Modeling Urban Land Use Change in the Upper Delaware River Basin

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May 2011

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- National Park Service Delaware Water Gap National Recreation Area (NPS DEWA)
- Dr. Eric Brown DeColstoun, Earth Sciences & Applications Inc. and NASA Goddard Space Flight Center
- Dr. Scott J. Goetz, The Woods Hole Research Center
- Pike, Wayne, Northampton, and Monroe counties in Pennsylvania; Delaware, Sullivan, and Orange counties in New York; Sussex and Warren counties in New Jersey; the Delaware River Basin Commission; and Common Waters Partnership.

Funding sources

This project was funded, in part, through grants from:

- The National Park Service
- The NASA Land Cover Land Use Change Program (grant NNG06GC43G to S. Goetz, C. Jantz and others)

Acknowledgements

We are grateful for the assistance and feedback we received from planning staff in counties throughout the region: Pike, Wayne, Monroe, and Northampton counties in Pennsylvania; Warren and Sussex counties in New Jersey; and Delaware and Sullivan counties in New York. We also received valuable feedback from individuals from the Common Waters Partnership and the Delaware River Basin Commission. Finally, we thank the many students at Shippensburg who assisted with GIS analyses for this project: Eric Atkins, Gary Lasako, Michael Maret, Jonathan Grantham, Ashley Reis, Matthew Long, Jim Spatz, and Toni Belskey.

Executive Summary

This project focuses on the issue of regional growth pressure and urban development in the Upper Delaware River Basin. Located at the intersection of the states of Pennsylvania, New York and New Jersey, this region is environmentally sensitive, including large, unbroken tracts of forest land, and important source water protection for millions. Our objectives were to:

- Use satellite derived maps to track urban development between 1984 and 2005;
- Accurately simulate observed patterns of development during this time period; and then
- Forecast future development under a variety of land use policy scenarios.

In this report, we provide a discussion of growth trends in the study area based on U.S. Census data (from 1900-2000) and satellite-derived maps (from 1984-2005). We then describe the methods and results of an application of the SLEUTH urban growth model, a land cover change model that simulates historic growth patterns and also generates forecasts of urban growth.

In terms of regional growth trends, Census data show that population growth trends over the past century mirror regional and national trends in industrialization, deindustrialization, and post-World War II urban sprawl. Growth pressures have intensified in the southern part of the watershed in recent decades, with many counties in the study area appearing among the fastest growing counties within their states between 2000 and 2009. Pike and Monroe counties in Pennsylvania rank 2nd and 3rd, respectively, in terms of statewide growth rates. In New York, Orange County ranks 1st and in New Jersey, Warren County ranks 4th and Sussex is 9th. Added to this pressure is the rate of seasonal homeownership, which in some counties exceeds 30% of the existing housing stock according to the 2000 Census. Based on our satellite derived maps, between 1984 and 1995, urban land cover increased by 54% and between 1995 and 2005, urban land cover increased by 77%. In contrast to the recent growth trends in the southern part of the watershed, the northern areas, especially Delaware County, have experienced slow growth and even a decline in population.

Using the land cover data time series and other data sets, we calibrated the SLEUTH model and generated forecasts to 2030 under four different policy scenarios: baseline, smart growth, best for natural resources, and limited planning. We also assumed three different growth rates: a linear growth rate (70% increase over 2005 levels), a 50% increase over 2005 levels, and a 25% increase.

Several key points came out of the forecast work. From the urban modeling perspective, we found that when incorporating policy components into local and regional urban modeling applications, the role of local experts in informing modeling work is invaluable. We also generated several useful products as part of this research, which can be used in additional applications: an urban land cover time series of more than 20 years, forecast data covering a wide range of scenarios, and a calibrated urban land cover model that can be re-applied to new scenarios.

In terms of what these results tell us about urban land cover trends and land use policy in the Upper Delaware region, policies that broadly support smart growth strategies and resource protection in will likely result in positive benefits for forests and landscape preservation. In an investigation of how future growth will impact water resources, it is clear that lower growth levels will minimize impacts on water resources, emphasizing the importance of limiting the footprint of urban land cover if protection of water resources is a priority. Pro-active and smart land use planning therefore remains paramount in this environmentally sensitive region.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

The Upper Delaware River Basin (Figure 1) represents a broad range of landscapes, ranging from tracts of unbroken, protected forests, to river and lake-side recreational communities, to small villages and towns. It includes several important natural and cultural areas of note, such as: the Upper Delaware Scenic and Recreational River; the Delaware Water Gap National Recreational Area; the Catskill Park and Catskill Forest Preserve; the Catskill/Delaware watersheds, which provide source water protection and reservoirs for New York City's water supply (New York City Department of Environmental Protection 2011); and the New Jersey Highlands, an environmentally sensitive region of source water protection for millions of residents in New Jersey (New Jersey Department of Environmental Protection 2004) and many other various state lands. The river basin, outlined in dark blue in Figure 1, comprises an area of 10,724 km^2 (4,141 mi^2). The study area for this project (shown in white in Figure 1) includes nearly the entire basin but also incorporates areas outside the basin, especially to the south where growth pressures are highest, and is 15,690 km^2 (6,058 mi^2) in area. We note that our study area was limited by the availability of urban land cover data (see section 2.0).

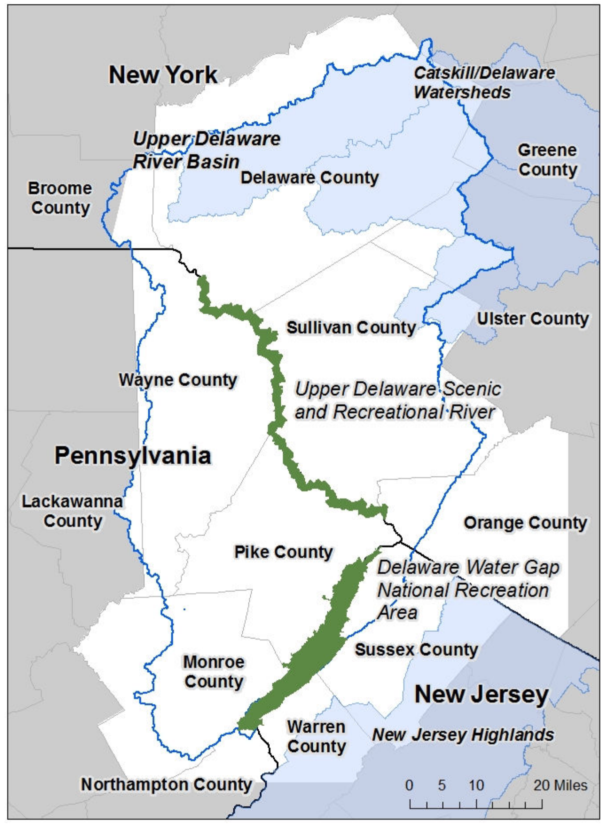

Figure 1. The project study area. Areas included in the modeling work are indicated in white, and encompasses much of the Upper Delaware River Basin, outlined in blue. National Park Service units are indicated in green and other important watershed protection areas are shown in light blue.

The Upper Delaware River Basin lies at the intersection of New York, New Jersey and Pennsylvania. The two National Park Service units, many state and privately owned recreational lands, and the area's natural and cultural amenities has long made this area an attractive destination for residents and visitors from the New York City metropolitan region. Many of the counties in the southern and central part of the study area have experienced sustained high growth rates over the past few decades (see section 2.0). Recent growth rates continue to be high, with many counties in the study area appearing among the highest ranked counties within their states in terms of growth rates between 2000 and 2009. Pike and Monroe counties in Pennsylvania rank 2nd and 3rd, respectively, in terms of statewide growth rates. In New York, Orange County ranks 1st and in New Jersey, Warren County ranks 4th and Sussex is 9th (U.S. Census 2000, U.S. Census 2010). Delaware County, NY stands out as an exception to this trend, having experienced relatively slow growth over the past century and a population loss between 2000 and 2009.

These growth pressures, combined with other pressures on natural resources from energy development (natural gas extraction in the Marcellus Shale) and expansion of energy infrastructure (gas pipelines and large-scale power lines), have contributed to increasing threats to natural, cultural, and scenic resources across the region, and to the Upper Delaware Scenic and Recreational River (UPDE) and the Delaware Water Gap National Recreational Area (DEWA) (American Rivers 2010, Upper Delaware Preservation Coalition 2007).

This project focuses specifically on the issue of regional growth pressure and urban development, and builds on previous local scale studies in Pike and Wayne counties in Pennsylvania (Jantz, Mrozinski, and Coar 2009) and Sullivan and Delaware counties in New York. Our objectives were to:

- Use satellite derived maps to track urban development between 1984 and 2005;
- Accurately simulate observed patterns of development during this time period; and then
- Forecast future development under a variety of land use policy scenarios.

2.0 Growth Trends in the Study Area

In broad terms, population growth trends over the past century mirror regional and national trends in industrialization, deindustrialization, and post-World War II urban sprawl. As seen in Figures 2 and 3, changes in population and population density for counties in the region between 1900 and 1950 show the growth of the industrial cities of Binghamton, NY (in Broome County), Scranton, PA (in Lackawanna County) and Allentown, PA (adjacent to Northampton County) and an apparent but weak influence of New York City to the southeast (i.e. Orange County, NY). Declines are noted in Pike, Wayne, and Delaware counties between 1900 and 1950 as the farm economies there diminished. Trends between 1950 and 2000 highlight the decline of the industrial economies of Binghamton, NY and Scranton, PA and the suburban boom related to the expansion of the greater New York City metropolitan area, which spurred rapid growth in the southern counties of the study region, especially Orange County, NY.

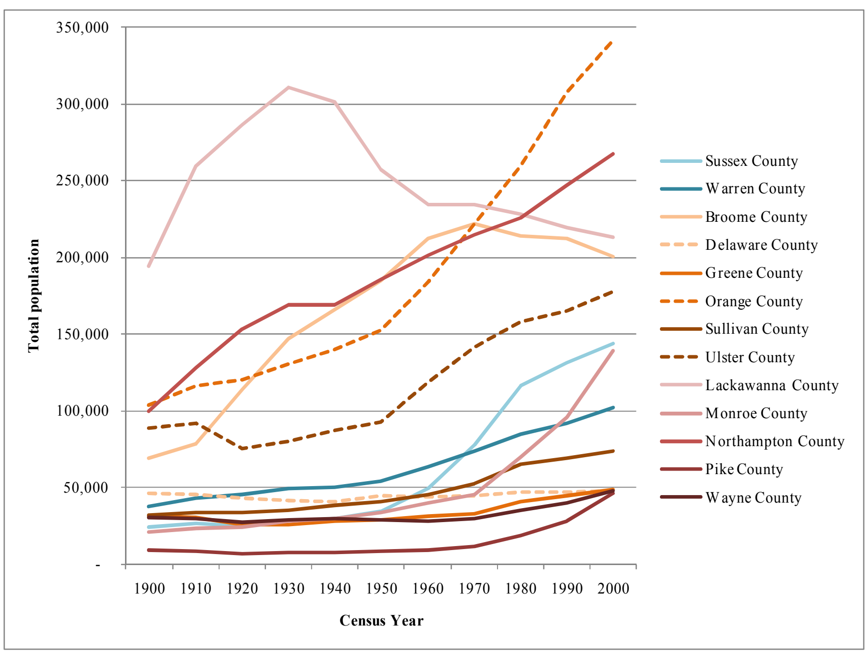

Figure 2. Decadal population dynamics in the counties of the region from 1900 to 2000. Source: GeoLytics 2001..

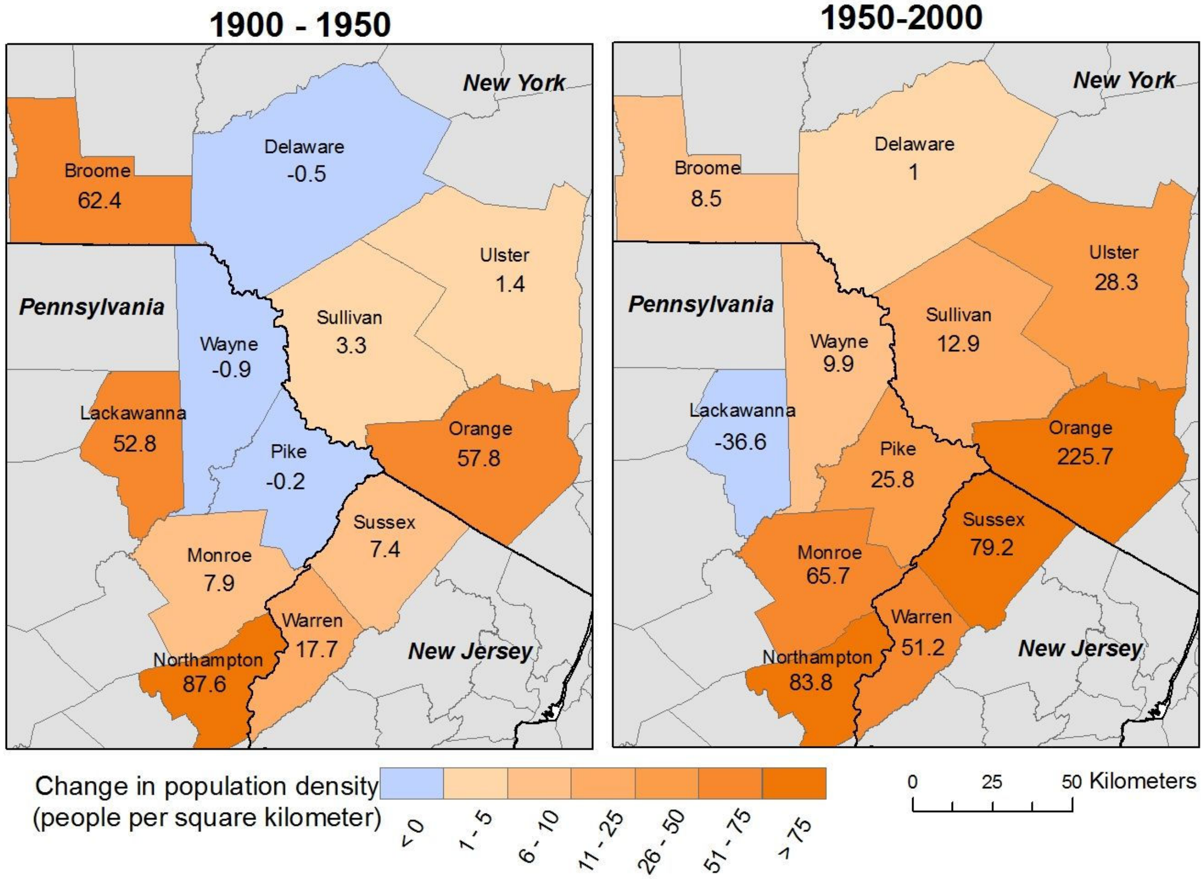

Figure 3: Changes in population density for counties in the region between 1900 and 1950 (left) and 1950 and 2000 (right). Source: GeoLytics 2001.

Another important characteristic of this region, in terms of urban dynamics, is the prevalence of seasonal housing in some counties (Figure 4). For example, in Pike and Wayne counties in Pennsylvania, in 2000 44% and 36%, respectively, of the total housing units are seasonal housing units. The counties with the highest rates of seasonal homeownership are the four counties that cover much of the Upper Delaware River Basin: Pike and Wayne counties in Pennsylvania and Delaware and Sullivan Counties in New York. Lake Wallenpaupack, located at the border of Pike and Wayne counties, is an attractive location for seasonal housing, and the many hunt clubs, public lands, and smaller lakes throughout these counties also serve to draw seasonal homeowners. These trends in seasonal housing add to the challenge of modeling urban development in this region. On the one hand, they represent a source of growth pressure that is not captured by trends in population growth. On the other hand, seasonal housing is increasingly being converted into permanent housing as the owners retire, again complicating the relationship between population growth and residential housing dynamics.

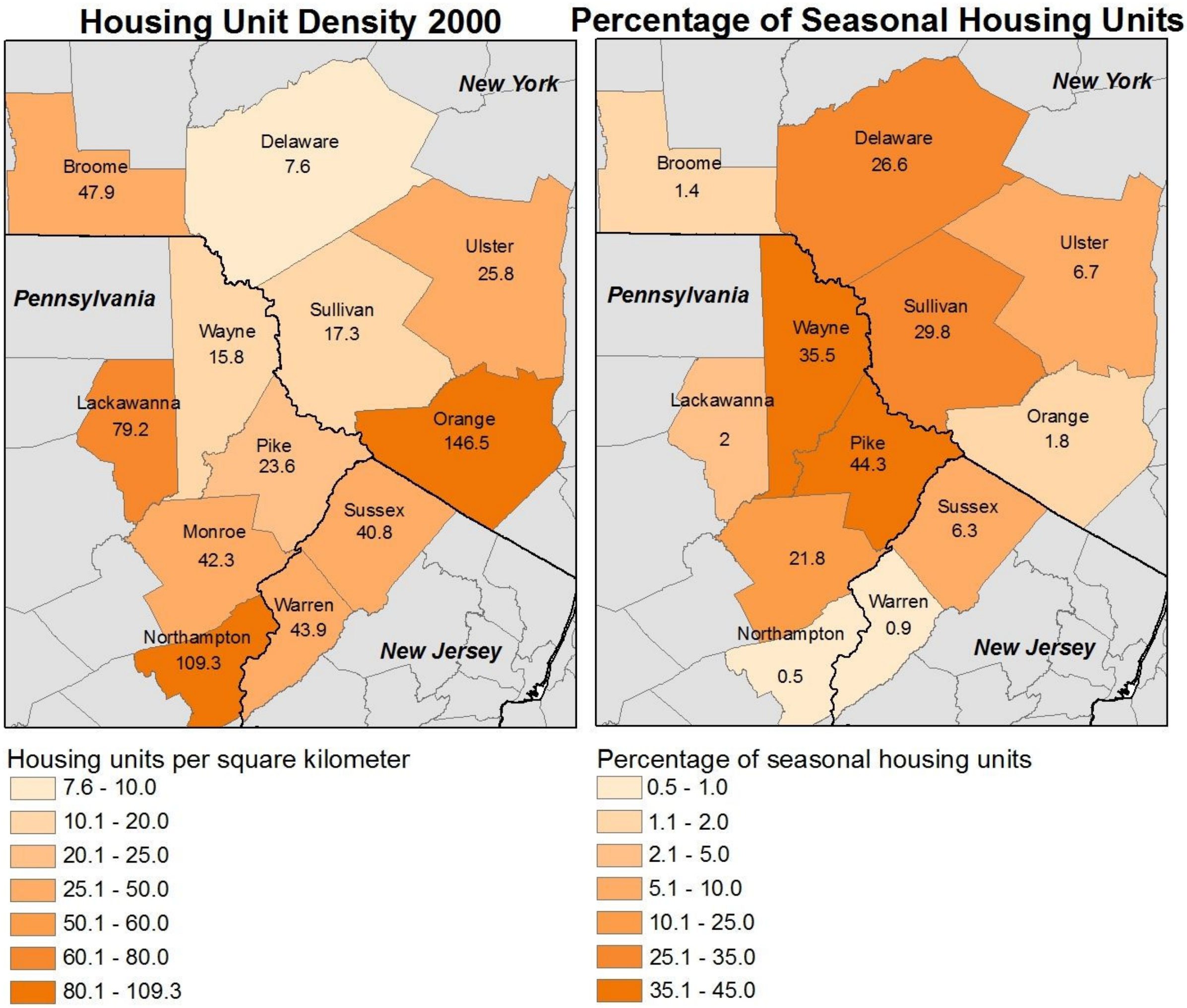

Figure 4. Housing unit density for study area counties in 2000 (left) and the percentage of total housing units comprised by seasonal housing units (right). Source: U.S. Census.

In terms of changes in urban land cover, Eric Brown de Colstoun, our collaborator at SAIC/NASA, created a time series of urban development that was derived from Landsat 5 Thematic Mapper (TM) satellite imagery for the years 1984, 1995 and 2005 (see section 3.2.1 and Jantz, Mrozinski, and Coar (2009) for a description of these data). We note here that the availability of urban land cover data was one factor that defined and, in some cases, limited our study area and analysis of growth trends. Dr. Brown de Colstoun selected two Landsat scene footprints that fully covered the Upper Delaware River watershed. However, the southern part of Northampton and Warren counties in New Jersey, and the eastern part of Orange County in New York were not included in the area covered by the Landsat data. This eliminated some of the areas experiencing high growth pressure, such as the cities of Easton in Northampton County and Newburg in Orange County. This data series nevertheless has proved to be valuable, and for our study area we were able to quantify and map changes in urban land cover over this 20+ year time span (Figures 5 – 7). Between 1984 and 1995, urban land cover increased by 54% and between 1995 and 2005, urban land cover increased by 77%.

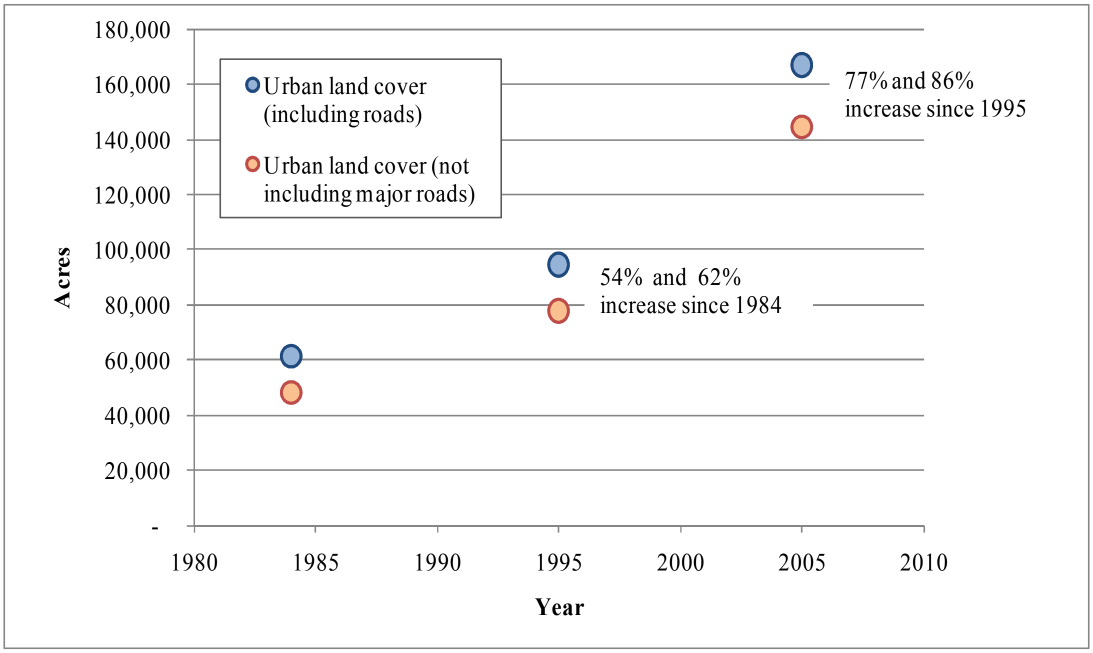

Figure 5. Total increases in urban land cover across the study area between 1984 and 2005. The orange points represent urban land cover excluding the primary road network, and the blue points show total urban land cover.

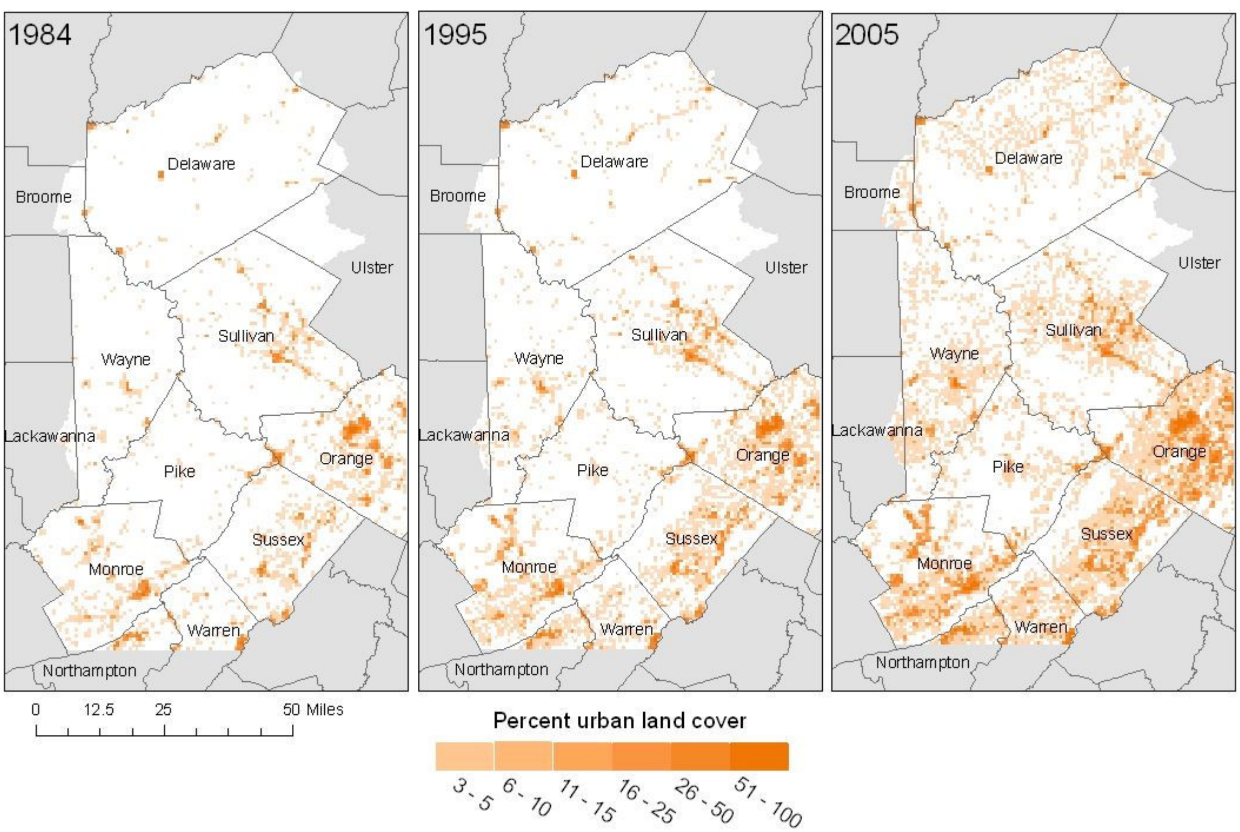

Figure 6. The location of urban land cover in 1984, 1995 and 2005. While the original data derived from the Landsat satellite imagery is at a resolution of 28.5 m x 28.5 m (~ 0.25 acres), the raw data have been summarized for 1 km x 1km pixels in order to visualize regional patterns.

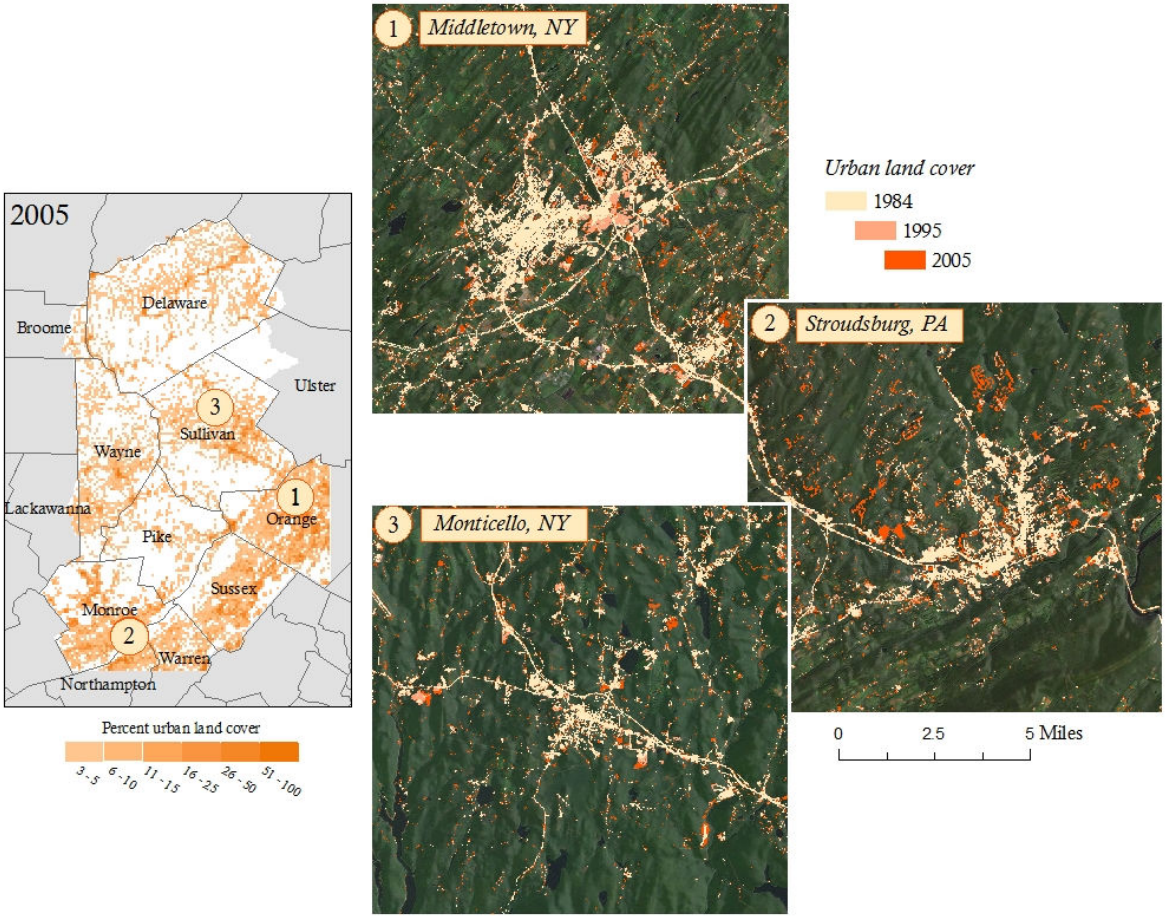

Figure 7. Examples of local-scale change for Middletown, NY, Stroudsburg, PA, and Monticello, NY. The images on the right show the full resolution of the Landsat-derived data.

3.0 Data and Methods

3.1 The SLEUTH-3r model

The model we adopted for this modeling work is SLEUTH[1]. SLEUTH is an open source model, first released in 1997 (Clarke, Hoppen, and Gaydos 1997). It has since been widely adopted and applied to dozens of locations across the U.S. and the world (Clarke 2008, Project Gigalopolis 2011). SLEUTH is a *cellular automata* (CA), where the study area is represented as a regular grid of cells (pixels) and each cell has only two states: urbanized or non-urbanized. Whether or not a cell will become urbanized is determined by four growth rules, discussed below, each of which attempts to simulate a particular aspect of the development process.

This project has benefited from research and development related to the SLEUTH model undertaken in previous studies in the Washington, DC region (Jantz, Goetz, and Shelley 2004), the

[1] SLEUTH is an acronym based on the inputs to the model: slope, land use, exclusion, urban extent, transportation, and hillshade. Full documentation about the model as well as the model code is available at the Project Gigalopolis Urban and Land Cover Modeling website (http://www.ncgia.ucsb.edu/projects/gig/).

Chesapeake Bay watershed (Jantz et al. 2010), and local scale studies in the Upper Delaware region (Jantz, Mrozinski, and Coar 2009). In our previous work with SLEUTH in the Chesapeake Bay, we developed a new version of the model, SLEUTH-3r, which is more computationally efficient and creates more accurate simulations at finer resolutions than the original version of the model (Jantz et al. 2010). SLEUTH-3r is the version of the model used in this work.

Implementation of the model occurs in two general phases: calibration, where historic growth patterns are simulated; and forecasting, where the historic patterns of growth are projected into the future. For calibration, the model requires inputs of historic urban extent for at least two time periods, a historic transportation network for at least two time periods, slope, and a data layer that describes where development is more or less likely to occur (exclusion/attraction layer). The exclusion/attraction layer contains probabilities of exclusion or attraction; areas that should be partially or completely excluded from development are assigned values between 51 and 100; areas that are neutral for development are given a value of 50; and areas that will attract development are given values less than 50. Based on these inputs, the model "learns" to replicate historic patterns of development (calibration) and the results are used for forecasting future urbanized extent.

SLEUTH simulates four types of growth, which are applied sequentially during each annual growth cycle:

- Spontaneous new growth simulates dispersed development patterns,
- New spreading centers simulates the development of new urban areas,
- Edge growth stems from existing urban centers,
- Road influenced growth simulates the influence of the transportation network on development patterns.

These growth types are defined through a set of five growth coefficients: slope (slope resistance), diffusion (spontaneous new growth), breed (new spreading centers), spread (edge), and road gravity (road-influenced). Each growth coefficient can take on a value from 1 to 100, which indicates the relative influence of each parameter on development patterns, with higher values producing a stronger influence. The specific value for each growth coefficient is derived during calibration, so the model is tailored to replicate the growth patterns for a specific study area. In conjunction with the exclusion/attraction layer, these five growth coefficients determine the probability of any given location becoming urbanized. The slope coefficient determines the effect of slope on the probability of urbanization and affects all growth types in the same way: as each location is being considered for urbanization, the slope at that location is considered. Higher slope coefficients result in a lower likelihood of urbanization on steep slopes. In this application, slopes above 20% cannot be urbanized, unless otherwise excluded in the exclusion/attraction layer.

3.2 Input data sets for calibration

As noted above, the SLEUTH-3r model requires the following input data sets for calibration: a series of maps showing urban development through time for at least two points in time, a transportation network for at least two points in time, a slope layer and an exclusion/attraction layer. All inputs are grids (rasters) and the cell (pixel) resolution for all inputs in this particular application is 28.5 m x 28.5 m (93.5 ft x 93.5 ft). The minimum mapping unit is therefore 812.25 m^2 or about 0.2 acres.

3.2.1 Urban development time series

As discussed above, our urban time series was derived from Landsat 5 Thematic Mapper (TM) satellite imagery for the years 1984, 1995 and 2005. The initial data set mapped the fractional impervious surface area (ISA) within each 28.5 x 28.5 m pixel for 1984, 1995 and 2005—in other words, each the value for each cell indicates the proportion of that cell that is made up of impervious surfaces (see Jantz, Mrozinski, and Coar (2009) for a complete description of mapping methods). Values range from 0 (no impervious surface) to 100 (100% covered by impervious surface). While the accuracy of this initial data set was high, these initial maps of fractional impervious surface area (ISA) required additional processing (Figure 8) prior to their use in SLEUTH. The processing steps here follow the method that was used in the local scale applications described in (Jantz, Mrozinski, and Coar 2009), which was extended to the entire study area.

First, SLEUTH requires maps that show pixels being either urban or not, so we were not able to incorporate the fractional ISA values. We therefore considered all pixels that had an ISA value greater than or equal to 20% as being "urban." Second, SLEUTH is extremely sensitive to the accuracy of the input maps. In particular, a high commission error rate can result in an over-estimation of urban development. To address this issue, we used high resolution air photos and GIS data provided by our collaborators to visually assess the accuracy of the 2005 urban land cover map within the study area. Pixels that were incorrectly mapped as urban (i.e. bare agricultural fields) were removed manually, as were occurrences of rock outcrops and quarries. This process of manually editing the urban land cover maps was labor intensive; however, it greatly improved the quality of the maps that would be used as input into the model.

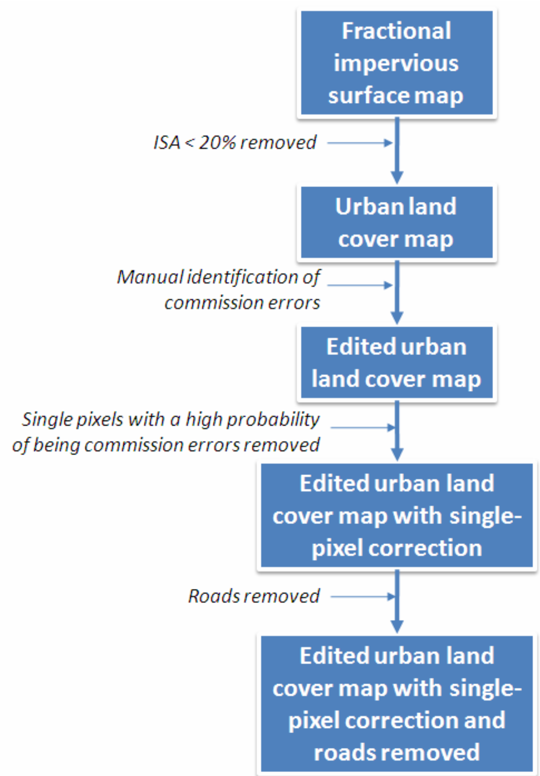

Figure 8. Editing steps applied to the original 2005 impervious surface map to prepare it for input into SLEUTH-3r.

Third, as we found in the local scale applications, single, isolated pixels located in agricultural landscapes tended to have a high error rate, so these pixels were identified and removed.

Then, because roads are provided to the model as a separate input layer, roads were removed from the urban land cover map. Within areas of high road density (i.e. within villages), roads remained as part of the urban land cover; in areas outside of high road density zones, urban pixels associated with roads were eliminated. To eliminate roads in rural areas a three pixel wide mask was created; a pixel was added on each side of the road pixel to account for spatial alignment errors between the GIS-based roads and the urban land cover map.

This final map for 2005 was then used to derive the maps for 1995 and 1984 by assuming that only unidirectional growth has occurred. In other words, if the 1995 map had a pixel identified as urban, but the same pixel in the 2005 map was classified as not urban, the pixel was assumed to be not urban in 1995. The 1995 urban map was then used to create the 1984 urban map. Thus, urban growth is unidirectional between 1984 and 2005. Examples of the final products are shown above in Figure 7

3.2.2 Slope and Roads

The slope layer was derived from the National Elevation data set (US Geological Survey, n.d.). Only primary roads were used to represent the transportation network, and were derived from a roads data set compiled by the National Park Service and based on 2000 Census Tiger line files from the Geography Network.

3.2.3 Exclusion/attraction layers

The exclusion/attraction layer is one of the most important inputs into the SLEUTH model. While SLEUTH is calibrated to the rates and patterns of development in the urban time series, the location of development is informed by factors that will repel or exclude development. The inputs and the relative influence of each input (weights) were determined through trial and error, running multiple calibration procedures (see section 3.3), and adjusting the inputs and weights to create a more accurate simulation of historic growth patterns.

For the 1984 – 2005 calibration time period, the regional factors that were found to be important were (Figure 9):

- Proximity to the New York-New Jersey-Pennsylvania combined metropolitan statistical area is a driver of development. The influence of other proximate metropolitan statistical areas (MSAs), such as Binghamton, NY and Allentown-Bethlehem-Easton, PA, was tested. However, the effect of these other MSAs was found to be negligible when compared to the greater New York City metropolitan area—a finding that coincides with a recent study that showed the growing influence of this metro region (Bram and McKay 2005).
- Areas that are already densely settled tend to resist new development. This finding is likely the result of multiple factors, including land use policies (zoning) and SLEUTH's inherent tendency to overestimate infill (Jantz and Goetz 2005).
- Proximity to major roads, and especially major interchanges, tends to attract development.
- Suitable soils tend to attract development; soils with engineering limitations tend to repel development.
- The Catskill/Delaware watersheds tend to repel development. This is likely due in part to the strict land use regulations in place to protect the drinking water supply for New York City, although this is also an area of slow economic and population growth.

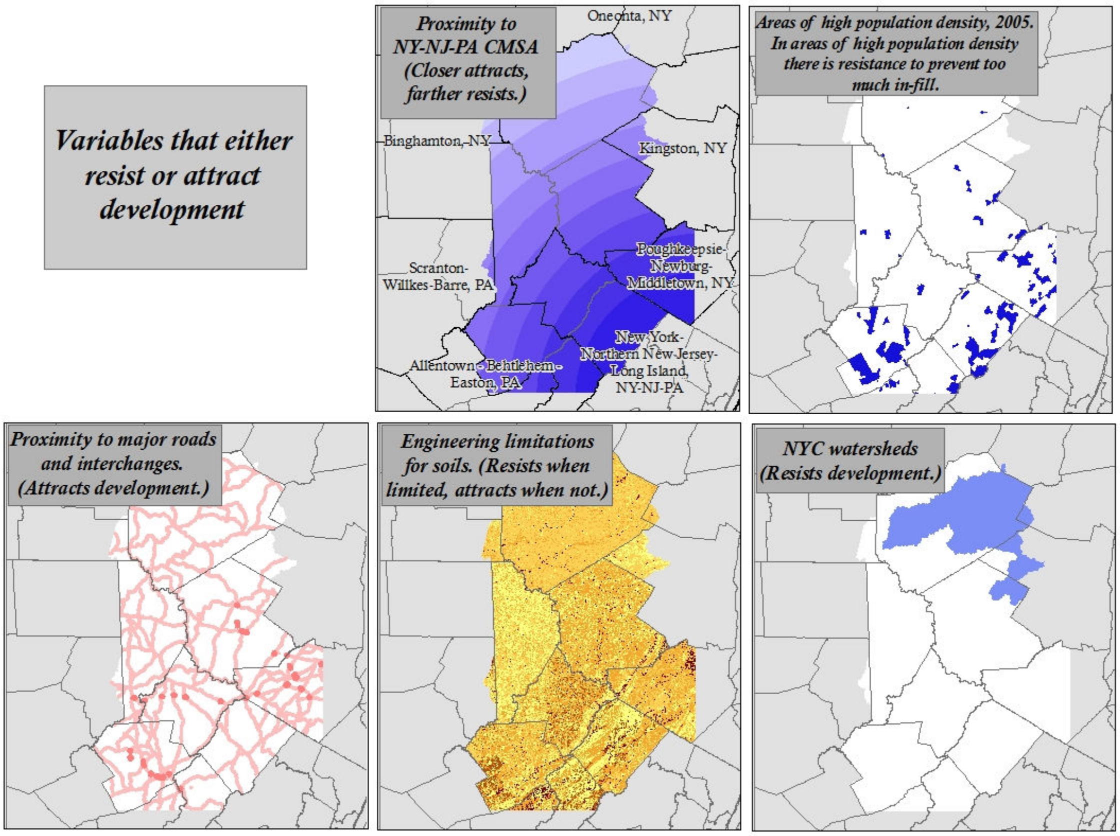

Figure 9. Regional factors that were determined to either attract or repel development over the 1984 – 2005 calibration time period.

In addition to identifying the factors above, lands that were completely protected from development were also included in the exclusion/attraction layer. The National Park Service had already compiled a data set representing protected lands (state and federal parks, hunt clubs, etc.). This layer was updated with input from county partners. In addition to parks, there were several other lands where development was excluded: wetlands, including buffers when dictated by state or local policy (e.g. a 100 ft buffer applies in the Catskill/Delaware watersheds and around New York's Department of Environmental Conservation designated wetlands); open water, including streams; riparian buffers were included when dictated by state or local policy (e.g. a 100 ft buffer applies in the Catskill/Delaware watersheds) ; slopes >15% in the Catskill/Delaware watersheds; airports and runways, including a 250 m buffer; prisons; and military bases (Figure 10). The final exclusion/attraction layer (Figure 11) represents a combination of all of these layers, with their assigned weights, and is the layer that performed the best over a series of three calibration trials, each testing different data inputs and weights (see sections 3.3 and 4.1).

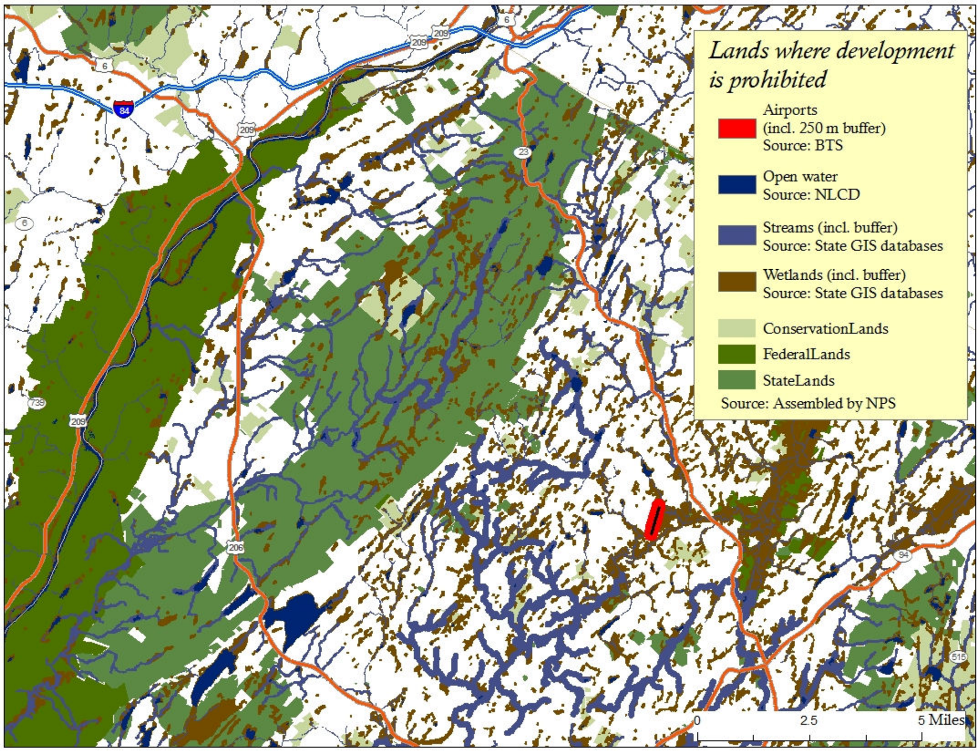

Figure 10. Example of lands that are completely protected from development.

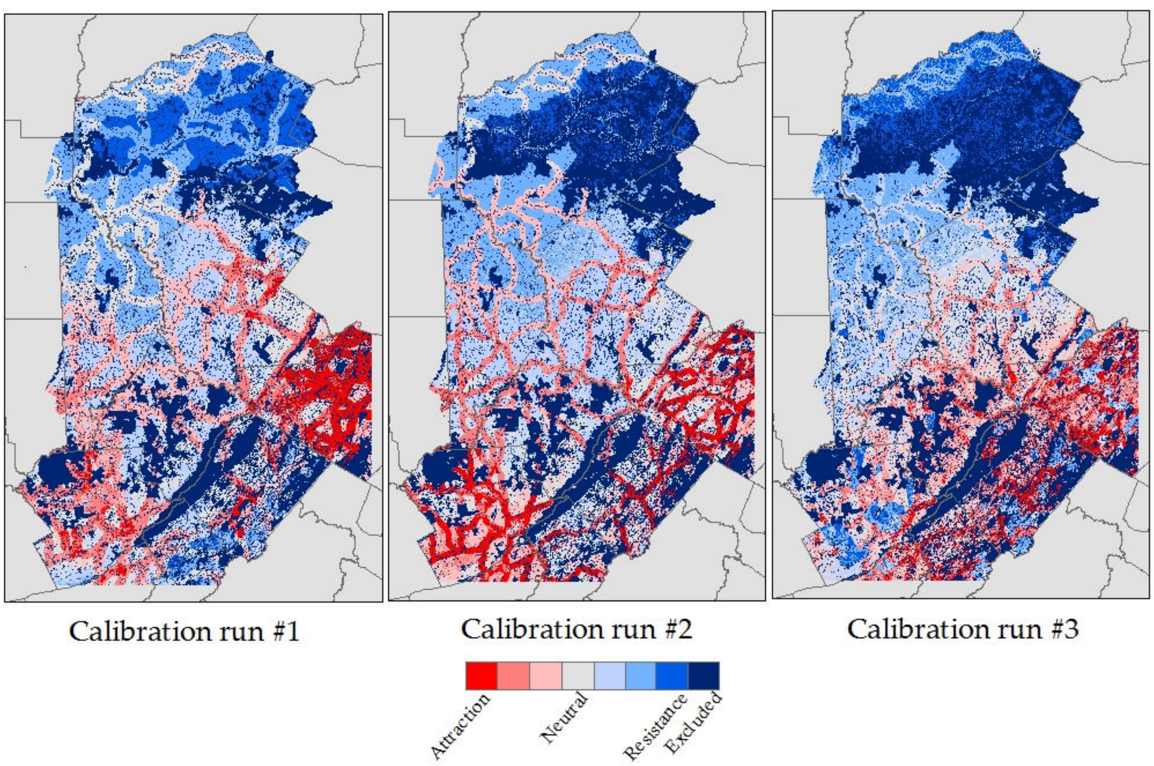

Figure 11. The three excluded layers that were tested over a series of three calibration trials. The final map, calibration run #3, was found to produce the most accurate results, and was the exclusion/attraction layer used in the final calibration.

3.3 Calibrating the SLEUTH model

The goal of SLEUTH calibration is to find a set of values for the growth parameters (diffusion, breed, spread, road-gravity and slope) that can accurately reproduce historic land-cover change within the study area. Calibration is typically undertaken using what is referred to as a "brute force" methodology. That is, a large number of combinations of parameter values are tested automatically and the user evaluates the results, locating a "best fit" set of parameter values through the use of statistics that measure how well the model is replicating historic patterns of urbanization. In this study, we tested 3,125 unique parameter combinations, a sufficient number of parameter sets to find a good fit for the model.

The choice of statistics is important, since it determines how SLEUTH will simulate urban patterns and how forecasts of urban growth will be created. For the calibration procedure in this work, we focused on measuring how well the model could match the total urban area in 2005, the number of urban clusters (a metric related to urban *pattern*), and the number of urban edge pixels (a measure of urban patch *shape*). We selected parameter sets that were able to match area and clusters within +/- 5%; matching edge pixels is more difficult so this third metric was used as a secondary fit statistic.

SLEUTH is a random model and thus utilizes the Monte Carlo method to generate growth simulations, which means that multiple simulations (or trials) of growth are created for each unique parameter set. The fit statistics that SLEUTH calculates are therefore averaged over the total number of Monte Carlo trials that were run. The Monte Carlo method also produces maps that show the *likelihood* or *probability* of development. For calibration, we initially used only seven Monte Carlo trials to economize computational processing time. Based on these initial results, we selected up to five parameter sets that did the best job of simulating rates and patterns of development. Then, each parameter set was tested over one-hundred Monte Carlo trials.

In order to provide additional assessments of the accuracy and utility of the model simulations, beyond those calculated by the model during calibration, we performed an extensive accuracy assessment. After the best fit parameters were identified for the region, the model was initialized in 1984 and run in predict mode to 2005, with one-hundred Monte Carlo trials. This resulted in a predicted development probability surface for 2005, which was then compared to the observed patterns for 2005. While aggregate performance measures for the region were calculated during calibration (i.e. model fit statistics), this additional assessment allowed us to quantify model performance at finer scales. Using regression analysis, we compared observed and simulated urban land cover for 2005 across 1 km^2 grid cells.

3.4 Forecasting Future Growth

Forecasts of future urbanization were created through modifications of the exclusion/attraction layers and by assuming different future growth rates. For the baseline scenario, we used the same excluded layer that was developed for calibration—in other words, we assumed no change in land use policies. A set of alternative scenario narratives, outlined below in Table 1, were developed in conjunction with the National Park Service and our partners to explore issues they identified as being most relevant. Based on these narratives, an exclusion/attraction map was generated for each scenario to represent the corresponding spatial changes to policies or drivers of land use change. These exclusion/attraction maps (Figure 12) were provided as input to the growth model.

Table 1. Land use policy scenarios for the region.

1. *Baseline/business as usual*
    a. Same excluded/attraction layer as in calibration, except the Highlands Preservation Area (created in 2004) was included in New Jersey.
2. *Smart growth*
    a. Focus growth into county-designated growth areas and around planned sewer service areas where available.
    b. Emphasize growth around transit stations, including planned new stations for the Lackawanna cutoff.
    c. De-emphasize development along road corridors.
    d. Use same protected lands as calibration, but add strong protection (not complete protection) of potential new lands: Cherry Valley and Wallkill wildlife refuges expansion area.
    e. For all streams and wetlands, add moderate/strong protection for at least a 100 ft. buffer.
3. *Best for resource protection*
    a. Start with smart growth excluded/attraction layer, but:
        i. Add strong protection for Nature Conservancy, National Park Service, and county-designated targeted protection areas/greenway corridors.
        ii. De-emphasize growth around roads and emphasize growth in growth areas and transit areas (including new along Lackawanna Cutoff).
        iii. Apply stronger protection to the Catskill/Delaware watersheds and the New Jersey Highlands Preservation Area.
        iv. Apply moderate protection to areas identified as having the least amount of human impact (derived from a natural landscape index (Theobold 2010)).
        v. Add complete protection to potential new lands (Cherry Valley, Wallkill expansion).
        vi. For all streams and wetlands, complete protection of at least 100 ft. buffer.
        vii. Completely protect all slopes >15%.
4. *Limited planning/protection of resources*
    a. Start with baseline exclusion/attraction layer, but:
        i. Emphasize growth along road corridors, transit and growth areas; and allow "sprawl" in other areas. Enhance growth pressures from adjacent MSAs.
        ii. Remove New Jersey Highlands Preservation Area and make Catskill/Delaware watershed protection less effective.
        iii. No additional protection (beyond baseline) on riparian and wetlands zones.
        iv. No new land acquisitions.

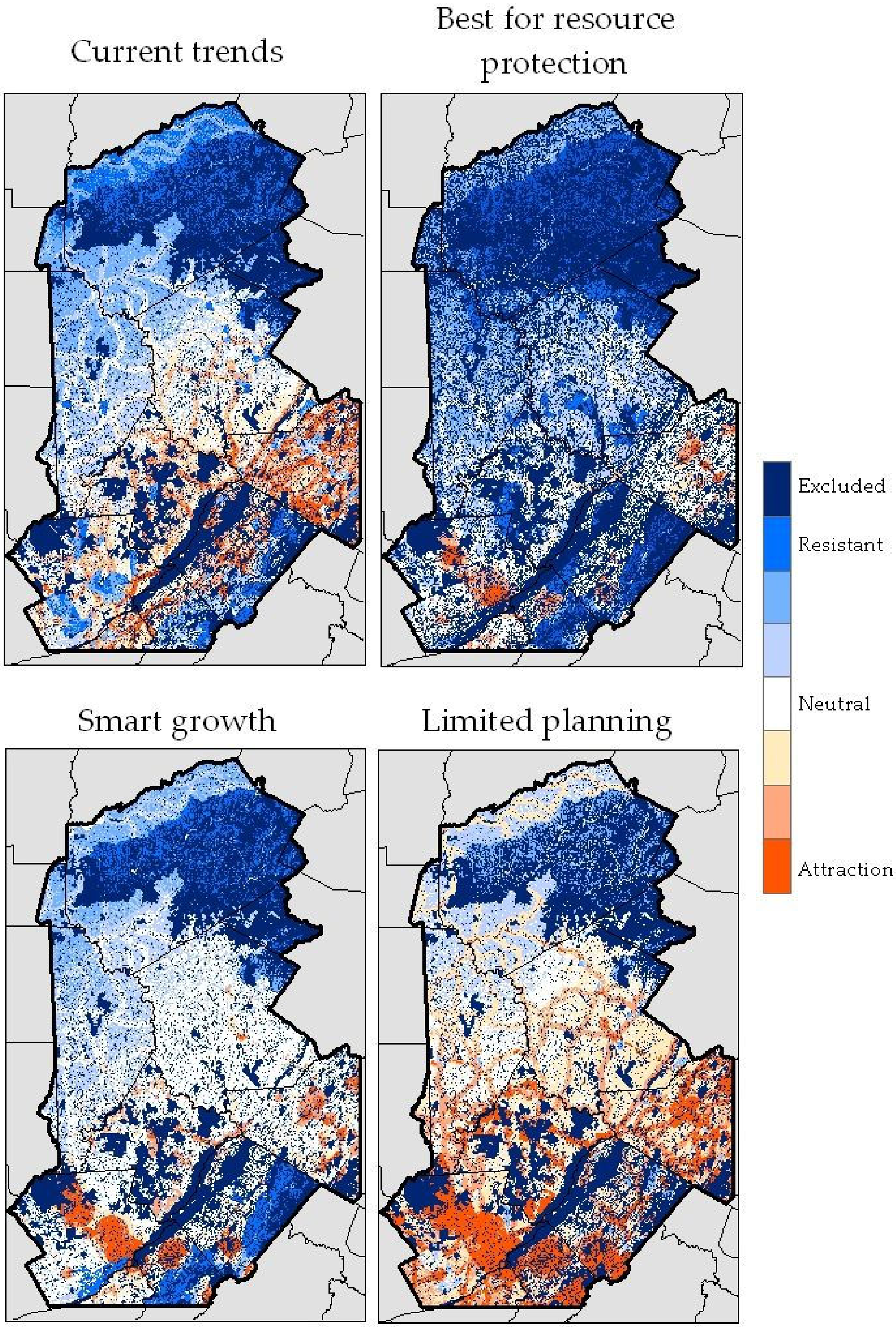

Figure 12. Scenarios maps to simulate the impacts of different future land use policies, as described in Table1.

For each scenario, three different growth rates were modeled: a linear growth rate (roughly 70% over 2005 levels), an increase in urban land of 50% (over 2005 levels), and an increase in urban land of 25% (Figure 13). These different growth rates were modeled to provide a range of growth scenarios. The linear growth rate is considered to be a high-growth scenario, assuming that the boom of the 1990s continues through 2030. The 25% increase scenario is a low-growth scenario, representing a leveling off of growth in the next few decades. Since we had four land use policy scenarios, a total of twelve simulations were run.

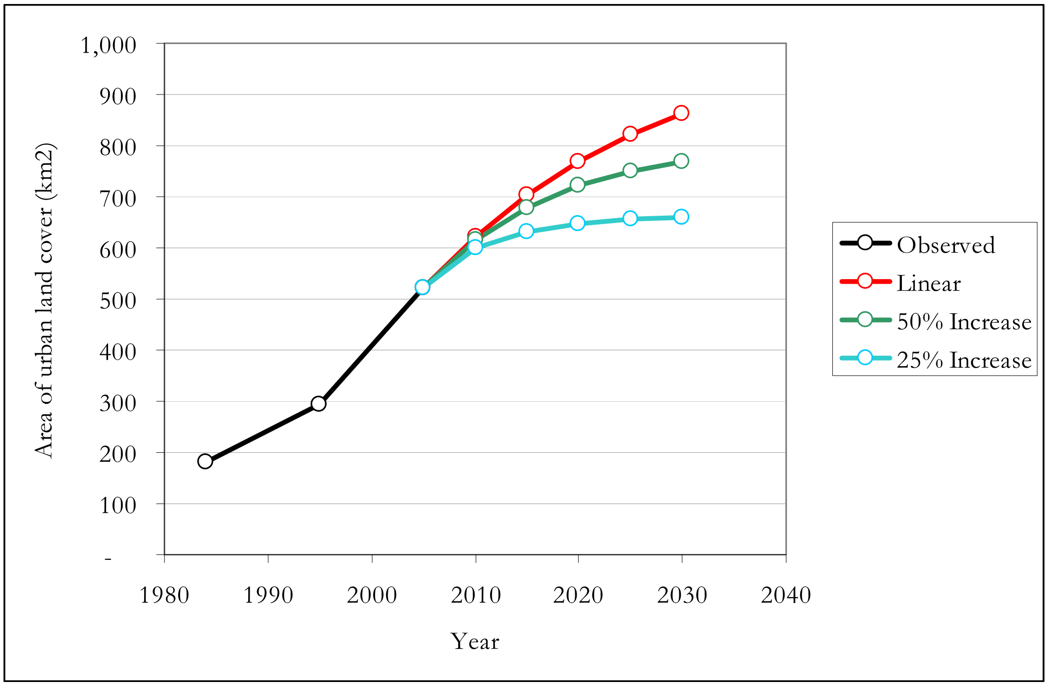

Figure 13. Growth rate scenarios that were run across all land use policy scenarios.

4.0 Results and Discussion

4.1 Calibration

As was noted in section 3.2.3, multiple calibrations were performed in order to identify the regional drivers of growth to be included in the exclusion/attraction layer (Figure 11) and to identify the best values for each of the five growth parameters. Each calibration run was evaluated at the regional scale using the fit statistics calculated by SLEUTH, regression analyses comparing mapped and modeled estimates of urban land cover at the scale of 1 km x 1 km grid cells (Table 2), and by examining the distribution of errors at the 1 km x 1 km scale (Table 3).

As shown in these results, the R^2 values do not vary much between calibration runs, and all three calibration runs perform relatively well based on the regional statistics calculated by SLEUTH (Table 2)—although it can be noted that the third calibration run has the highest area match and edge pixel match. The third calibration also has a much narrower distribution of error, with 80% of the simulated estimate of urban land cover within 1 km x 1km cells falling within 2.5% of the actual estimate, and 95% falling within 5% (Table 3).

Table 2. Regional fit statistics, comparing mapped and modeled estimates of urban area, clusters, and edge pixels for 2005, for each calibration run. The values here indicate the fractional over- or underestimation of the model, and values closer to zero indicate a good match. R^2 values were calculated in a regression analysis comparing mapped and modeled estimates of urban land cover at the 1 km x 1km scale (N = 15,667 cells); values closer to 1 indicate a good match.

	Area match	Urban cluster match (pattern)	Edge pixel match (shape)	R^2 (1 km x 1 km cells)
Calibration #1	-0.03	-0.03	-0.17	0.84
Calibration #2	-0.01	-0.002	-0.12	0.85
Calibration #3	-0.002	-0.03	-0.06	0.83

Table 3. Distribution of errors for the 1 km x 1km array (N = 15,667 cells).

	Percent (number) of cells where the modeled estimate is within 2.5% of the observed estimate	Percent (number) of cells where the modeled estimate is within 5% of the observed estimate
Calibration #1	63% (9,989)	76% (11,865)
Calibration #2	62% (9,700)	73% (11,360)
Calibration #3	80% (12,557)	95% (14,896)

Visually, it can be shown that in the first two calibration runs, there is persistent underestimation of urban growth in the northern and southern parts of the region (corresponding to the Catskill/Delaware watersheds and what became the Highlands Preservation Area, respectively) and persistent overestimations in and around existing towns and villages. While these patterns are still evident in the third calibration, these errors have been minimized (Figure 14).

It should be noted that this region presents unique challenges for urban modeling due to the heterogeneity of urban land cover patterns and land use policies. As noted in section 2.0 the southern counties tend to have higher growth rates and a more extensive settlement pattern than the northern counties. Likewise, this region covers three states, multiple counties, and several areas with special land use regulations. Despite these challenges, we were able to achieve excellent calibration results, primarily due to the insights and feedback we received from our local partners throughout this process. The final parameter values derived for the third calibration are: diffusion = 50, spread = 25, breed = 100, slope resistance = 25, and road gravity = 50.

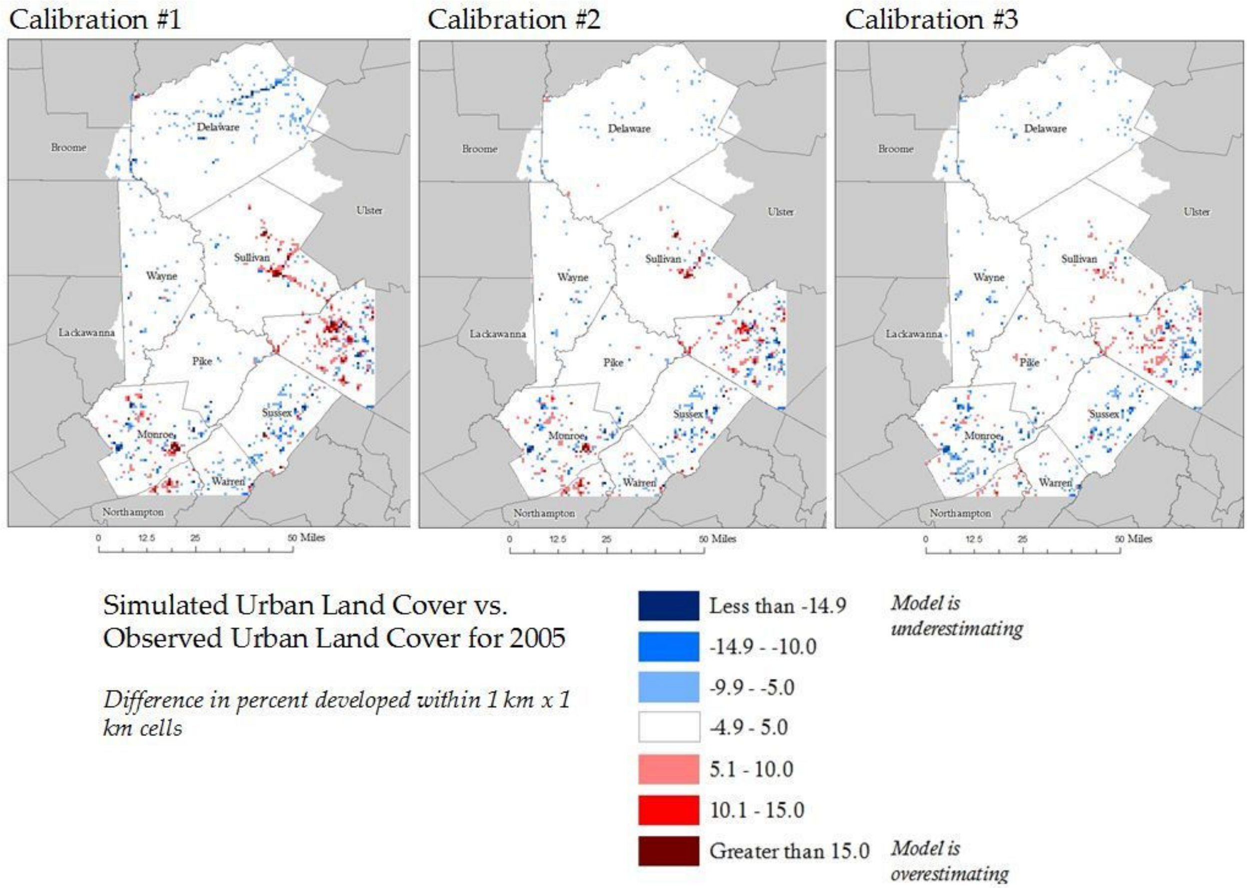

Figure 14. Simulated urban land cover compared to observed urban land cover for 2005 at the 1 km x 1 km scale. Shades of blue show areas of underestimation; shades of red show areas of overestimation. In white areas, the model matches observed within +/- 5%.

4.2 Forecasts of Future Urban Growth

As noted in section 3.4, a total of twelve forecasts were run (four land use policy scenarios, each at three different growth levels). Here we present highlights of our findings from these scenarios, including an exploration of how water resources might be impacted.

Figure 15 shows 2005 and forecasts to 2030 under the baseline policy scenario, for the linear growth rate (a 70% increase over 2005 levels), a 50% increase over 2005 levels, and a 25% increase over 2005 levels. These maps illustrate the variability in growth levels across these three growth rates. Across all three growth rate scenarios, the southern counties in the study area continue to experience the highest growth pressures, although additional lower-intensity development is observed to occur in the central and northern counties as well. As expected, in the lower growth scenario, these patterns are less intense.

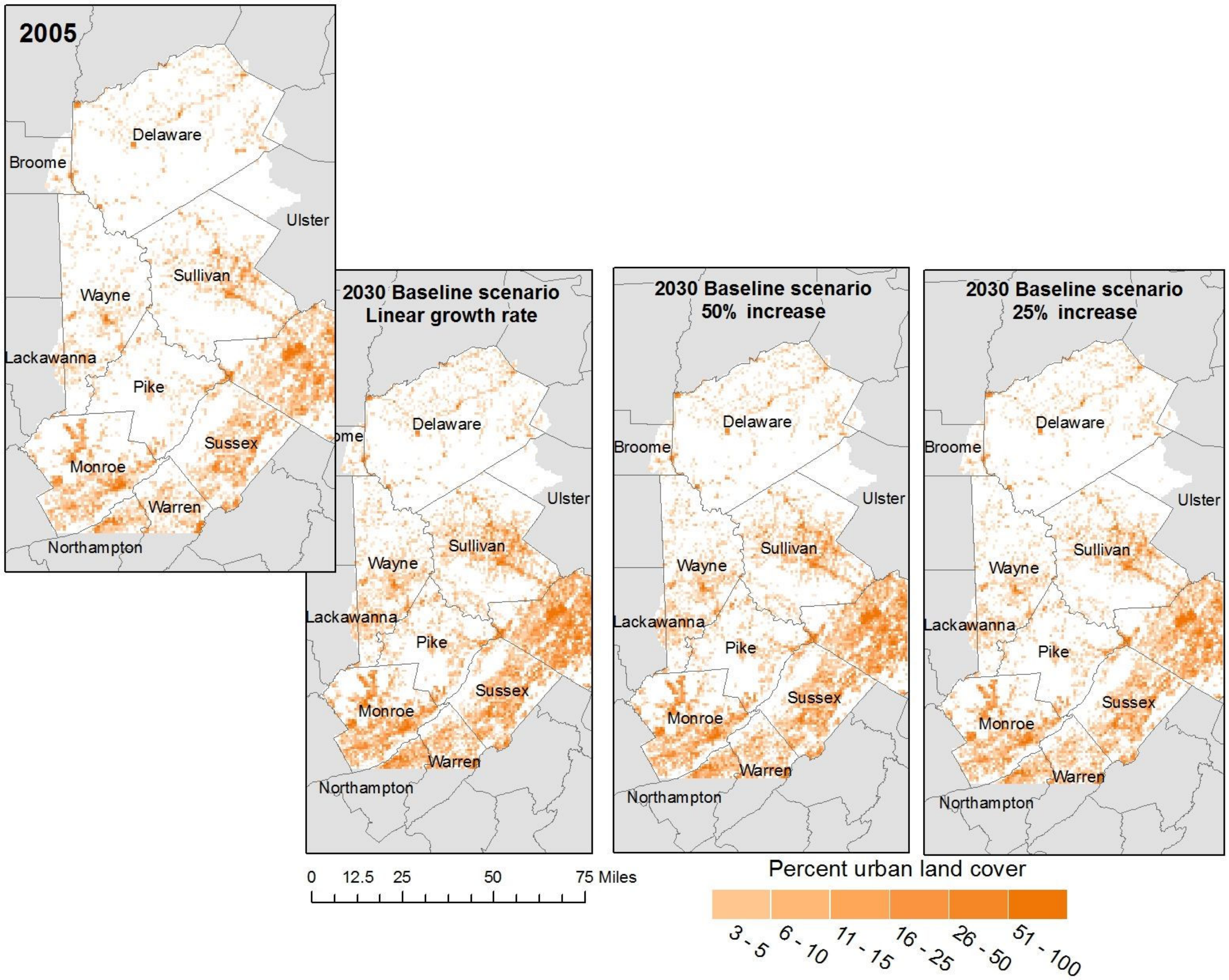

Figure 15. Urban development in 2005 (upper left) and forecasts to 2030 under a linear growth rate (lower left), an increase of 50% (lower middle), and an increase of 25% (lower right).

The land use policy scenarios were developed to test the influence of policy on *where* development would occur. To highlight differences between the scenarios, Figure 16 shows the difference between the baseline scenarios and each of the alternative scenarios (limited planning, smart growth, resource protection) (see Table 1) for the growth rate scenario that assumes a 50% increase over 2005 levels. Shades of orange indicate areas of high growth in an alternative scenario relative to the baseline; shades of blue indicate areas of lower growth in an alternative scenario relative to the baseline. Spatial patterns of these differences for the other growth rate scenarios are similar, although vary in intensity.

There are several observations that can be drawn from the comparisons presented in Figure 18. Of the three alterative scenarios, the limited planning scenario is most similar to the baseline scenario. In this scenario, we assumed a stronger influence of adjacent MSAs, and this becomes apparent especially for the Allentown-Bethlehem-Easton, PA MSA, resulting in much higher levels of growth in Monroe County. Orange County also exhibits more growth, especially around Middletown. The smart growth scenario and the resource protection scenario are strikingly similar. Both scenarios emphasize infill development around existing towns and villages, which is strongly apparent throughout the region. Both scenarios also show a striking decrease in development pressure throughout Warren and Sussex counties in New Jersey, due primarily to increased levels of protection to the Highlands Area and a concentration of growth in other locations. The fact that additional protections on resource lands in the resource protection scenario do not seem to have a strong influence likely indicates that those areas are not forecasted to experience strong development pressures, at least by 2030.

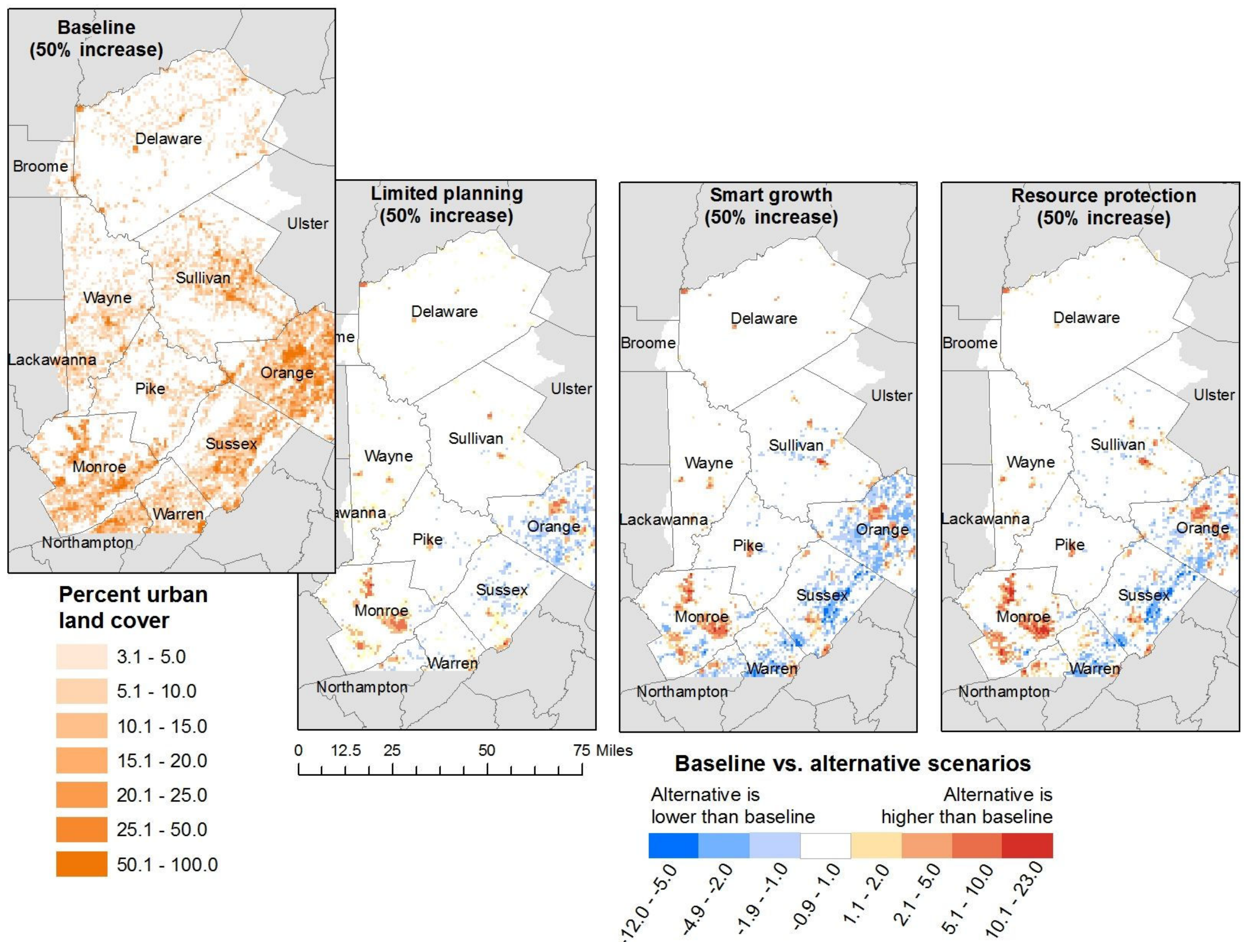

Figure 16. Urban development in 2030 under the baseline scenario, assuming a 50% increase in development over 2005 levels (upper left). The lower three maps show the difference between the baseline forecast for 2030 and each of the three alternative scenarios.

4.2.1 Impacts on Water Resources

Water is a critical resource in this region. There are two source water protection areas that provide clean drinking water for significant populations in New York and New Jersey. Excellent water quality also provides the basis for many recreational opportunities in the region, an important component of the regional economy. We therefore focused some attention on identifying how watersheds might be impacted due to forecasted development.

It is relatively well-documented that stream health is negatively impacted when impervious surfaces cover 10% or more of the watershed area (Snyder, Goetz, and Wright 2005, Arnold and Gibbons 1996). The inputs and outputs of the SLEUTH model, however, provide estimates of urban land cover, not impervious surface. Since we had access to impervious surface estimates as well as urban land cover estimates from the land cover data product developed by Dr. Brown de Colstoun, we were able to establish a relationship between the area urban land cover and impervious surface area within HUC 12 watersheds for 2005. As can be observed in Figure 17, these two variables show a strong, linear correlation. Using this linear relationship, we were able to estimate the impervious surface area within watersheds based on SLEUTH's forecasts of urban land cover in 2030.

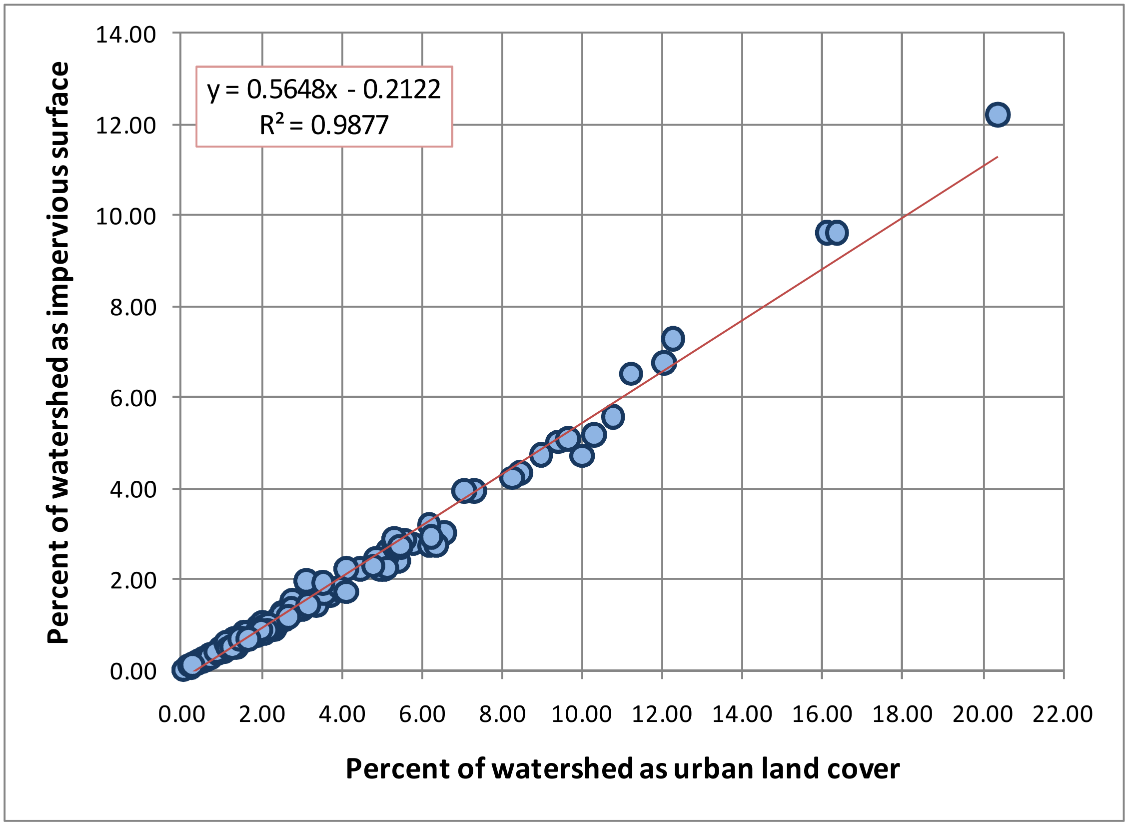

Figure 17. Urban land cover area vs. impervious surface area for HUC 12 watersheds.

At the watershed level, spatial patterns estimated impervious surface area are similar across all land use policy scenarios, although differences can be observed between different levels of growth (Figures 18 – 20). In these figures, watersheds with at least 10% of their area covered by impervious surfaces are highlighted in dark red; according to the forecasts, these are watersheds where stream health will likely experience degradation. Medium red shows watersheds with 7 – 10% of their watershed area covered by impervious surface and would be considered at high risk for potential impacts on water resources. Light red shows 5 – 7% impervious surface cover, indicating lower risk watersheds, and watersheds in white are below 5% and will likely maintain high quality stream health.

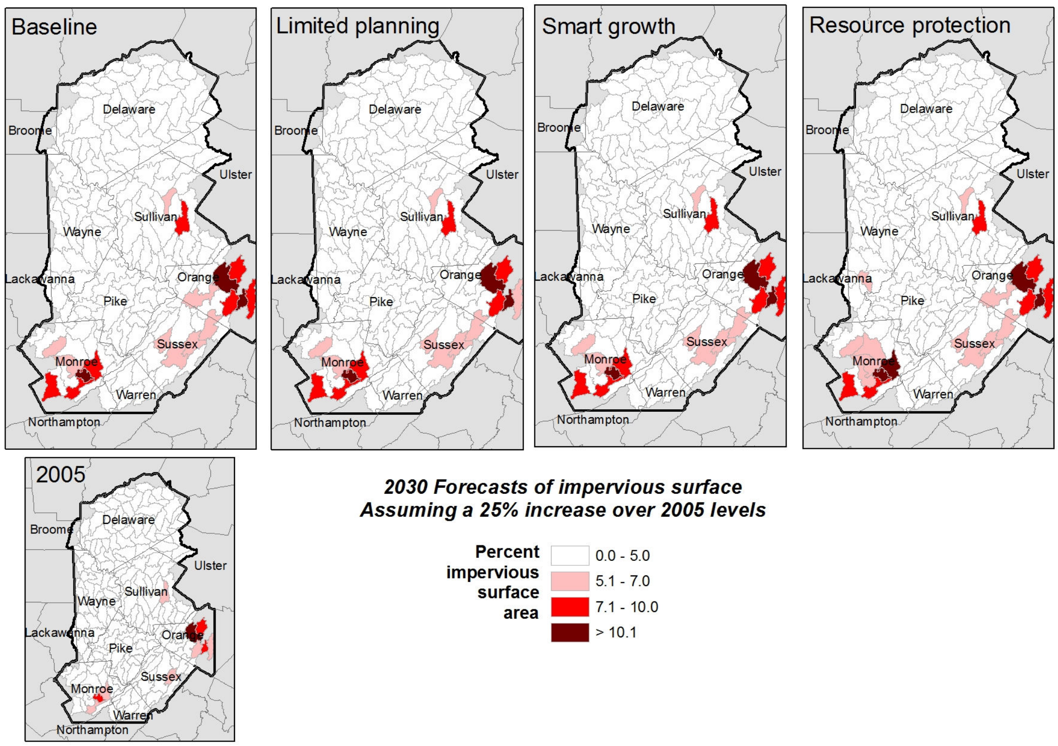

Figure 18. Impervious surface area in 2005 (lower left) and forecasted impervious surface area in 2030 for each land use policy scenario, assuming a 25% increase in development over 2005 levels.

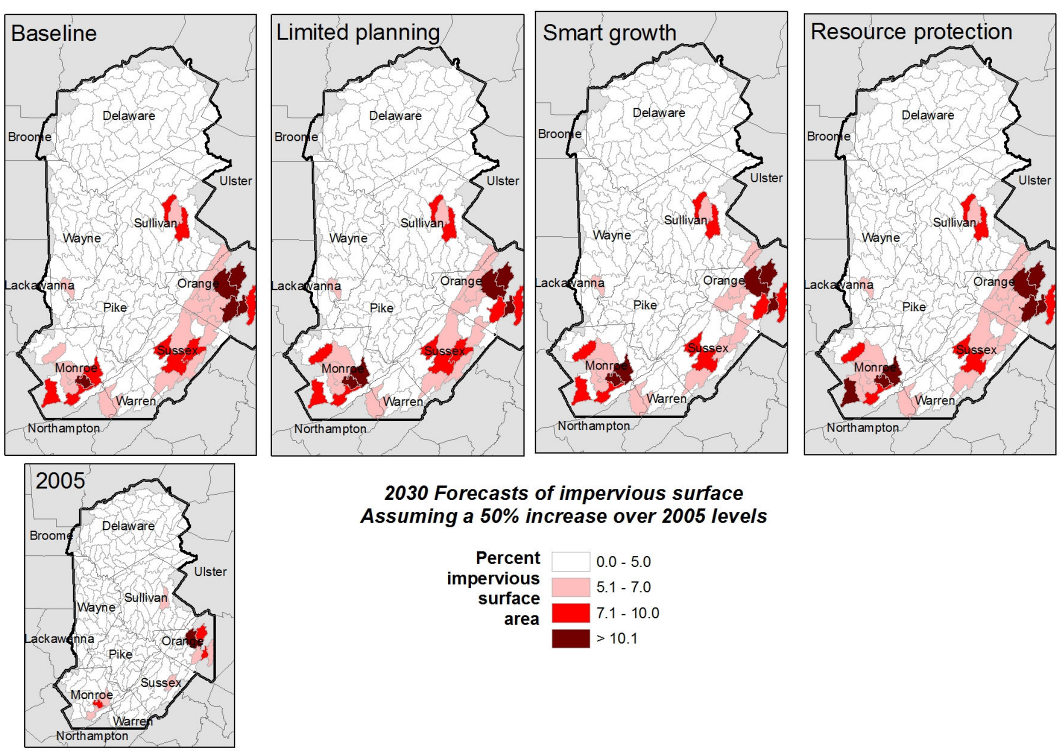

Figure 19. Impervious surface area in 2005 (lower left) and forecasted impervious surface area in 2030 for each land use policy scenario, assuming a 50% increase in development over 2005 levels.

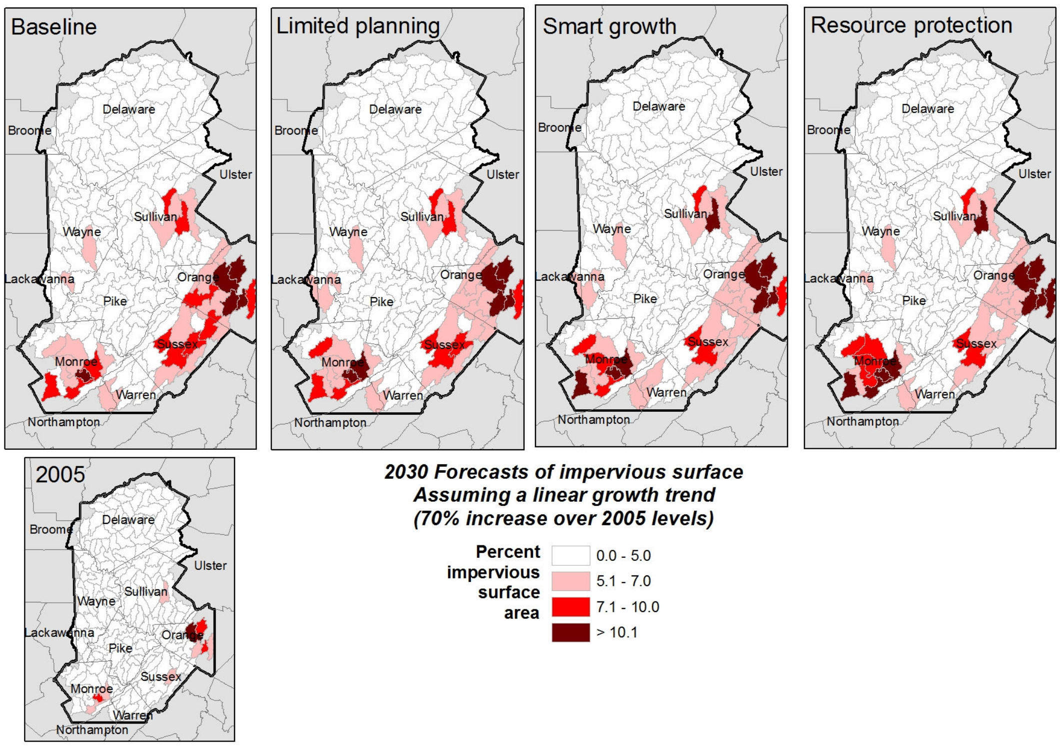

Figure 20. Impervious surface area in 2005 (lower left) and forecasted impervious surface area in 2030 for each land use policy scenario, assuming a linear growth rate, or a 70% increase in development over 2005 levels.

5.0 Conclusions

Several conclusions can be drawn from this work. From the urban modeling perspective, we found that the SLEUTH model's performance can be improved through the incorporation of local knowledge and data sets. Especially when incorporating policy components into local and regional urban modeling applications, the role of local experts cannot be underestimated. We also generated several useful products as part of this research, which can be used in additional applications: a 20+ urban land cover time series, forecast data covering a wide range of scenarios, and a calibrated urban land cover model that can be re-applied to new scenarios.

In terms of what these results tell us about urban land cover trends and land use policy in the Upper Delaware region, policies that broadly support smart growth strategies and resource protection in will likely result in positive benefits for forests and landscape preservation (Figures 17 and 18). While impacts on water resources of the various policies we tested are less clear, it is clear that lower growth levels will minimize impacts on water resources (Figure 19 – 21). This result is perhaps not surprising, but it does emphasize the importance of limiting the footprint of urban land cover if protection of water resources is a priority. We note that this study does not incorporate population or employment forecasts, so it is important to keep in mind that the three growth levels we forecasted in this study might accommodate similar levels of population and employment growth assuming a higher density ("smart growth") in the low growth scenario and a lower density ("sprawl") in the high growth scenario. Pro-active and smart land use planning therefore remains paramount in this environmentally sensitive region.

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