Integrated Analysis of Ecosystem Interactions With Land Use Change: The Chesapeake Bay Watershed

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The Chesapeake Bay is the largest estuary in the United States, encompassed by a watershed extending 168,000 km^2 over portions of six states and Washington, D.C. Restoration of the Bay has been the focus of a two-decade regional partnership of local, state and federal agencies, including a network of scientists, politicians and activists interacting through various committees, working groups, and advisory panels. The effectiveness of the restoration effort has been mixed, with both notable successes and failures. The overall health of the Bay has not declined since the restoration was initiated in 1983, but many of the advances have been offset by the pressure of increasing population and exurban sprawl across the watershed. The needs of the Chesapeake Bay Program are many, but the greatest is accurate information on land cover and land use change, primarily to assess the implications for water quality, examine various restoration scenarios, and calibrate spatial models of the urbanization process. We report here on a number of new land cover and land use data products, and associated applications to assist vulnerability assessment, integrated ecosystem analysis, and ultimately Bay restoration. We provide brief overviews of applications to model new residential development, assess losses and vulnerability of resource lands, and identify the factors that disrupt the health of streams in small watersheds. These data products and approaches are being applied by a number of agencies involved with the restoration effort, including the Chesapeake Bay Program's activities focused on living resources, water quality, and sound land use.

1. INTRODUCTION

1.1. The Chesapeake Bay Estuary and Watershed

Much has been written about the Chesapeake Bay, including hundreds of scientific articles and technical reports, as well as dozens of popular books and tourist guides. The estuary itself is a unique ecosystem covering over 6100 km^2, fed by more than 100 rivers and thousands of tributary streams. It is geologically young, under 10,000 years old, having reached its present form about 3000 years BP with submersion of the Susquehanna river drainage from sea level rise following the late Pleistocene glaciation.

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Because it is relatively shallow, just over 6 meters on average, the Chesapeake is rapidly flushed by tidal currents and freshwater inputs from its 168,000 km^2 watershed. The same freshwater sources, however, introduce tremendous loads of a wide variety of toxic pollutants, nutrients and sediments. The Susquehanna River, the largest of the Bay tributaries, alone delivers about half of the freshwater input to the Bay, along with nearly 100 million metric tons of sediment [*Lang-*

land and Cronin, 2003] and some 50 thousand tons of nitrogen on an annual basis [*Preston and Brakebill*, 1999]. Toxic pollutants from the Susquehanna have dropped to just over 12,000 metric tons in 1999, from more than 27,000 tons in 1989 [*CBPO*, 1999]. Inputs of this magnitude adversely affect the physical properties of the estuary, including water clarity, dissolved oxygen concentrations, temperature and salinity gradients, as well as biological components ranging from phytoplankton densities, aquatic vegetation habitat, and trophic structures topped by a diverse fisheries. The latter include 32 species of year-round residents, as well as some 260 migrants, mostly anadromous shad, herring and perch. The vast majority of these are subject to wide population variations that have resulted from a combination of over-harvesting, loss of aquatic habitat for feeding and spawning, and natural fluctuations associated with the changing environmental conditions in the Bay and the Atlantic shelf.

Ecosystems services provided by the Chesapeake Bay are myriad, including extensive water filtering by shellfish, provision of habitat for a diverse range of wildlife, including millions of resident and migratory waterfowl, and production of oxygen and habitat by submerged aquatic vegetation, among others [*Bockstael et al*., 1995; *Costanza*, 2003]. In economic terms the Bay is a valuable resource to the more than 15 million people within the drainage basin, providing income from recreation, tourism, real estate and commercial fisheries. The latter alone averages 227 thousand metric tons annually, worth up to $200 million in some years [*NCBO*, 2000]. Much of the fishery has been or is currently in decline, however, particularly the once abundant oysters and, most recently, the symbol of the Bay itself—the Chesapeake blue crab. The latter is of particular concern because crabs are currently, by far, the single most valuable commercial resource of the Bay, comprising over 70% of the total harvest value. Extensive fisheries management plans have been formulated, but implementation requires consensus from a diverse group of stakeholders, some without priorities for long-term sustainability.

1.2. The Chesapeake Bay Restoration Effort

The Chesapeake restoration activity, in its broadest sense, is focused on collecting observational data required for monitoring to establish baselines for environmental assessment, and to track indicators from which progress towards restoration goals can be assessed. These "status and trends" indicators form the basis for adaptive management strategies. Major initiatives are focused on indicators associated with reducing toxics, reducing nutrient enrichment, and protecting and enhancing living resources. A number of active Bay Program subcommittees address specific commitments for restoration, including protection and restoration of living resources, habitat, water quality, stewardship, and sound land use.

Progress in the restoration effort has been steady, not least of which was setting up the structure from which changes can be assessed, and putting together the tools and human resources to meet the objectives. The overall health of the estuary has, however, not markedly improved since the monitoring of indicators was initiated in the mid-1980s. There have been successes associated with reduction of point pollution source outputs, reduced rates of tidal wetland loss, increased stream miles opened to anadromous fish, reduced phosphorus loads, and increasingly effective management and consequent rebound of some fisheries, particularly striped bass. There have also been some failures, or lack of progress, on a number of fronts including highly variable but increasing biological "dead zones," increased prevalence of pathogen outbreaks, including the dinoflagellate *Pfiesteria*, increased rates of freshwater wetland loss, and less viable fisheries, including traditional staples such as menhaden and crabs, but particularly shellfish.

Each year since 1998 the Chesapeake Bay Foundation (cbf.org), an influential environmental organization of 110,000 members whose $20 million annual budget compares with the federally funded Chesapeake Bay Program, publishes a "State of the Bay" report that tracks various indicators of the estuary's health. On a scale of 1 to 100, where 100 indicates a pre-colonial Chesapeake, the Bay currently has a score of just 28. This has changed little since it was initiated, fluctuating just a point or two. CBF's near-term goal is to reach a score of 40 by the year 2010.

1.3. The Relevance of Land Cover and Land Use

As noted earlier, one of the successes of the Bay Program has been its role in the reduction of pollutants from point sources, particularly municipal waste water treatment facilities, but more recently including industrial animal farming operations. The other significant source of material fluxes into the Chesapeake Bay are from non-point sources, i.e., those distributed across the landscape and closely associated with land cover and land use. It is generally accepted that increased population growth and changes in land use have offset many of the gains that would otherwise have been realized. Our work has focused on providing the data sets needed to address this issue, and to research their utility for a more effective integrated analysis that benefits the restoration effort.

1.3.1. Land cover variables. The greatest share (~40%) of excess nutrient pollutants are introduced to the Bay through agricultural practices, thus accurate estimates of land in agricultural uses are important for constraining uncertainties in predictions from the Bay Program's watershed modeling activities. A wide variety of "best management practices" are gradually being implemented to address nutrient and other pollutants from farms, many of them focused on preserving the integrity of land cover and utilizing vegetation as natural buffers.

Other substantial non-point sources of nutrients and toxics introduced to the Bay originate in urban or suburban areas, including the transportation network, through storm water runoff. Accurate tracking of these developed areas, dominated by impervious surfaces (such as buildings, roads, houses, driveways, parking lots, and the like), is required at relatively fine spatial resolution. Impervious areas also modify stream hydrology and can result in substantially increased sediment transport.

Some of the adverse effects of impervious and agricultural areas can be mitigated by tree cover and streamside vegetation buffers, which reduce the force of overland flows, uptake excess nutrients, maintain stream bank integrity, and provide shade that reduces solar warming of waterways. Accurate maps of forest cover and riparian tree canopy density are needed for the ecosystem models that are integral to the Bay Program's restoration efforts. When used together, maps of land cover types, impervious surface area, and tree cover provide fundamental variables needed by the models to better represent either the impacts they impart, the ecological functions they serve, or both.

1.3.2. Watershed model. The watershed model used for Bay Program implementation and assessment activities is HSPF (Hydrological Simulator Program–Fortran) [*Linker et al.*, 2001]. A number of model subroutines partition precipitation and evaporation across nearly 100 sub-watersheds, route overland flow across the terrain and subsurface flow through the geological and soil substrate, and simulate the sediment, nutrient and toxics fluxes into the estuary. A 3-dimensional estuary model uses the output of the watershed model, and a separate airshed model, to simulate the mixing dynamics and fate of these constituents within the Bay.

Implementation strategies designed to meet local nutrient management goals, including caps on loadings set through a combination of monitoring and modeling activities, are addressed through tributary strategies teams—alliances of local governments, watershed associations, regional organizations, and a variety of other local stakeholders. Basin-wide compliance with caps on nutrient and sediment loadings is addressed through 44 jurisdictions, partitioned by sub-watershed. Compliance with jurisdictional allocations is further specified through total daily maximum loads, the regulatory limits water bodies can assimilate without causing violations of water quality standards. Using this approach, the watershed restoration process is shared by all Bay residents, and reflected in the way they use the land, its resources, and ecosystem services.

2. A NEW VIEW OF LAND COVER ACROSS THE WATERSHED

As a result of the strong need for improved land cover maps of the Chesapeake Bay watershed [*CBPO*, 1998], work was initiated in 1999, primarily through funding from the NASA Applications Program, to advance the use of geospatial mapping techniques in the various CBP partner agencies. This work was continued through a combination of additional resources provided through the partner agencies themselves, particularly the Chesapeake Bay Program Office, the Chesapeake Bay Foundation, the Maryland Department of Natural Resources, and the Virginia Department of Conservation and Recreation. This activity continues, and the foundation is being laid for a monitoring effort with a 5 year repeat interval, as well as more frequent updating of rapid land use change associated with residential development.

2.1. Land Cover and Agricultural Crop Types

Classifications of land cover types and agricultural crops were done using multi-temporal Landsat imagery, based on the spectral information extracted from training areas selected for their representation of unique categories. A total of 100 Landsat scenes were analyzed, including 40 leaf-on and leaf-off scenes for circa 1990 mapping, and 60 scenes capturing spring, summer and fall conditions for circa 2000 mapping. All scenes were radiometrically calibrated, converted to top-of-atmosphere reflectance, orthographically rectified using USGS 30m digital elevation data sets, corrected for topographic illumination effects, temporally normalized between scenes, and cloud and shadow masked [*Varlyguin et al*., 2001].

2.1.1. Land cover types. The land cover type mapping was done using a classification tree approach [*Brieman et al*., 1984]. The algorithm searches for a dependent variable that, if used to split a population of pixels into two groups, explains the largest proportion of deviation of the independent variable. At each new split in the tree, the same exercise is conducted and the tree is grown until it reaches terminal nodes, each representing a unique set of image areas that are then assigned a specific class based on the training information.

Land cover/use was mapped into 16 classes approximating a modified Anderson level-2 hierarchical classification scheme (Plate 1). Over 3800 field sites were sampled for training data, including some 1400 sites visited in the summer of 2000 and 2001. The remainder of the training data was acquired from collaborators, and publicly available data sets. All field data were

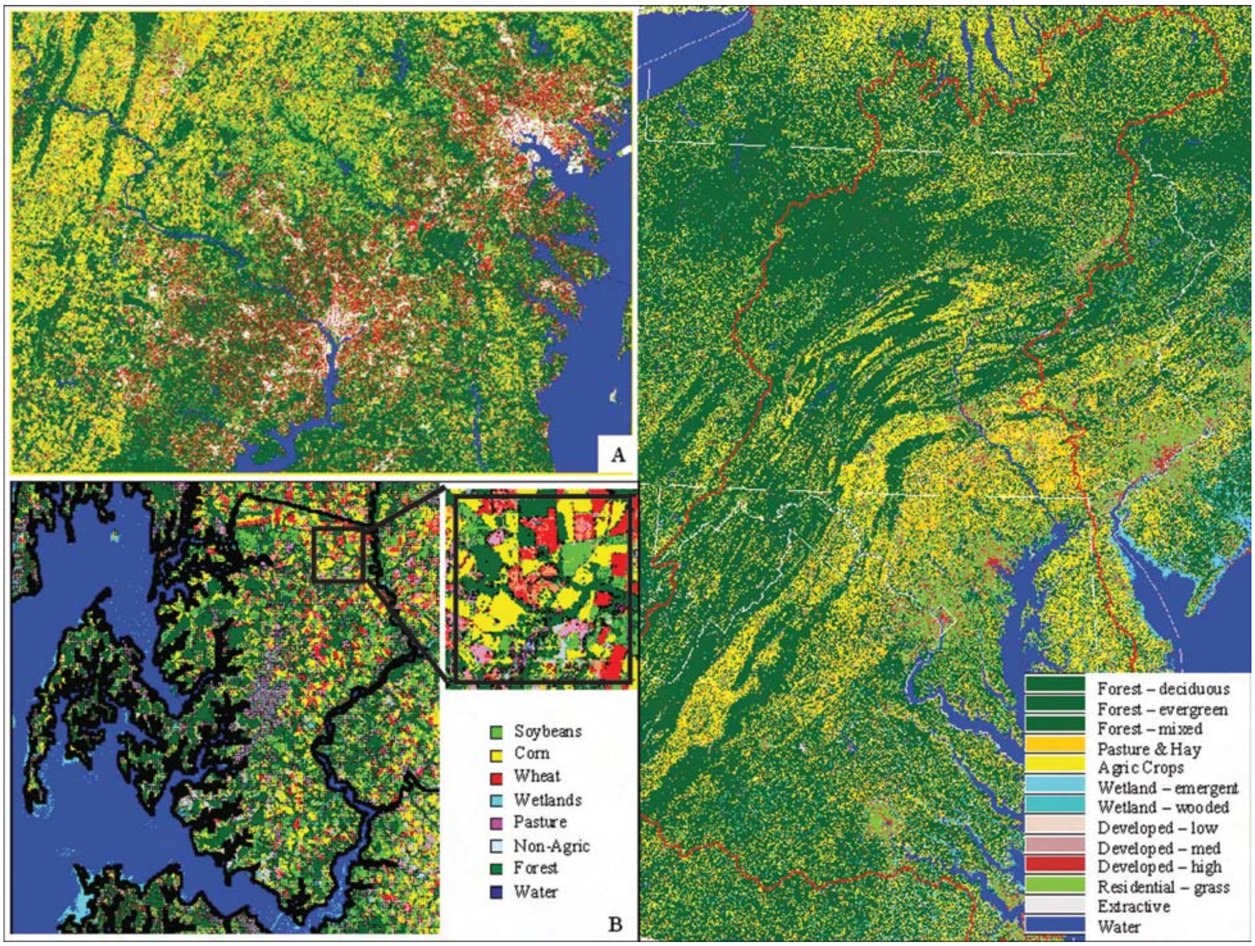

Plate 1. Right panel: Chesapeake Bay watershed map of land cover types produced from multitemporal Landsat ETM imagery for the year 2000. The watershed boundary is depicted in red, and state boundaries in white. Left: The inset images show (A) land cover type detail with finer discrimination of cover types and better spatial resolution and (B) specific crop types for Talbot County on Maryland's eastern shore of the Chesapeake.

screened for quality and representation of surrounding land cover/use through application of a 90 x 90 m spatial filter.

The map produced from the classification tree algorithm using the satellite and field data was an improvement on previous land cover maps of the region, particularly the discrimination between agricultural crops and pasture (Plate 1A). Overall accuracy assessed by cross-validation with over 814,000 samples was 86%, although some of the land use class accuracies were less than 70%. Classification errors were comparable between rates of omission and commission, suggesting no systematic biases in the mapping approach.

To evaluate the contribution of multi-temporal information for the classification, three independent decision tree runs were performed for: (i) a single peak growing season date, (ii) leaf on–leaf off dates, (iii) multi-temporal (all available) dates. When compared to the single date imagery alone, incorporation of the multi-temporal data into the analysis improved discrimination of specific classes, particularly those dominated by vegetation [*Goetz et al.*, 2000]. Differences among deciduous, evergreen, and mixed forest types, as well as among croplands, pastures, and grasslands were improved over single-date and two-date acquisitions. Discrimination of urban and suburban areas, however, did not significantly benefit from multi-temporal image acquisitions.

2.1.2. Crop types. An agricultural crop type map was produced, for the state of Maryland only, using unsupervised classification and iterative cluster labeling based on detailed field level information. Unique access to field-level crop data collected by the USDA National Agricultural Statistical Service (NASS) was granted for the state of Maryland, allowing us to digitize field boundaries from mylar map overlays. Over 300 individual fields were digitized and multispectral data extracted without reference to proprietary field location information. These provided a valuable training data source for use in classification of specific crop types.

Although double-cropping is common in the mid-Atlantic (typically a 2-year 3-crop rotation), use of multitemporal ETM+ imagery permitted discrimination of these multi-cropped areas (Plate 1B). Comparisons with NASS county aggregated area statistics compiled from over 1200 field samples were within a few percent. Accuracies assessed with an independent sample of field locations were 83% (soybeans), 88% (corn), 91% (wheat) and 94% (soybean–wheat sequence). The Maryland map product is available through the NASS (www.usda.gov/nass).

2.2. Impervious Surfaces—the Built Environment

Maps of the built environment, represented by impervious surface areas, are required for a variety of Bay Program applications, described earlier. We derived Bay-wide impervious surface area maps for the time periods 1990 and 2000 at unprecedented resolution using our Landsat database together with high resolution IKONOS satellite imagery, GIS maps of local planimetrics, and regression tree classifiers. In the case of the regression trees, a continuous variable is output (e.g., proportion impervious between 0–100%), rather than categorical classes as with the land cover type mapping. The two approaches differ primarily in the number of terminal nodes that are produced, and the mode in which the node characteristics are applied to produce output image maps.

The impervious surface maps were developed at fine resolution (30 m) but, importantly, each cell provides subpixel information on the proportion of the 900 m^2 that is occupied by impervious surface features (Figure 1). These maps represent a continuum of imperviousness derived from the Landsat imagery and separate regression tree algorithms that were grown and then cross-validated, incorporating combinations of variables as input, until robust trees were developed. A diverse set of rules were employed to constrain the tree size and complexity.

Validation of the maps is ongoing, but initial results using several different approaches suggest high accuracies were achieved. A sample of digital orthophoto images (DOQs) was acquired throughout the region for validation across a broad range of conditions. These were selected using a stratified random sample design, resulting in 24 areas of 25 km^2, each visually interpreted to produce maps enumerated by feature type. In addition, an ancillary set of point data on other areas was collected in 1999 and 2000 during field campaigns, and from high resolution GIS data sets of agricultural fields and other data sources made available by collaborators. Moreover, the DOQs were used for an independent cross-validation, where 193 of the 689 sampling blocks used for algorithm development, each roughly 1.8 km by 1.2 km in size, were randomly separated into 5 groups of roughly 100,000 pixels each. Together, assessments based on these data sets suggest an overall RMS error of just 2.7% for area means ranging from 0 to more than 40% impervious [*Smith et al.,* 2004].

The impervious surface maps provide unique information relevant to a range of applications, including stream health assessments, but also can be used to provide accurate rates of change through time, or "sprawl metrics." A few widely applicable uses include basic statistical summaries of how impervious areas vary across land uses, and the proportion of impervious areas comprised of transportation infrastructure (roads, parking lots and driveways). The latter are important for improved estimates of toxic pollutants from vehicles, and the former because heretofore they were the only manner by which imperviousness was estimated over large areas.

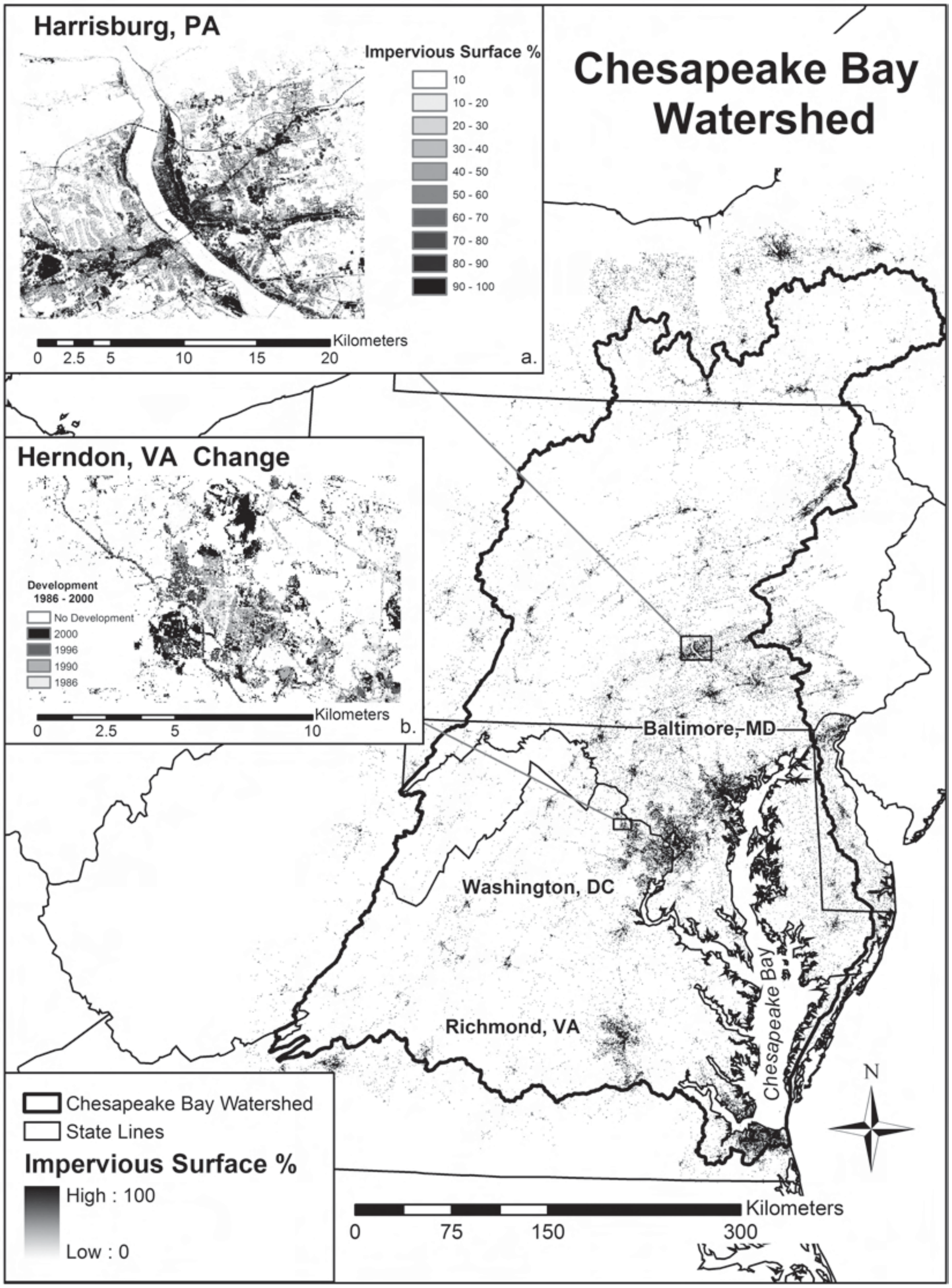

Figure 1. Chesapeake Bay watershed map of the gradient in impervious surface area produced from multitemporal Landsat ETM imagery for the year 2000. The inset images depict (a) an image subset focused on Harrisburg, Pennsylvania, showing more spatial detail in the range of subpixel impervious cover, (b) changes in urban extent, as depicted by all areas where impervious cover exceeded 10%, for each of four years between 1986 and 2000.

Using simple GIS overlays of roads with edge boundaries on our impervious maps, for the state of Maryland, we estimate roads comprise 36% of all impervious areas, although this figure typically exceeds 60% or more when parking lots and driveways are included. In more developed areas, like Montgomery County, the latter value approached 72%. Our estimates of land use class imperviousness, calculated by overlaying land use polygons from the Maryland Department of Planning (MDP), are summarized in Table 1.

The amount of impervious area per land use polygon that we derive from our maps are systematically lower than traditional estimates based on assigning coefficients from the literature to various land use classes. This is primarily because our maps are continuous estimates, where each image pixel may range between 0 to 100% impervious on a subpixel level. This has implications for reassessing the way imperviousness is estimated over large areas, and the levels of imperviousness expected to impact, e.g., stream water quality. We explore this issue further in our assessments of stream health, and elsewhere [*Dougherty et al*., 2004], but our results suggest the Landsat subpixel maps are not only more accurate than the traditional "classify and multiply" approach, they also provide the spatial configuration of impervious areas across the landscape—which has key advantages for assessing proximity to streams and for mapping changes associated with exurban sprawl. Comparable maps using a similar approach have been developed for other areas [e.g., *Yang et al*., 2003].

2.3. Tree Cover—Canopy Density

Continuous tree cover maps have been produced using the same approach as that for the impervious surface maps, except rather than using GIS planimetric data sets for training the regression tree algorithm, we use fine scale maps of tree cover derived from DOQs and from high-resolution IKONOS satellite imagery. The latter were precision georeferenced image data sets acquired and processed over an 1800 km^2 area in central Maryland. Very high spatial resolution imagery like IKONOS brings with it a whole new set of issues associated with the resolution of individual scene elements, but the images were very successfully classified into tree cover maps, making use of forest cover interpreted from the DOQs as training data. The accuracy of the tree cover classification was over 97%, as assessed with an independent validation sample of some 600,000 point locations [*Goetz et al.,* 2003].

The resulting tree cover maps derived from the Landsat imagery (Plate 2) are, as with the impervious maps, expressed as a continuous value between 0–100%. The USGS National Land Cover Database (NLCD), which has initiated a nationwide mapping program expected to be completed by 2010, use a similar approach and refer to the resulting maps as tree canopy density [*Huang et al*., 2004]. Similar maps have also been produced at coarser resolution on a global scale [*Hansen et al*., 2002]. Applications to integrated ecosystem analysis are explored in the next section.

Table 1. Comparison of impervious surface values by land use category. The MDP values are best guesses from the literature based on a variety of different estimates. Note, e.g., the difference in the bare soil class, and in Institutional, which includes schools, military installations, hospitals, and similar land uses.

Land Use Category	MDP % Impervious	Subpixel % Impervious	Relative % Difference
Commercial	82.0	47.9	-42
Industrial	70.0	51.2	-27
Bare soil	50.0	2.2	-96
Institutional	50.0	22.0	-56
High residential	46.0	43.1	-6
Medium residential	25.7	22.5	-12
Low residential	12.5	3.7	-70
Extractive	11.0	8.9	-19
Crop lands	5.0	1.5	-69
Pasture	5.0	1.9	-62

3. ECOSYSTEM ANALYSIS IN THE CONTEXT OF CHANGING LAND USE

Ecosystem analysis is complex, as evidenced by the diverse and multi-layered structure of the Chesapeake Bay restoration effort, but the task is facilitated to some extent when simplified indicators of the functional integrity of the ecosystem can be expressed. This is the essence of the various indicators tracked by the Bay Program, the annual CBF State of the Bay report, and related efforts aimed at more global ecosystem assessments [e.g., *Woodwell*, 2002; *UNEP*, 2003]. Following, we explore some analyses of ecosystem impacts associated with land use change within the Chesapeake Bay watershed.

3.1. Loss of Resource Lands to Exurban Sprawl

Using the map data products just described, a number of ecosystem assessments were conducted, including quantifying the loss of valuable resource lands (forests, agriculture and wetlands), and providing indicators of the impacts on stream health, both from past and expected future urbanization.

3.1.1. Observations of recent change. The impervious maps described in section 2.2 have utility for tracking land use change associated with urbanization, including the low density residential development commonly known as suburban sprawl. We have used the circa 1990 and 2000 impervious surface maps to provide metrics of the location and amount of

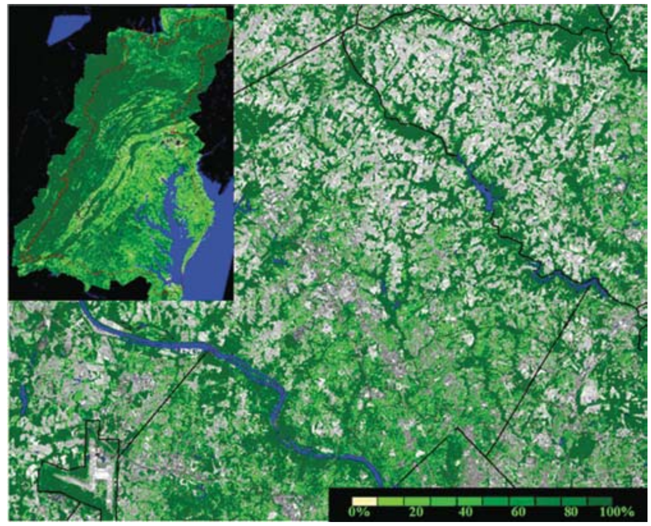

Plate 2. Map of the gradient in tree cover (or canopy density) produced from multitemporal Landsat ETM imagery for the year 2000, for an area centered on Montgomery County, Maryland. The Potomac River and Dulles airport are visible in the background panchromatic image. The inset image depicts the same data for the entire Chesapeake Bay watershed.

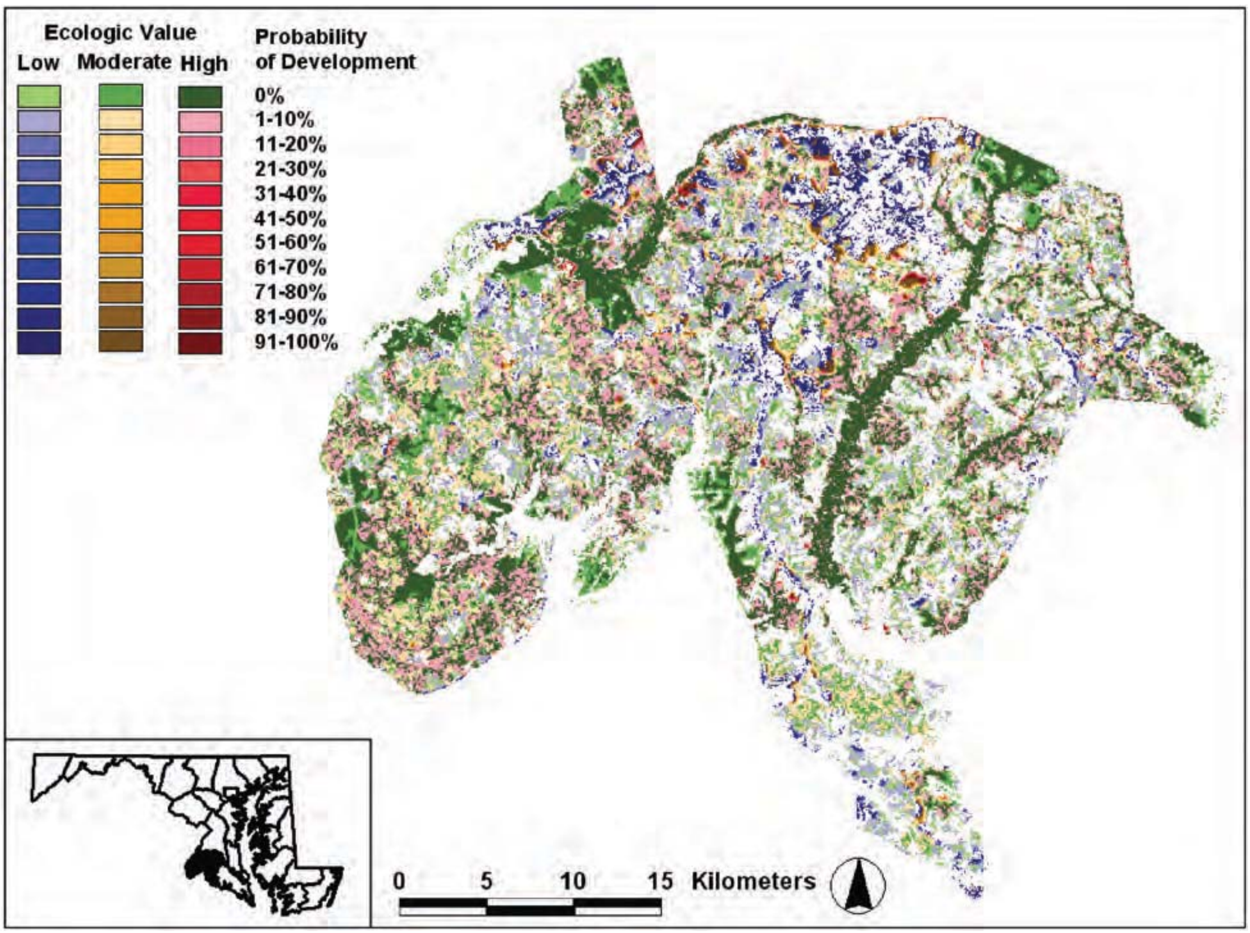

Plate 3. Vulnerability of priority forest resource lands in Charles County, Maryland, as predicted using the probability of future urbanization by year 2030 under a current trends scenario. Vulnerabilities range from low (greens) to high (reds), and vary within categories of ecological value (high, medium, low).

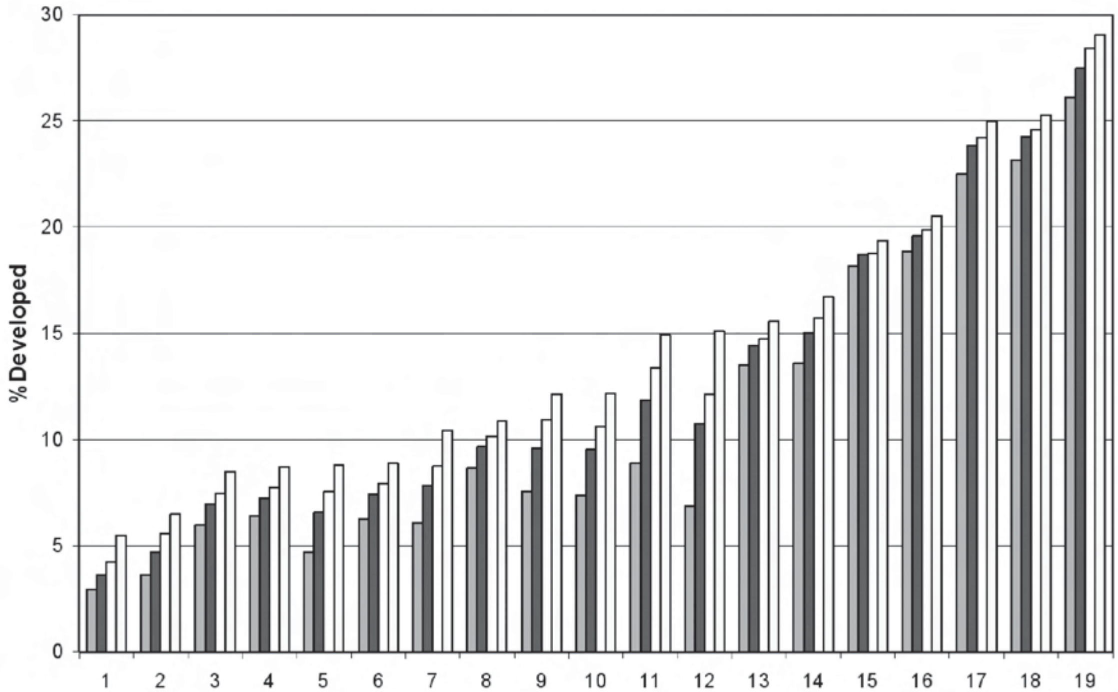

Figure 2. Urban land use change between 1986-2000, within and between 19 small watersheds of the Anacostia river basin, as measured by the time series of impervious surface area maps. Note the rapid urbanization of many (e.g., #7 & #12), and the critical thresholds passed (discussed in section 3.3).

change that has occurred across the entire watershed. We also monitored change at finer temporal resolution (1986, 1990, 1996 and 2000) for a sequence of Landsat images centered on the Baltimore–Washington, D.C., metropolitan area (Figure 1b). An example of sprawl metrics depicting land use change associated with urbanization across small subwatersheds within the Anacostia River basin—one of the more polluted Chesapeake tributaries—is depicted in Figure 2

Similar metrics have also been summarized across watersheds, jurisdictions, and other spatial units of interest. Tabular summaries of these data alone are useful to a broad range of applications, and agencies tasked with tracking the implications of such change, but the map data are even more powerful as monitoring and assessment tools. We show one such assessment, the loss of resource lands, in the next section. In this case, the context is simulated future urbanization, but the same analysis has been done using the observations of past change.

3.1.2. Predictive modeling of future change. Predictions of future land use are important for a number of Chesapeake Bay Program goals, including targeting for restoration, assessing the impacts of possible restoration and mitigation scenarios, and determining the vulnerabilities of various resource lands to future land conversion. Knowing the probability of land conversion from agriculture, wetland or forest (resource lands) to residential, commercial, industrial (developed) allows the various committees of the Bay Program to develop practical alternatives and plan contingencies related to Bay trends and indicators—key components of the Chesapeake 2000 agreement to track progress on Bay restoration goals.

When simulating and forecasting spatial patterns of urban development, it is a challenge to capture both the rate and the locations of urban land cover change. Supply–demand–allocation models [e.g., *Theobald,* 1998] are completely statistical, extrapolating development rates from historic trends and allocating change spatially using arbitrary neighborhood operations. Microeconomic models [e.g., *Bockstael*, 1996] offer perhaps the best option for process-based modeling, but require highly detailed parcel-level spatial economic data in order to model the economic aspects of the development decision. Because of these considerable data requirements, economic models currently are not applicable over large areas such as the Chesapeake Bay watershed. Cellular automaton models [e.g., *O'Sullivan*, 2001] are pattern-based mechanistic models, but offer some insight into the constraints (e.g., topography) and "drivers" (e.g., road building) of the development process.

We are integrating aspects of economic and cellular automaton (CA) models, but initially explored the applicability of the SLEUTH (*s*lope, *l*and use, *e*xclusion, *u*rban extent, *t*rans-

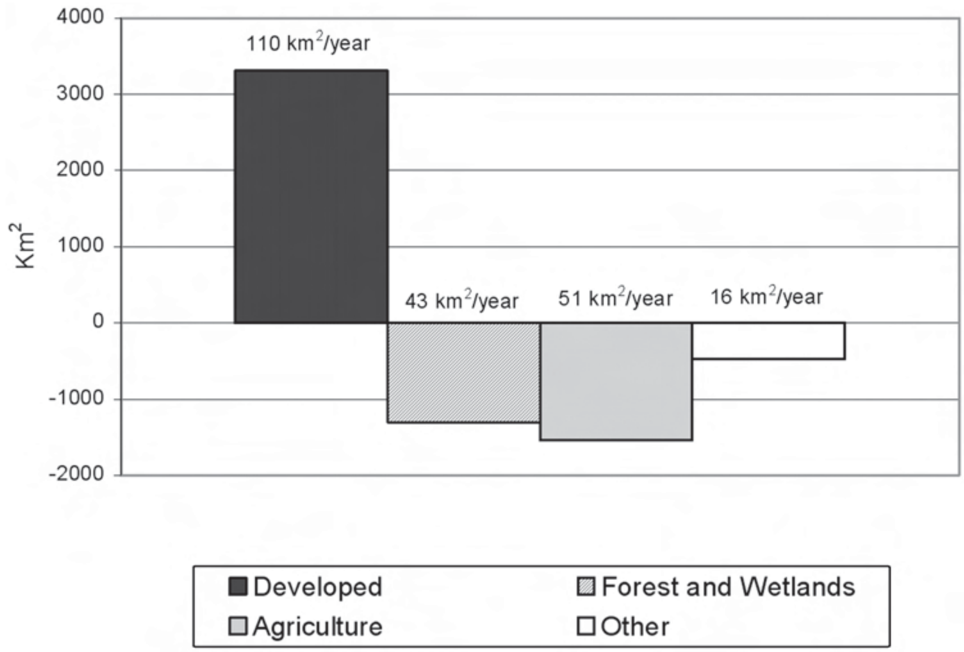

Figure 3. Predicted loss of resource lands 2000–2030 over a 23,700 km^2 area centered on the greater Baltimore–Washington, D.C., metropolitan region.

portation, *h*illshade) [*Clark et al.*, 1997] CA model to simulate patterns of urban change in an area comprising about 15% of the Chesapeake Bay Watershed. We are working towards Bay-wide modeling, but the computational demands are substantial—the current simulations required over a week of CPU time on a 16 node Beowulf PC cluster. SLEUTH is essentially a pattern-extrapolation model, which simulates urban dynamics through the application of four growth types: spontaneous new growth, which simulates the random urbanization of land; new spreading center growth, or the establishment of new urban centers; edge growth; and road influenced growth.

The model was calibrated to simulate urban development patterns using the series of impervious area maps described in the previous section. During calibration, a set of growth parameters were derived that maximized the model's ability to match the rate of growth, but which also performed well in terms of spatial fit. Calibrated model predictions of spatial patterns across the time period 1986 to 2000 were able to nearly exactly match the observed patterns (93% overall accuracy) and successfully simulate the historic rate of development, although some areas of northern Virginia experienced land conversion rates higher than the model could capture. SLEUTH did not wholly succeed in replicating the spatial pattern of development at the pixel scale, but aggregating multiple simulation results to watersheds or county units produced robust estimates of change [*Jantz et al.,* 2004].

Future urban extent maps, predicted out to 2030 under various land protection scenarios, were useful for visualizing and exploring potential development (see figures at espso.gsfc.nasa.gov/ftp_docs/lithographs/Urban_ Growth_ Lith.pdf), as well as for assessing the impacts on resource lands. For the latter, we overlaid the predicted urban extent maps on our current (year 2000) land cover type map, for the 23,700 km^2 area common to both. We estimate that the 80% increase in developed land area predicted to occur over the next 30 years, under a current trends/business-as-usual scenario, will consume 5% of wetlands, 14% of forest and 23% of agricultural lands, primarily through exurban sprawl (Figure 3).

3.2. Vulnerability Assessment of Resource Lands

Vulnerability assessments can be conducted using the various map products previously described, as well as the model predictions of the rates and spatial patterns of future urbanization. We initiated one such assessment, using the SLEUTH urban extent maps for 2030, in which a set of threat probabilities were developed for a range of priority forest resource lands. Because the model results are based on probabilities derived from 100 Monte Carlo simulations, the likelihood of outlying low density residential cells being selected repeatedly is limited, despite realistic representation of these cells in individual simulations. While this reflects the risk of development associated with any particular cell in exurban areas, it is a potential constraint in terms of performing vulnerability assessments. For this reason we performed assessments using the probability maps aggregated to the areal extent of the

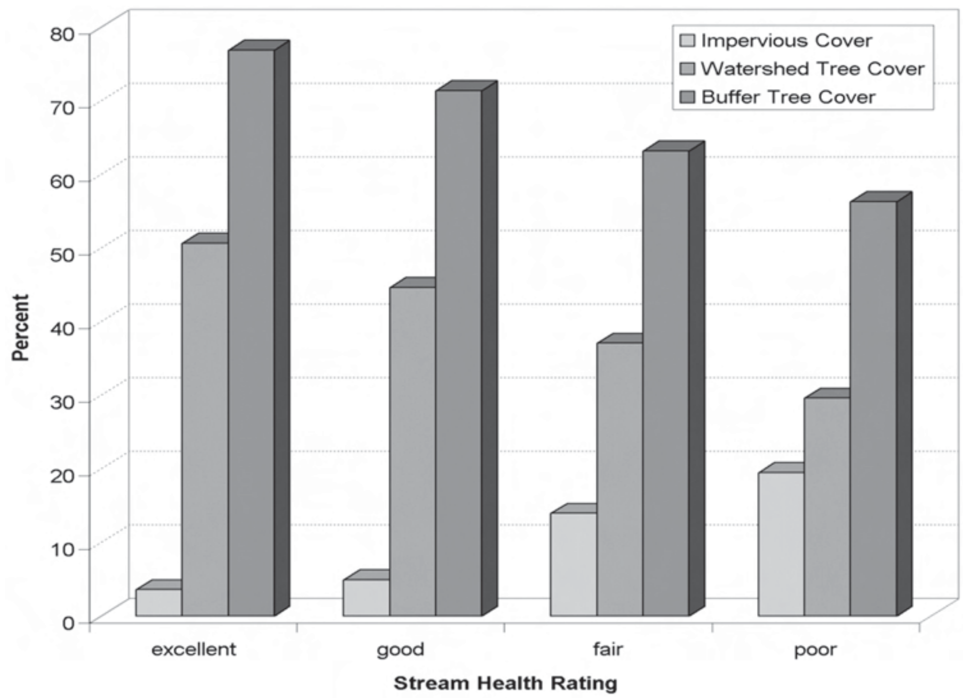

Figure 4. Small watershed stream health rankings in relation to impervious surface cover, watershed tree cover, and riparian buffer zone tree cover.

priority forest land polygons. The same could be done using spatial pattern metrics, such as dispersed development, as a vulnerability measure.

The priority forest land polygons were developed by the Maryland Department of Natural Resources under their Green Infrastructure (GI) and Strategic Forest Lands Assessment (SFLA) program [*Weber and Wolf*, 2000]. We have a collaborative applications research project with MD–DNR to incorporate the land cover variable maps into the GI and SFLA, and inform a range of land prioritization and vulnerability assessments.

Vulnerability of the forest resource lands to urbanization pressure (predicted probabilities) varied across the state with, as expected, much higher vulnerability in areas already densely settled. Nonetheless, there were surprises, including substantial threats to forests in western Maryland—a mostly rural area that is being developed for tourism, second homes, and resort communities. Vulnerabilities were also high in Charles County, Maryland, an area south of Washington, D.C., where exurban sprawl has increased markedly in recent years (Plate 3), partly due to easy water access to the Bay.

3.3. Consequences for Stream Health–Tributary Strategies

The altered composition and configuration of land use, such as expansion of impervious surface areas within a watershed, disrupt the hydrology and ecology of stream ecosystems. The inhibited infiltration of rainwater and snowmelt in impervious areas results in reduced base flows and flashier stream hydrographs that exhibit a reduced lag time between storm events and peak discharge [*Moglen and Beighley,* 2002]. Stream channels are modified by these changes, quickening bank and stream bed erosion and increasing sediment loads. A number of studies have demonstrated the association of these land use changes with the degradation of biological, chemical and physical properties of streams within the Chesapeake Bay watershed [e.g., *Palmer et al*., 2002]. Stream health impacts have been carefully documented in Maryland using macroinvertebrate and fish Indices of Biological Integrity (IBI), resulting in 46% of all streams having been classified in poor ecological condition [*Boward et al.*, 1999].

We documented the statistical association between our mapped land cover variables and stream health data sets across 246 small watersheds in central Maryland. These spanned a wide range of land uses, from predominantly agricultural to mostly residential. The IBI rankings were based on data from a number of sampling stations within each subwatershed, including metrics on taxonomic richness, composition, instream habitat preference, tolerance to stressors, and feeding mode, among others [*Stribling et al*., 1998]. Stream health was then ranked as excellent, good, fair, or poor, based on a combination of the IBI scores and physical stream properties such as dissolved oxygen, pH, and temperature measured between 1996 and 2001 [*Van Ness et al*., 1997].

A variety of land cover variables were incorporated as independent predictor variables, including impervious cover, tree canopy density, agricultural cropped area, and topographic slope indices. We also incorporated landscape configuration metrics such as mean distance from impervious areas to the stream channel along a topographically defined flow path, as well as clumpiness and contagion indices, which define the dispersion or aggregation of land cover within the watershed. The data sets and methods used for this analysis are described in some detail by *Goetz et al.* (2003) and *Snyder et al*. (forthcoming).

Our results, based on stepwise logistic regression models, demonstrated that the primary indicator of stream health was the amount of impervious surface within a watershed, followed by the amount of tree cover within the stream buffer zone (30 m either side of the stream channel). These observations, summarized in Figure 4, support anecdotal evidence that reducing impervious cover in new residential and commercial development, or reducing the impacts of impervious areas through mitigation measures such as retention ponds, is beneficial to stream water quality and associated biotic health. The results also indicate that despite the importance of tree cover in the stream buffer zone, the overall proportion of impervious cover throughout the watershed was the overriding factor in predicting the health of streams within small watersheds.

Based on these results, guidelines for achieving a rating of excellent stream health would be to restrict watershed impervious surfaces to no more than 6% of the total area, and ensure that at least 65% of the riparian buffer zones were occupied by vegetation, in this case tree cover. To achieve an overall rating of good watershed health required no more than 10% impervious area, and at least 60% buffer zone vegetation cover.

3. CONCLUSIONS AND THE WAY FORWARD

The land cover maps used for the ecosystem assessments described here have provided a new way of viewing and analyzing the landscape. Since the causes of impairment of the Chesapeake Bay operate principally on the land, this capability is important. Beyond categorical classification of land cover, the maps of continuous land cover variables permit detection of critical features in the landscape, such as low density residential development and density of tree cover in riparian buffers. In the case of stream health assessment, they allow consideration of landscape configuration variables that would have not been possible to produce from categorical maps of land cover or county-level statistical summaries.

The applications of the data can be expanded in a number of directions; stream health can be implemented in a predictive mode, where small watersheds that have not been surveyed for stream health metrics can be prioritized for detailed assessments. Similarly, watersheds and priority resource lands most vulnerable to future urbanization, as predicted with the land use change models, can be more adequately protected and negative impacts can be minimized.

The contributions of this landscape approach clearly indicate the need for regular monitoring of land cover to detect changes, probably on a 5 year interval, as well as more frequent (biannual) updates of the urbanization process associated with residential sprawl. Having a CBW land use change monitoring system in place would substantially improve the information available for ecosystem vulnerability assessment, targeted restoration, adaptive management and, ultimately, more effective protection of the Bay. With recent proposals for a Chesapeake Bay National Park, the capabilities conferred by the appropriate application of improved land use change information take on a more crucial role than ever.

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