of nonforest would yield a very high edge density.

Optimization – The Theoretical Approach. While a strategy of conserving currently forested land that is highly productive for forest products can be viewed as a simple ranking procedure, the choice of nonforest pixels for afforestation when the desire is to both maximize potential carbon sequestration and minimize forest fragmentation can be either simple or complex. The complexity of this problem depends on the concurrent spatial patterns of potential forest productivity and land cover. Analyses assumed an objective function (J) in which forest productivity (NPP) and edge density (ED) were a linear combination:

$$J = a(\text{NPP}) - b(\text{ED}),$$

where **a** and **b** are weighting parameters for the respective factors. Strategically, the goal for any unit of area (such as a county) would be to plant forest in nonforest pixels that would maximize NPP and minimize ED. Remember that minimizing ED is equivalent to maximizing the decrease in forest fragmentation. In practice, values for **a** and **b** need to be determined for each county, thus indicating the local relative preference between carbon sequestration and reducing forest fragmentation and affecting the optimal solution. In the absence of knowing such preferences, a theoretical framework was developed to categorize counties into strategies for approaching this issue.

Theoretical landscapes with 75% forest cover were developed that ranged in edge density from 0.25 to 0.75, using only forest and nonforest land covers. These landscapes represent the range of possible “clumpiness” of forest that may exist across the State of Maryland. Each of these landscape compositions was matched with forest net primary production values that were normally distributed, skewed toward low production, or skewed toward high production. These distributions of productivity reflect the fact that counties in Maryland may have relatively narrow or rather wide-ranging potentials for forest productivity. In addition, each combination was also matched with two patterns of productivity distribution – completely random and a strong gradient (one-dimensional) across the map. These spatial patterns of productivity represent the east-west pattern of productivity commonly associated with the rain shadow effect in Western Maryland as well as the opposite extreme of completely random spatial heterogeneity in potential productivity. This latter extreme is obviously unlikely in most landscapes but for analysis provides the alternative in pattern to a one-dimensional gradient. Collectively these combinations of the factors necessary to consider in a spatial optimization should capture the variation in productivity and landscape factors inherent in the State of

Maryland. This spatial information was then analyzed for the objective function (J) using the linear programming solver in the Optimization Toolbox of MATLAB, with the goal of determining under what landscape conditions it would be reasonable to optimize only for carbon sequestration ($b = 0.0$; fragmentation reduction is unlikely or very difficult), only for fragmentation reduction ($a = 0.0$; potential forest productivity is so uniform relative to forest distribution that choice among pixels for afforestation is irrelevant), or both carbon sequestration and fragmentation reduction. To do this, optimizations were run for each landscape combination using $a = 0.0$ or $b = 0.0$ and a decision matrix was formulated with ratios of NPP_E / NPP_N and ED_E / ED_N where:

NPP_E = Potential forest productivity when minimizing forest fragmentation,
 NPP_N = Potential forest productivity when maximizing forest production,
 ED_E = Forest edge density when minimizing forest fragmentation, and
 ED_N = Forest edge density when maximizing forest production.

Thus the former ratio reflects the fraction of possible forest productivity achieved when the analysis aims only to minimize fragmentation; the latter indicates edge density achieved when minimizing edge density relative to edge density achieved when maximizing only forest productivity. A high value was chosen as a cutoff point for these ratios to decrease the likelihood that county level strategies would not consider forest productivity. Using a cutoff for these ratios of 0.8 the resulting decision matrix is:

	$NPP_E / NPP_N < 0.8$	$NPP_E / NPP_N > 0.8$
$ED_E / ED_N < 0.8$:	NPP Maximization & ED Minimization	ED Minimization
$ED_E / ED_N > 0.8$:	NPP Maximization	Neither

Classification of counties using this decision matrix would yield three clearly different strategies and one where neither maximizing forest productivity nor minimizing edge density (maximizing reduction in forest fragmentation) would be appropriate.

County-Level Optimization. For Maryland counties where the most logical afforestation strategy would be to pursue only carbon sequestration (even if fragmentation were of concern), maps showing those pixels most likely to result in high forest productivity provide strong guidelines for management. For counties where afforestation focused on reducing fragmentation would still yield strong gains in carbon sequestration, optimization and mapping is unlikely to be particularly informative because the result would suggest filling in holes in the forest. This can be done more effectively through on-the-ground surveys or very recent land cover maps. However, for counties where consideration of both carbon sequestration and fragmentation reduction could be used for

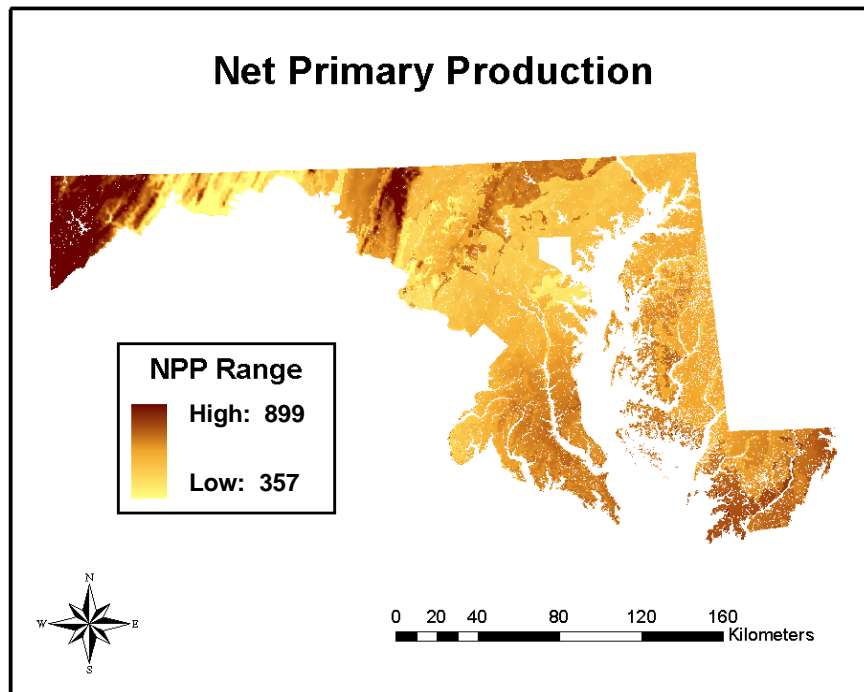
afforestation decisions, optimization analyses were carried out to provide initial possibilities for management. Four weighting scenarios for NPP versus ED were analyzed: $a = 0.75, b = 0.25$; $a = 0.5, b = 0.5$; $a = 0.25, b = 0.75$; $a = 0.0, b = 1.0$.

RESULTS

With analyses and maps being completed for all 23 counties in Maryland, the number of maps to be presented exceeds 100. Thus a map directory was established on an internet site to facilitate electronic access to all maps (Appendix A). Discussion in this report is largely limited to three counties that represent salient features of the analyses: Frederick, Prince George's, and Caroline Counties.

Patterns Of Forest Productivity. At the State level, simulated potential forest net primary productivity is patchy (Figure 2). Clearly notable are the high rainfall, high potential productivity areas of the western Appalachian Plateau and portions of the Blue Ridge Mountains, and the rain shadow of the Ridge-and-Valley. Central Maryland is quite patchy, with generally moderate potential forest productivity, as is the Eastern Shore and Southern Maryland. At the State level potential forest productivity ranged widely from $897 \text{ gC} / \text{m}^2 / \text{yr}$ down to $360 \text{ gC} / \text{m}^2 / \text{yr}$.

Figure 2. Simulated potential net primary productivity ($\text{gC} / \text{m}^2 / \text{yr}$) for forest vegetation in Maryland. Potential productivity varies widely across the state with concentrations of high productivity in western and west-central Maryland.



More informative than these extremes in individual pixel values, however, are mean productivity values within each county (Table 1). Overall means for Maryland counties range from 728 gC / m² / yr for Garrett County to 507 gC / m² / yr for Allegany County. Notably both of these counties are in the western portion of Maryland, with the large differences in productivity resulting from a rain shadow created by the Appalachian Plateau. For each county, most of the land area is classed as forest, nonforest, or developed. Because productivity simulations were run without regard to current land use, potential forest productivity can be compared among these categories. In only two counties (Frederick and Allegany) does currently forested land have a notably higher mean potential forest productivity (Table 1) than nonforest land. Here again this difference is a topographic effect with Allegany County being in the Ridge-and-Valley and the western portion of Frederick partly situated in the Blue Ridge Mountains. Thus for most counties nonforest land is as viable for future forest production as current forest land. For ten Maryland counties the highest mean potential forest productivity is for developed land which is unlikely to be useful for afforestation or forest conservation, although in no case is this difference particularly large. Although these mean differences by land use are interesting, the high variance of potential productivity in the forest and nonforest category of each county indicates that within each there is opportunity for effective carbon sequestration activities and, conversely, ample opportunity for carbon sequestration investments to yield a relatively poor return.

Forest Conservation And Afforestation. Two strategies for use of forest in carbon sequestration are considered here: conservation of currently forested land (which could include management by thinning, harvesting and reforestation), and afforestation of currently nonforest (primarily agricultural) land. These strategies are equivalent to optimization with the weighting factor for reducing fragmentation (*b*) equal to 0.0, except that either existing forest land or nonforest land is considered for use in storing carbon. Either strategy is driven by the distribution of potential forest primary productivity. For Frederick County, there is a clear patch of high potential productivity in the northwest portion of the county and a generally higher level of potential productivity in the western end of the county (Figure 3a). The highest potential productivity area is generally coincident with current forest cover (Figure 4a), thus the 25% of forest pixels most amenable to high carbon sequestration or storage (Figure 4b) are highly clumped. This part of Frederick County is dominated by Catoctin Mountain Park, Cunningham Falls State Park, Gambrill State Park, and the City Of Frederick Municipal Forest, thus it is unlikely that intensive forest management activities or deforestation will occur here. Nonetheless, private forest lands around these parks hold the highest potential for carbon sequestration projects. The 25% of nonforest pixels that have the highest potential for carbon sequestration if converted to forest are also highly clumped (Figure 4c) because of the secondary area of high productivity in the southwest portion of the county (Fig. 3a) where agriculture is the most common land use. Without a high proportion of developed land (not including exurban development), confinement of the highest potential productivity land in the west end of the county, and strong segregation between forest and nonforest land in the west end of the county, choice of specific pixels for carbon sequestration projects would be highly dependent on management plans for public land or private landowner participation.

Table 1. Simulated potential forest net primary production (gC / m² / yr) by county and current landuses.

COUNTY	LANDUSE	PROPORTION	NPP MEAN	NPP VARIANCE	NPP MINIMUM	NPP MAXIMUM
Allegany	Overall		506.5	7307	368	752
	Developed	0.03	477.7	6310	373	697
	Unforestable	0.01	622.7	3965	435	726
	Forest	0.85	508.3	7278	368	752
	Non-Forest	0.10	486.1	5797	368	728
Anne Arundel	Overall		533.7	1846	360	643
	Developed	0.23	509.4	1785	409	641
	Unforestable	0.01	524.9	918	460	565
	Forest	0.52	536.1	1585	369	643
	Non-Forest	0.24	552.1	1584	360	639
Baltimore	Overall		546.5	1651	409	641
	Developed	0.20	526.8	293	410	641
	Unforestable	0.01	532.6	507	456	618
	Forest	0.42	547.6	1697	410	635
	Non-Forest	0.37	556.2	2046	409	634
Calvert	Overall		603.0	175	540	654
	Developed	0.08	604.8	177	543	653
	Unforestable	0.00	0.0	0	0	0
	Forest	0.66	602.7	176	540	654
	Non-Forest	0.25	603.3	174	541	654
Caroline	Overall		566.5	202	519	679
	Developed	0.02	557.0	357	524	579
	Unforestable	0.00	0.0	0	0	0
	Forest	0.30	563.4	323	519	679
	Non-Forest	0.68	568.2	135	519	679
Carroll	Overall		566.5	1822	428	654
	Developed	0.02	575.4	2269	432	647
	Unforestable	0.00	511.5	4378	435	552
	Forest	0.24	568.4	1863	428	649
	Non-Forest	0.74	565.6	1790	428	654
Cecil	Overall		543.9	287	427	615
	Developed	0.05	542.4	265	440	592
	Unforestable	0.01	548.1	216	488	564
	Forest	0.45	540.7	330	427	612
	Non-Forest	0.50	546.8	235	428	615
Charles	Overall		567.6	1227	365	635
	Developed	0.07	578.3	1118	427	630
	Unforestable	0.00	561.8	1678	501	616
	Forest	0.71	563.6	1264	365	635
	Non-Forest	0.22	577.6	948	421	632
Dorchester	Overall		586.6	802	475	688
	Developed	0.03	593.5	1053	484	688
	Unforestable	0.00	0.0	0	0	0
	Forest	0.36	589.3	976	479	688
	Non-Forest	0.61	584.6	677	475	688
Frederick	Overall		568.0	7261	414	897
	Developed	0.03	523.2	2494	415	863
	Unforestable	0.00	504.2	1416	415	615
	Forest	0.36	614.8	10732	415	897
	Non-Forest	0.61	543.2	3484	414	886

Table 1 (continued). Simulated potential forest net primary production.

COUNTY	LANDUSE	PROPORTION	NPP MEAN	NPP VARIANCE	NPP MINIMUM	NPP MAXIMUM
Garrett	Overall		727.6	2704	495	838
	Developed	0.01	733.1	2609	496	825
	Unforestable	0.01	693.9	3191	503	812
	Forest	0.79	725.0	2953	495	838
	Non-Forest	0.20	739.3	1495	506	830
Harford	Overall		544.7	1160	450	651
	Developed	0.08	535.8	267	456	651
	Unforestable	0.00	552.6	1696	461	623
	Forest	0.43	545.2	1188	450	648
	Non-Forest	0.49	545.6	1259	450	646
Howard	Overall		531.2	950	465	634
	Developed	0.14	521.6	255	499	627
	Unforestable	0.00	0.0	0	0	0
	Forest	0.40	527.2	676	466	633
	Non-Forest	0.47	537.4	1306	465	634
Kent	Overall	1.00	563.6	395	453	679
	Developed	0.02	563.6	343	503	675
	Unforestable	0.00	0.0	0	0	0
	Forest	0.21	561.3	540	457	676
	Non-Forest	0.77	564.2	354	453	679
Montgomery	Overall	1.00	527.5	1031	435	648
	Developed	0.22	535.5	276	442	640
	Unforestable	0.00	527.2	166	512	542
	Forest	0.37	525.0	950	435	643
	Non-Forest	0.41	525.6	1463	436	648
Prince Georges	Overall	1.00	565.1	567	495	622
	Developed	0.29	556.6	393	504	622
	Unforestable	0.01	546.9	338	499	591
	Forest	0.48	568.3	601	495	622
	Non-Forest	0.22	570.1	578	495	622
Queen Annes	Overall	1.00	569.6	662	456	642
	Developed	0.03	569.0	809	492	641
	Unforestable	0.00	598.1	0	598	598
	Forest	0.25	568.2	671	456	640
	Non-Forest	0.72	570.1	652	463	642
Somerset	Overall		635.3	656	541	715
	Developed	0.03	639.4	527	543	706
	Unforestable	0.00	634.5	1502	599	676
	Forest	0.56	633.6	658	546	715
	Non-Forest	0.41	637.4	653	541	715
St. Marys	Overall		608.6	225	540	657
	Developed	0.08	611.4	242	540	657
	Unforestable	0.00	608.6	909	542	654
	Forest	0.62	608.7	220	540	657
	Non-Forest	0.30	607.5	229	540	656
Talbot	Overall	1.00	589.7	641	463	661
	Developed	0.05	583.2	700	469	643
	Unforestable	0.00	0.0	0	0	0
	Forest	0.31	591.8	640	463	661
	Non-Forest	0.64	589.1	631	464	658

Table 1 (continued). Simulated potential forest net primary production.

COUNTY	LANDUSE	PROPORTION	NPP MEAN	NPP VARIANCE	NPP MINIMUM	NPP MAXIMUM
Washington	Overall	1.00	567.6	4755	357	899
	Developed	0.04	583.4	2665	388	800
	Unforestable	0.00	579.6	7289	457	803
	Forest	0.40	557.1	7843	357	899
	Non-Forest	0.55	573.9	2555	391	890
Wicomico	Overall	1.00	588.6	506	498	663
	Developed	0.06	585.3	429	501	663
	Unforestable	0.00	590.0	0	589	590
	Forest	0.48	588.4	564	502	663
	Non-Forest	0.46	589.2	454	498	663
Worcester	Overall	1.00	623.1	511	501	701
	Developed	0.02	630.1	491	526	677
	Unforestable	0.00	652.5	0	652	652
	Forest	0.55	620.9	568	501	695
	Non-Forest	0.43	625.6	424	503	701

In contrast to Frederick County, Prince George's County is extensively developed (Figure 5a) with much of that development extending south over areas of land that hold high potential for forest productivity (Figure 3b). Because the highest potential forest productivity is located in the southern end of the county, both forest most highly suitable for conservation (Figure 5b) and agricultural land most highly suitable for afforestation (Figure 5c) are located in the south. Unlike Frederick County, current forest and nonforest land covers are interspersed over this highly productive portion of Prince George's County. Because most of the county's total forest area is located in the south, most conservation forest appears clumped (Figure 5b). Even though nonforest land is more widely dispersed in the county the 25% of nonforest pixels that would be most valuable for forest carbon sequestration remains largely clumped in the east-southeast. This pattern of interspersed forest and nonforest land across a productive portion of the county may make optimal choice of land for carbon sequestration projects a more localized, or sub-county, issue.

Caroline County has a minor north to south gradient of increasing potential forest productivity (Figure 3c) that eventually concentrates somewhat higher potential forest productivity in the southern part of the county. Thus, like Frederick and Prince George's Counties, forest conservation and afforestation for carbon sequestration would be most effective in southern Caroline County. Unlike the other two counties, Caroline County has a preponderance of agricultural land with forest scattered rather uniformly across the county (Figure 6a). Thus a carbon sequestration strategy that aimed to conserve current forest would focus on almost all forest in the southern part of the county except for the largest block of continuous forest, which is located in an area of lower productivity (Figures 3c and 6b). Afforestation could focus on almost any nonforest land in the south central portion of the county (Figure 6c).

Carbon Sequestration Versus Reducing Fragmentation. Optimizing the allocation of land area to afforestation for carbon sequestration while simultaneously increasing habitat

Figure 3. Simulated potential forest net primary productivity ($\text{gC} / \text{m}^2 / \text{yr}$) for Frederick County (a), Prince George's County (b), and Caroline County (c). Note that the simulations assumed continuous forest cover on terrestrial sites rather than different land uses. Color shades do not signify the same productivity for each county. White areas, particularly prominent in Caroline County, are pixels dominated by water or wetlands.

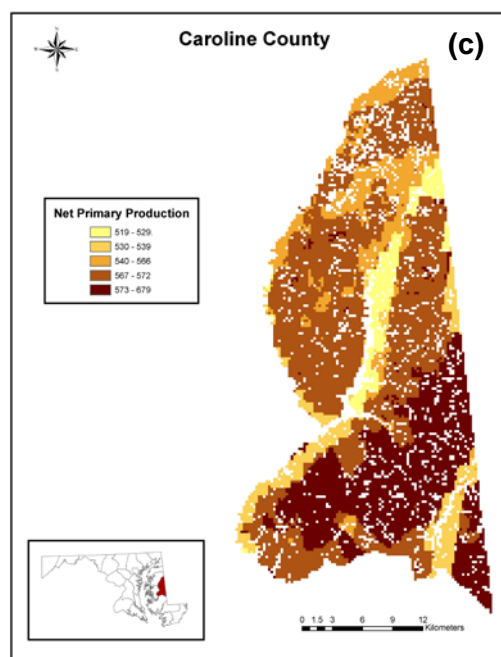
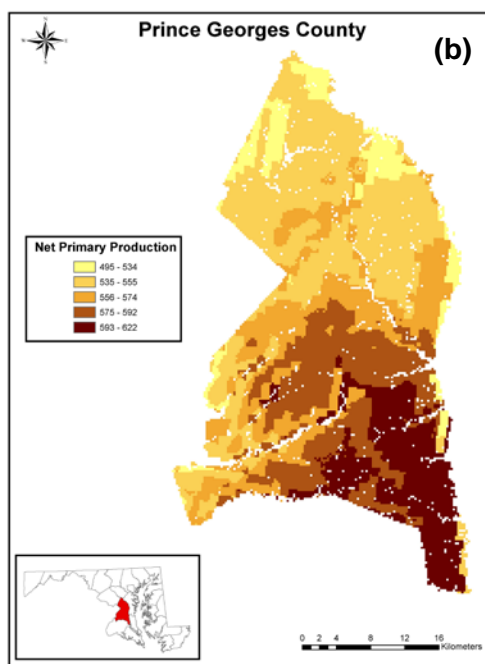
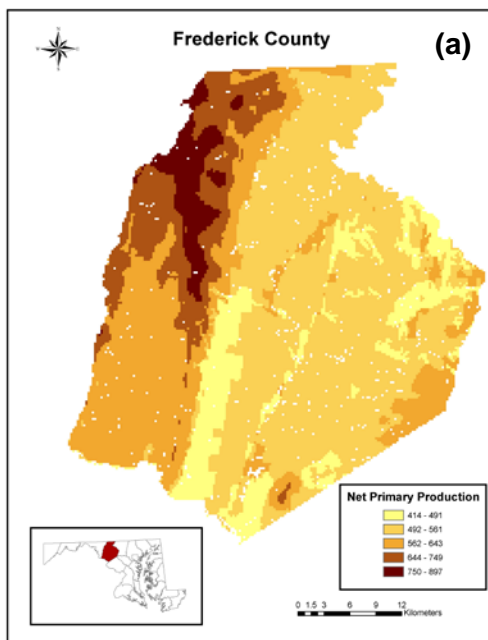


Figure 4. Frederick County land use/ cover (a), the top quartile of forest pixels ranked by potential forest productivity (b), and the top quartile of non-forest pixels ranked by potential forest productivity (c).

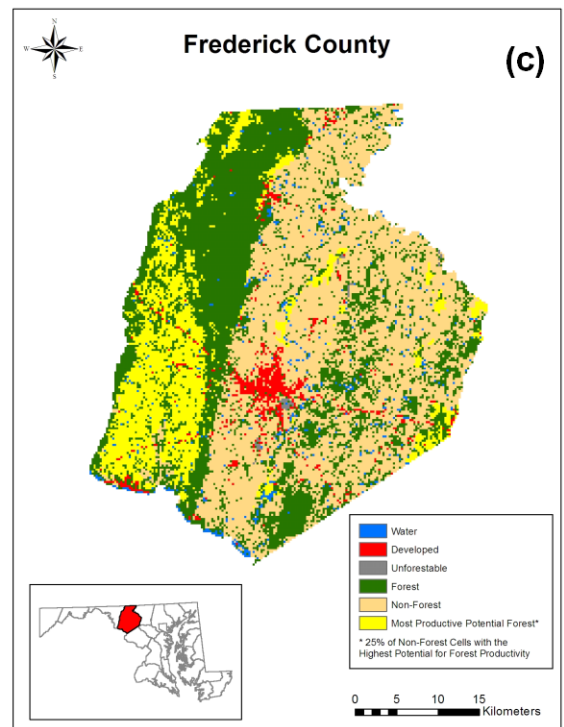
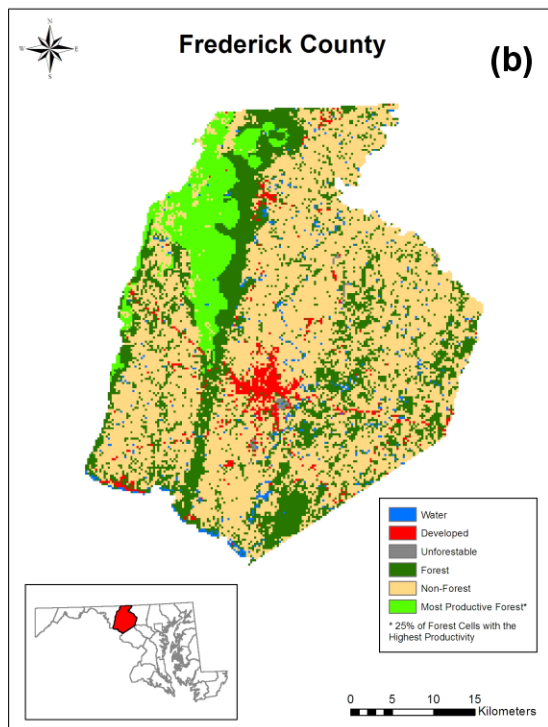
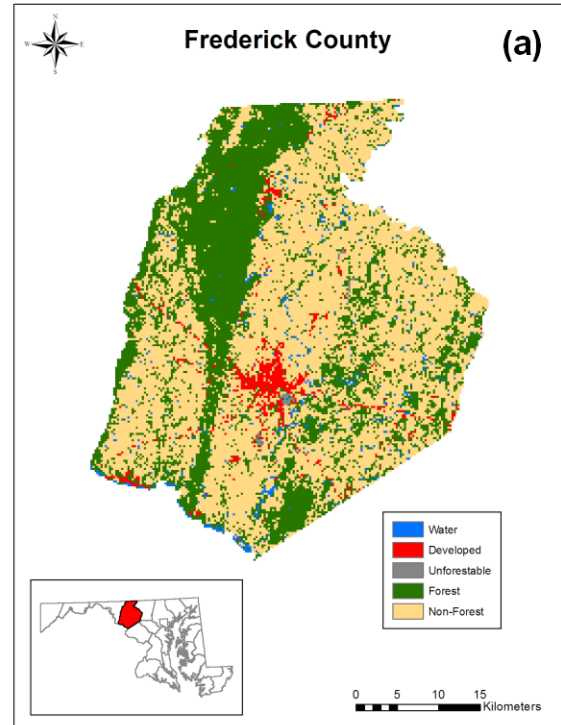
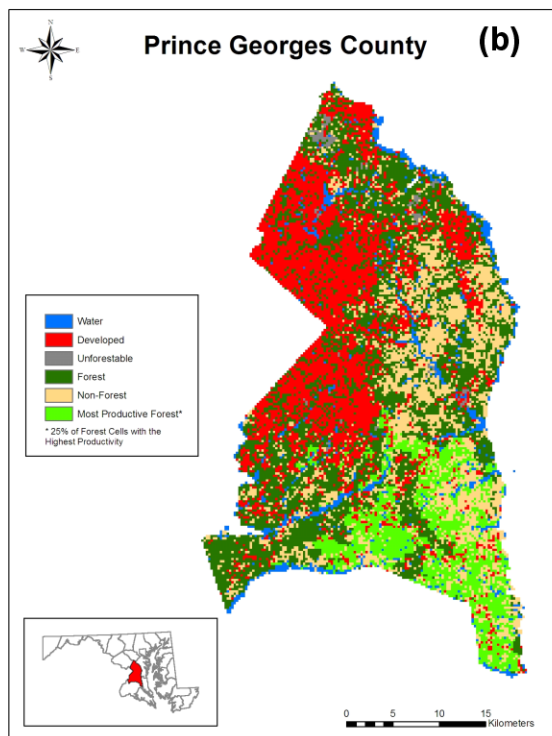
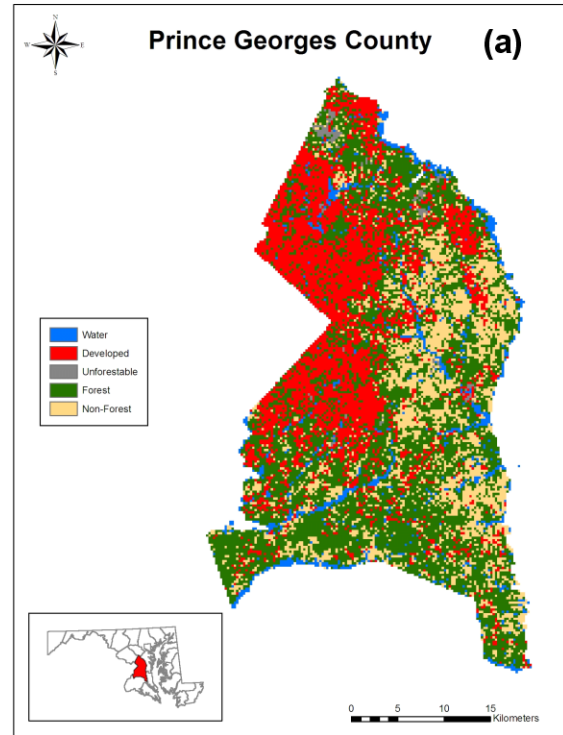
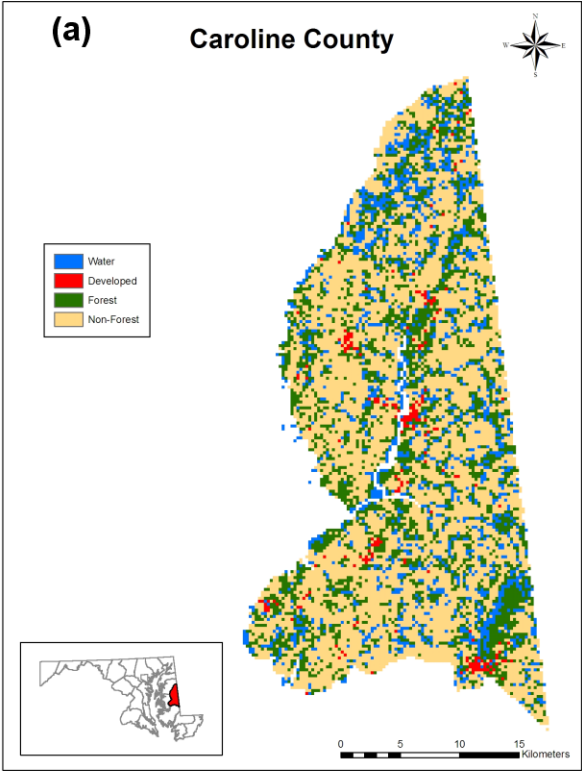


Figure 5. Prince Georges County land use/ cover (a), the top quartile of forest pixels ranked by potential forest productivity (b), and the top quartile of non-forest pixels ranked by potential forest productivity (c).

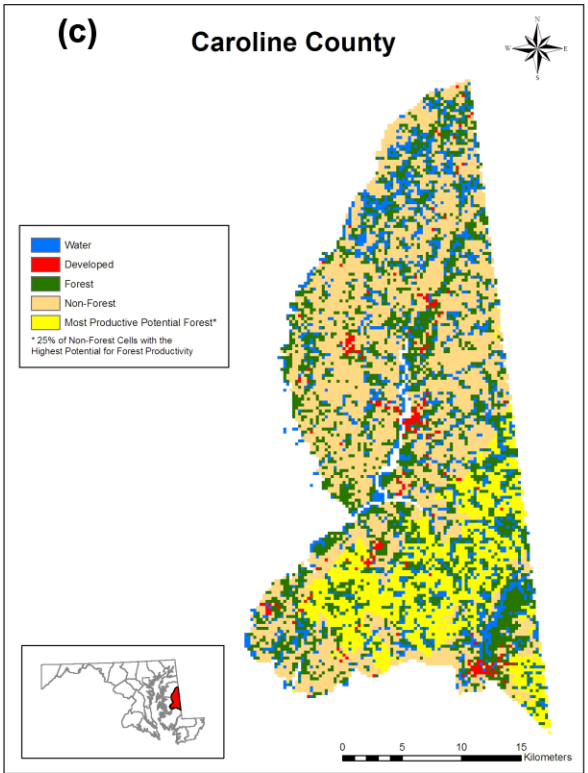


(c)

Figure 6. Caroline County land use/cover (a), the top quartile of forest pixels ranked by potential forest productivity (b), and the top quartile of non-forest pixels ranked by potential forest productivity (c).



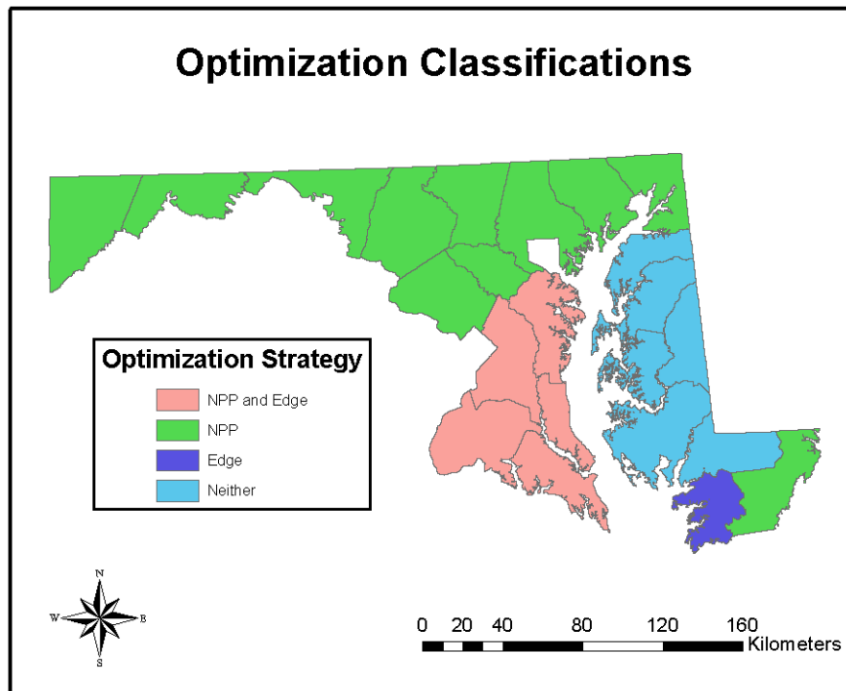
(b)



quality can be a complex function of the spatial distributions of potential forest productivity and land use/cover or a relatively simple matter of prioritization. The primary productivity and fragmentation characteristics of each county in Maryland were compiled and compared to our decision matrix rules in order to suggest the most parsimonious allocation strategies to meet these goals. As a result, Maryland counties can be placed into four categories (Figure 7):

- Category 1: Allegany, Baltimore, Carroll, Cecil, Frederick, Garrett, Harford, Howard, Montgomery, Washington, Worcester
- Category 2: Anne Arundel, Calvert, Charles, Prince George's, St. Mary's
- Category 3: Caroline, Dorchester, Kent, Queen Anne's, Talbot, Wicomico
- Category 4: Somerset

Figure 7. Based on spatial pattern of current land cover/use and the distribution of potential forest productivity four different strategies for afforestation are suggested. If the management goal is to both increase carbon sequestration and decrease forest fragmentation. Only counties in southern Maryland have characteristics that suggest the need for a mixed strategy requiring detailed spatial optimization.



For many counties, the optimal strategy is to focus solely on either the carbon sequestration or fragmentation reduction goal. For example, the strategy for Category 1, which includes primarily the western, northern and north-central portions of Maryland, is to focus solely on afforestation of land with high potential forest productivity, which is the equivalent to the afforestation strategy previously described for Frederick County (Figure 5c). However, this strategy results from either wide-spread forest cover over varying levels of potential forest productivity or extensive forest on pockets of high potential productivity. For example, Allegany County has an extensive forest cover (85%; Table 1) that yields a low degree of fragmentation. Low forest fragmentation is coupled with very high variation in potential primary productivity (Table 1). Consequently the most parsimonious strategy when carbon storage and reducing fragmentation are equally important would be to plant new forests on highly productive land. This action could simultaneously decrease fragmentation by “filling in holes” in the forest but overall would have little impact on fragmentation statistics at the county level. Frederick County also has very high variation in potential forest productivity but in contrast to Allegany County only 36% forest cover (Table 1). This county falls into Category 1 because most existing forest land is concentrated in the northwest portion of the county where high primary productivity prevails (Figures 3 and 4). Like Allegany County, even afforestation efforts that value both carbon storage capacity and fragmentation reduction should focus on nonforest areas within the forest clumps unless the county’s landscape is transformed by massive forest planting. At the opposite extreme is Somerset County on the south end of Maryland’s Eastern Shore (Figure 7), the only county classed as Category 4. Somerset County is 46% forested but there is relatively low spatial variation in potential forest productivity (Table 1; Figure 2). With little gain to be made by selecting afforestation sites for potential productivity, focusing on reducing fragmentation would be a more valuable contribution to forest ecosystem services. Note that any afforestation effort would still sequester carbon but reducing fragmentation would be the primary factor in decisions on where afforestation should occur.

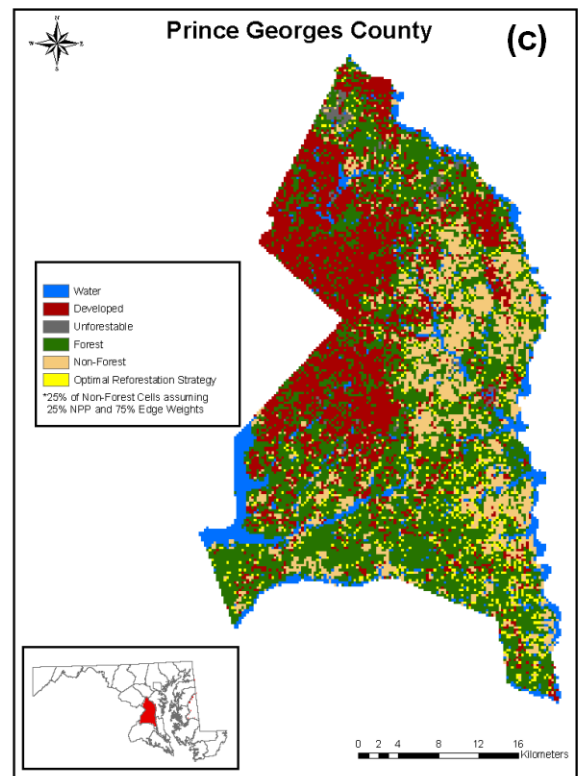
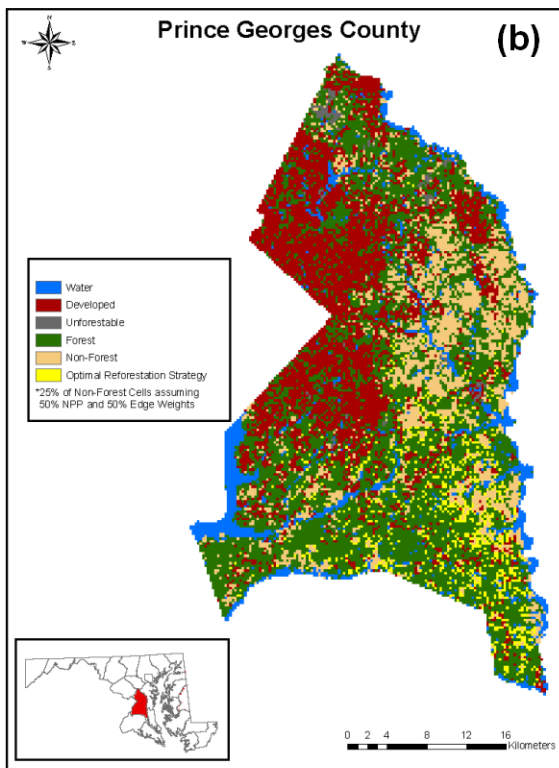
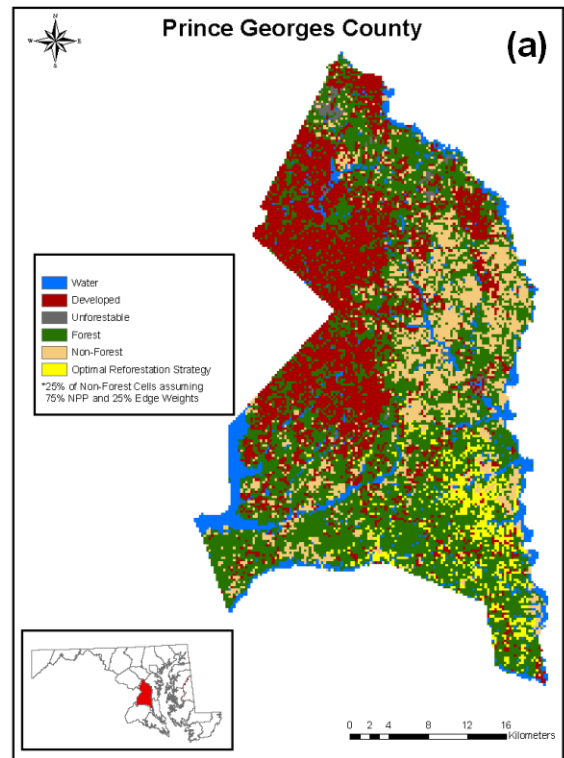
Category 3 counties are interesting in that optimization analyses are unlikely to be of assistance in planning afforestation for either carbon sequestration or reduced forest fragmentation. These counties have less forest cover and extensive areas of agricultural land that vary little in potential forest productivity (Table 1). Caroline County typifies this category with 30% forest cover (Figure 6, Table 1), at best moderate potential forest productivity (519 – 679 gC / m² / yr), and low spatial variability in productivity (Variance = 202). The degree of afforestation needed to positively impact forest fragmentation is so extensive and so uniformly needed across the county that optimization analyses would rank most pixels as having the same priority for planting. Even though spatial variation does exist in potential productivity, analyzing nonforest land mathematically would also result in most pixels of equivalent priority. Although optimization methods are unlikely to be of planning assistance for counties in Category 3, afforestation projects would produce at least nominal carbon storage and spatial aggregation of such projects would avoid further contribution to the forest fragmentation problem.

The five counties in Category 2, clustered in southern Maryland, are clearly candidates for application of optimization techniques (Figure 7) to direct afforestation for simultaneously sequestering as much carbon as possible and reducing forest fragmentation. These counties range from 45-65% forested, have some of the highest potential forest productivities in the state outside of Western Maryland, and generally have high variance in potential productivity (Table 1). For each of these counties the spatial mixing of forest and nonforest land in areas of relatively high potential productivity or along a gradient of potential productivity makes an optimal solution more complex than simply focusing on one of the objectives. Prince George's County exemplifies Category 2 with an increasing north-south gradient in productivity and interspersed forest and nonforest land in the south as well as along the productivity gradient (Figures 3b and 5a). Simultaneous optimization of carbon sequestration and fragmentation reduction was carried out with different relative weights for these dual objectives. With potential forest productivity weighted heavily ($a = 0.75$) and fragmentation reduction considered less important ($b = 0.25$), significant clumping of new forest drawn from agricultural land is apparent in the more productive southern part of the county (Figure 8a). This clumping decreases (Figure 8b) as the dual objectives are weighted evenly ($a = b = 0.5$) and lapses into selection of scattered parcels for afforestation when reduction in forest fragmentation is considered the primary objective (Figure 8c; $a = 0.25$, $b = 0.75$). Obviously, further emphasis on fragmentation reduction would disperse these selected parcels even more. These general patterns reflect the interaction of management optimizations with current land use heterogeneity and underlying potential productivity distribution. However, the patterns show the outcome of afforestation applied to 25% of the nonforest pixels. The full management impact of these optimizations comes with the realization that pixels are chosen in the analysis in order of their contribution to realizing the objectives of the analysis. Thus each pixel can be prioritized and management actions targeted as precisely as the databases entered in the analysis allow. In reality, on a pixel by pixel basis, large differences in management impact are unlikely with each successive pixel chosen in the analysis. Nonetheless it is feasible to specify land areas for afforestation based on available funds and also the relative emphasis on carbon sequestration and fragmentation reduction, and then solve for the "best" pixels for achieving that goal. For example, if funding were available to plant forest on 1.0 km², then the first 16 pixels chosen would be the optimal solution to meet those objectives.

DISCUSSION AND CONCLUSIONS

Spatial heterogeneity is a characteristic of all ecological phenomena. For environmental management this heterogeneity really means managing the health and flow of ecosystem services from multiple patches of interacting natural and human-dominated ecosystems. This management of flows is clearly complicated, however, when spatial patterns of ecosystems impact the production of services. For the purpose of using forests to mitigate atmospheric CO₂, three levels of management complexity can be recognized. The simple approach is to plant new forests or manage existing forests more intensively to maximize carbon sequestration with no particular regard for spatial variation in

Figure 8. Optimization of afforestation for Prince Georges County when relative weighting for potential forest productivity forest fragmentation reduction are (a) 0.75 and 0.25, (b) 0.5 and 0.5, and (c) 0.25 and 0.75.



potential productivity. When potential forest productivity is significantly heterogeneous, a second, slightly more complex strategy is to allocate afforestation and management resources to areas of high productivity. In other words, management is predicated on understanding ecosystem heterogeneity. Foresters have understood the economic production consequences of site quality for many decades, but it is unclear whether the developing carbon trading market has embraced the consideration of county-level spatial heterogeneity for varying carbon offsets. A third and higher level of complexity arises when carbon mitigation strategies through forest management are coupled with production of other ecosystem services. In this situation, the influence of spatial heterogeneity on multiple resources must be balanced or optimized. Economic accounting of forest ecosystem services other than carbon sequestration may be difficult, but as a carbon trading market flourishes there is potential for an influx of new funds to forest management that can enable this advanced level of ecosystem service management across private, industrial, and public forest lands. This project attempts to provide a template for forest management in Maryland that considers spatial variation and thus reflects these latter two levels of management complexity.

Forest inventory and analysis (FIA) data have proven very useful in estimating timber production and describing forest composition at the county level. However, spatial interpolation among FIA sampling sites is problematic because FIA plots are selected to provide a statistically valid sample of forest composition and growth over a given area, not one that is stratified to sample the range of potential forest productivity. In addition, interpolation among FIA sites can be hindered by heterogeneity of physical factors that drive forest productivity. Ecosystem models, such as PnET-CN, provide another means to estimate and continuously map potential forest productivity over large spatial scales. PnET-CN, like any model, is subject to its own assumptions and the quality of variable inputs. Applying models in a spatial sense also results in susceptibility to resolution and accuracy of spatial driving variables. These issues are apparent in this application of PnET-CN at a 250 m resolution. Even though the model is capable of simulating forest productivity at smaller spatial scales, driving variable resolution makes that application tenuous. Thus, how the 250 m resolution meshes with forest management for carbon mitigation strategies needs consideration. Each model pixel represents 6.25 ha or 15.4 acres. Land cover/use data is usually scaled up from 30 m resolution remotely sensed images, thus the land cover/use classification for each pixel in this project's data is the dominant land cover for about 70 remotely sensed 30 m pixels. Assuming that the land cover/use classification at 250 m resolution simply represents the most common pixel identity from the 30 m resolution classification, then each simulated pixel should minimally represent about half of each pixel's area - 3.1 ha or 7.7 acres. Thus, on the ground, each simulated pixel classed as forest may actually be between 3.1 ha and 6.25 ha of forest (i.e., 50-100%). Whether practicing forestry on 3.1 – 6.25 ha areas is economically viable depends on management type and costs. The economic efficiency of planting or managing forest is obviously higher when working with large contiguous areas. Results presented here by either simple ranking of nonforest land or through optimization models identify many multi-pixel clusters that might be economically feasible for afforestation. However, the economic value of afforestation of individual pixels would need to be gauged by comparing management costs with the potential

productivity of that pixel and the value of that pixel in reducing forest fragmentation. A sufficiently high potential forest productivity, that should ideally command a higher value on the carbon trading market, may be worth the higher management expense. This example illustrates the possible usefulness of having potential forest productivity mapped at as fine a resolution as possible. If potential carbon sequestration can be verified or certified at a fine resolution, both large and small landowners can better gauge opportunity for market participation and receive appropriate carbon sequestration payments.

Carbon trading policies are developing at national and international levels, yet actual carbon storage projects are implemented locally. Within Maryland, the state-wide variation in potential forest primary productivity presented in this project (Figure 2) is not particularly new information, but if the State of Maryland wishes to pursue carbon management policies based solely on potential forest productivity and on-the-ground storage, then western Maryland is an obvious choice. Alternatively, plantation forestry, with faster growing, short-rotation species that produce wood products for long-term carbon storage, would be viable in many areas of the State. Consequently, selection and implementation of efficient forest carbon storage policies is best carried out at the county level – the smallest overarching political and management structure and, for many Maryland counties, a large enough variation in landscape cover and productivity to encourage alternative approaches to carbon management. Mapping of county-level potential forest productivity and current land use/cover provided by this project make available the minimal tools for Level 2 planning at the county level. Maps of spatial variation in potential productivity make clear what general areas of each county should be most useful for carbon storage projects and thus should command a higher value in carbon trading. Maps depicting current forests that are most valuable to retain, for active management or conservation coupled with carbon storage, and maps of land most valuable for afforestation to store carbon should provide both local and public assistance in land use planning and participation in carbon trading markets.

The analyses presented here indicate that when considering only two forest ecosystem services, potential carbon sequestration and habitat quality (as reflected by fragmentation reduction), the choices for optimizing these services are often not complicated at the county level. The majority of counties should simply attempt to maximize forest productivity, only one should aim to minimize fragmentation, and several on the Eastern Shore are unlikely to benefit from either approach in a mathematical sense. It should be emphasized that these results do not mean that carbon sequestration projects should not be undertaken on the Eastern Shore or that reduction of forest fragmentation should not be attempted in most of Maryland. Afforestation projects, even if on relatively low productivity sites, will still store some amount of carbon; forest management practices can always be implemented that minimize forest edge. The results do suggest that optimization analyses at the county level will not provide informative directions for how to maximize these two ecosystem services except for five counties in southern Maryland. However, spatial heterogeneity within each county virtually assures that on some land area within each county, with appropriately scaled information, there is an optimal management solution for both forest productivity and fragmentation reduction. Potential

productivity maps and analyses of land use provided by this project hopefully will assist county-level management in identifying such areas and guiding development of county-level planning policy.

For five Maryland counties, optimal county-wide strategies for simultaneously planning afforestation / carbon storage projects and reducing forest fragmentation are possible. One means of viewing this possibility is that these counties have the strongest potential for payments from carbon offsets to positively impact other forest ecosystem services associated with decreased fragmentation. Interestingly, all five of these counties are clustered in southern Maryland where development pressure is paramount and intensive planning for natural ecosystem services is perhaps needed most. Forest carbon storage projects may be a key economic tool for managing the landscape in these counties and the additionalities associated with fragmentation reduction need to be included in those economic models. The fragmented landscape associated with these counties also makes analyses at the finest possible scale of resolution desirable. With finer resolution data input and greater information on local planning objectives, land ownership, zoning regulations, etc. optimization of forest ecosystem services should become even more useful for these counties. Clearly, forest carbon sequestration projects are only one of many local competing land uses. Many Maryland counties face severe development pressure, with land values that overshadow potential carbon offsets. Development obviously also places pressure on other competing public interests, such as agro-tourism, historic preservation, and green space retention. These complications won't be solved by maps of potential forest productivity, but a stronger understanding of yet another possible, economically valuable ecosystem service from undeveloped land provides another incentive to individuals and the public for open space conservation.

The complexity of issues associated with land management in southern Maryland counties has the potential to create multiple objective optimization problems that become intractable, either mathematically or from a data quality perspective, or simply have no solution because of the number of competing interests. Consequently, from both conceptual and mathematical points of view, development or recognition of ecosystem service "indicators" would be useful. Such an indicator may be defined as a readily computed metric that serves as a barometer for the quality and/or quantity of multiple ecosystem services. This concept was adopted implicitly for this project with the assumption that forest fragmentation, measured by edge density, reflects multiple aspects of forest ecosystem function, quality, and services. As a surrogate for many topics of conservation concern (e.g., habitat quality for multiple species, invasibility by exotic species, biodiversity, and perhaps forest nutrient retention) forest fragmentation served in these analyses to complement the commercial product aspects (e.g., timber, fiber, durable manufactured products, etc.) of forest management that are aptly reflected by potential forest productivity. Quantification of the correlation between fragmentation and quantity/quality of other forest ecosystem services will be needed to confirm its indicator status.

SUMMARY

Simulated spatial patterns of potential forest productivity indicate that both state-wide and within most Maryland counties there is enough spatial variation in productivity to warrant consideration of this factor when establishing carbon sequestration projects. Consideration of spatial heterogeneity in potential productivity for landscape planning would be most effective at the county level where local land use regulations, economic development initiatives, etc. could efficiently enter the planning process. County-level maps of potential forest productivity, the most highly productive current forest that may warrant conservation, and nonforest land that would support the most productive new forest were produced that may be useful for county-level planning.

Maryland counties vary highly in the magnitude and range of potential forest productivity and the distribution of current forest across that heterogeneity in productivity. Consequently, the opportunity to utilize afforestation in carbon sequestration projects to simultaneously gain other forest ecosystem services (reflected by reduction in forest fragmentation) varies among counties. Analyses at the county level suggest that most county-level strategies should plan for maximizing forest productivity while placing less emphasis on fragmentation reduction. Most counties on the Eastern Shore have low variation in productivity and extreme forest fragmentation, leading to no clear optimization strategy. Intense plantation forestry, centered on the most productive areas in each county, could function in forest carbon sequestration projects and perhaps create managed forest pockets that would be of low fragmentation. Southern Maryland counties hold strong potential for finding optimal mixes of afforestation for carbon storage and fragmentation reduction. Analyses that weight these two ecosystem services differentially provide insight to how these optimal solutions might be implemented spatially.

REFERENCES

- Aber, J.D., S.V. Ollinger and C.T. Driscoll. 1997. Modeling nitrogen saturation in forest ecosystems in response to land use and atmospheric deposition. *Ecological Modelling* 101: 61-78.
- Andersson, K. and K.R. Richards. 2001. Implementing an international carbon sequestration program: can the leaky sink be fixed? *Climate Policy* 1:173-188.
- Bailey, N., J.T. Lee and S. Thompson. 2006. Maximising the natural capital benefits of habitat creation: spatially targeting native woodland using GIS. *Landscape and Urban Planning* 75: 227-243.
- Bayon, R. 2004. Making environmental markets work: lessons from early experience with sulfur, carbon, wetlands, and other related markets. *Forest Trends* (www.forest-trends.org), Washington, DC. (Web site accessed July 2004).

- Beshears, D.D. and C.D. Allen. 2002. The importance of rapid, disturbance-induced losses in carbon management and sequestration. *Global Ecology and Biogeography* 11: 1-5.
- Borgmann, K.L. and A.D. Rodewald. 2004. Nest predation in an urbanizing landscape: the role of exotic shrubs. *Ecological Applications* 14: 1757-1765.
- Boulmier, T., J.D. Nichols, J.E. Hines, J.R. Sauer, C.H. Flather and K.H. Pollock. 2001. Forest fragmentation and bird community dynamics: inference at regional scales. *Ecology* 82: 1159-1169.
- Boyd, J. and S. Banzhaf. 2006. What are ecosystem services? The need for standardized environmental accounting units. *Resources For The Future Discussion Paper*. 06-02.
- Brush, G.S., C. Lenke and J. Smith. 1980. The natural forests of Maryland: an explanation of the vegetation map of Maryland. *Ecological Monographs* 50:77-92.
- Caparros, A. and F. Jacquemont. 2003. Conflicts between biodiversity and carbon sequestration programs: economic and legal implications. *Ecological Economics* 46: 143-157.
- Capoor, K. and P. Ambrosi. 2006. State and trends of the carbon market 2006. International Emissions Trading Association and The World Bank.
- Collinge, S.K. 1996. Ecological consequences of habitat fragmentation: implications for landscape architecture and planning. *Landscape and Urban Planning* 36: 59-77.
- Creedy, J and A.D. Wurzbacher. 2001. The economic value of a forested catchment with timber, water and carbon sequestration benefits. *Ecological Economics* 38: 71-83.
- Feng, H. and C.L. Kling. 2005. The consequences of cobenefits for the efficient design of carbon sequestration programs. *Canadian Journal of Agricultural Economics* 53: 461-476.
- Frieswyk, T.S. and D.M. DiGiovanni. 1988. Forest statistics for Maryland – 1976 – 1986. USDA Forest Service, Northeastern Forest Experiment Station, Resource Bulletin NE-107.
- Gardner, R.H. and E.J. Gustafson. 2004. Simulating dispersal of reintroduced species within heterogeneous landscapes. *Ecological Modelling* 171: 339-358.
- Huston, M.A. and G. Marland. 2003. Carbon management and biodiversity. *Journal of Environmental Management* 67: 77-86.
- Kennett, S.A. 2002. National policies for biosphere greenhouse gas management: issues and opportunities. *Environmental Management* 30: 595-608.

- Marland, G., K. Fruit and R. Sedjo. 2001. Accounting for sequestered carbon: the question of permanence. *Environmental Policy and Analysis* 4: 259-268.
- Matthews, S. R. O'Connor and A.J. Plantinga. 2002. Quantifying the impacts on biodiversity of policies for carbon sequestration in forests. *Ecological Economics* 40: 71-87.
- McMillan, J. 2002. *Reinventing the bazaar: a natural history of markets*. W.W. Norton and Company. New York.
- McNulty, S.G. 2001. Hurricane impacts on US forest carbon sequestration. *Environmental Pollution* 116: S17-S24.
- Murray, B.C., S.P. Prisley, R.A. Birdsey and R.N. Sampson. 2000. Carbon sinks in the Kyoto Protocol: potential relevance for U.S. forests. *Journal of Forestry* 98: 6-11.
- O'Connell, K. (Editor). 1998. *Forest fragmentation in the Chesapeake Bay watershed*. Society of American Foresters Publication 08-09. Bethesda, MD.
- Richards, K. and K. Andersson. 2001. The leaky sink: persistent obstacles to a forest carbon sequestering program based on individual projects. *Climate Policy* 1: 41-54.
- Ritters, K.H., J.W. Coulston and J.D. Wickham. 2003. Localizing national fragmentation statistics with forest type maps. *Journal of Forestry* 101: 18-22.
- Ritters, K.H., J.D. Wickham, R.V. O'Neill, K.B. Jones, E.R. Smith, J.W. Coulston, T.G. Wade and J.H. Smith. 2002. Fragmentation of continental United States forest. *Ecosystems* 5: 815-822.
- Rogers, C.E. and J.P. McCarty. 2000. Climate change and ecosystems of the Mid-Atlantic Region. *Climate Research* 14: 235-244.
- Seagle, S.W. and B.R. Sturtevant. 2005. Forest productivity determines invertebrate biomass and ovenbird (*Seiurus aurocapillus*) reproduction in Appalachian forest landscapes. *Ecology* 86: 1531-1539.
- Sedjo, R.A., J. Wisniewski, A.V. Sample and J.D. Kinsman. 1995. The economics of managing carbon via forestry: assessment of existing studies. *Environmental and Resource Economics* 6: 139-165.
- Sturtevant, B.R. and S. W. Seagle. 2004. Comparing estimates of forest site quality in old second-growth oak forests. *Forest Ecology and Management* 191: 311-328.

Turner, M.G., W.H. Romme, R.H. Gardner and W.W. Hargrove. 1997. effects of fire size and pattern on early post-fire succession in subalpine forests of Yellowstone National Park, Wyoming. *Ecological Monographs* 67: 411-433.

Van Kooten, G.C., A.J. Eagle, J. Manley and T. Smolak. 2004 How costly are carbon offsets? A meta-analysis of carbon forest sinks. *Environmental Science and Policy* 7: 239-251.

Watkins, B.Z., J.Q. Chen, J. Pickens and D.D. Brososke. 2003. Effects of forest roads on understory plants in a managed hardwood landscape. *Conservation Biology* 17: 411-419.

APPENDIX A: COUNTY MAPS CD DESCRIPTION

Map Directory Structure

Information to guide the user through the maps on this website is included in the “Readme” file on the CD. Maps are sorted into folders by county. Within each county there are four maps:

1. Potential forest productivity. This a scaled map showing the range and distribution of potential net primary productivity ($\text{gC} / \text{m}^2 / \text{yr}$) for forests calculated by application of the model PnET-CN GIS to each pixel in each county regardless of current land use. [Format: *county_name_NPP.jpg*]
2. Land use / cover. This map displays land use / cover data for the county based on NREL data (1992), with the land use/cover aggregated to forest, nonforest, developed, and unforestable. Definition of what recognized NREL land use/cover types are included in each of these categories can be found in the text. [Format: *county_name_landuse.jpg*]
3. Land use / cover with highest productivity forest. All forest pixels were examined and forest pixels that also were in the upper quartile (top 25%) of simulated potential forest productivity were placed in a new category. This map shows which currently forest pixels would be the most beneficial to retain as productive forest (managed or otherwise) in terms of potential carbon storage. [Format: *county_name_MPF.jpg*]
4. Land use / cover with highest productivity nonforest. All nonforest pixels (primarily crop, pasture and other agricultural use) were examined and the nonforest pixels that also were in the upper quartile (top 25%) of simulated potential forest productivity were placed in a new category. This map shows which nonforest pixels would likely support the most productive forest if undergoing afforestation. [Format: *county_name_MPPF.jpg*]

In addition to these four maps, the following counties have four additional maps resulting from optimization analyses in their folder: Anne Arundel, Calvert, Charles, Prince George's, and St. Mary's. These are the five counties that, under the assumptions presented in the text, would likely benefit from county-wide optimization analyses if landscape management goals included both maximizing forest carbon sequestration through afforestation and maximizing reduction in forest fragmentation through afforestation. These maps are:

5. Land use / cover optimization weighting productivity (0.75) and fragmentation (0.25). This map results from simultaneously optimizing forest productivity and reduction in forest fragmentation as 0.75 and 0.25, respectively. Higher weighting values means greater emphasis on that objective. The map shows the top ranked 25% of nonforest pixels to meet these weighted objectives by afforestation. [Format: *county_name_75_25.jpg*]
6. Land use / cover optimization weighting productivity (0.5) and fragmentation (0.5). This map results from simultaneously optimizing forest productivity and reduction in forest fragmentation equally weighted. Equal weighting values means equal emphasis on each objective. The map shows the top ranked 25% of nonforest pixels to meet these weighted objectives by afforestation. [Format: *county_name_50_50.jpg*]
7. Land use / cover optimization weighting productivity (0.25) and fragmentation (0.75). This map results from simultaneously optimizing forest productivity and reduction in forest fragmentation as 0.25 and 0.75, respectively. Higher weighting values means greater emphasis on that objective. The map shows the top ranked 25% of nonforest pixels to meet these weighted objectives by afforestation. [Format: *county_name_25_75.jpg*]
8. Land use / cover optimization weighting productivity (0.0) and fragmentation (1.0). This map results from simultaneously optimizing forest productivity and reduction in forest fragmentation as 0.0 and 0.75, respectively. Higher weighting values means greater emphasis on that objective. The map shows the top ranked 25% of nonforest pixels to meet these weighted objectives by afforestation. [Format: *county_name_0_100.jpg*]

Note that optimization maps are not listed for the scenario of weighting productivity and fragmentation as 1.0 and 0.0, respectively. Such a map would be equivalent to map (4) described above.