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Downscaling climate change scenarios in an urban land use change model

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Abstract

The objective of this paper is to describe the process through which climate change scenarios were downscaled in an urban land use model and the results of this experimentation. The land use models (Urban Growth Model [UGM] and the Land Cover Deltatron Model [LCDM]) utilized in the project are part of the SLEUTH program which uses a probabilistic cellular automata protocol. The land use change scenario experiments were developed for the 31-county New York Metropolitan Region (NYMR) of the US Mid-Atlantic Region. The Intergovernmental Panel on Climate Change (IPCC), regional greenhouse gas (GHG) emissions scenarios (Special Report on Emissions Scenarios (SRES) A2 and B2 scenarios) were used to define the narrative scenario conditions of future land use change.

The specific research objectives of the land use modeling work involving the SLEUTH program were threefold: (1) Define the projected conversion probabilities and the amount of rural-to-urban land use change for the NYMR as derived by the UGM and LCDM for the years 2020 and 2050, as defined by the pattern of growth for the years 1960–1990; (2) Down-scale the IPCC SRES A2 and B2 scenarios as a narrative that could be translated into alternative growth projections; and, (3) Create two alternative future growth scenarios: A2 scenario which will be associated with more rapid land conversion than found in initial projections, and a B2 scenario which will be associated with a slower level of land conversion.

The results of the modeling experiments successfully illustrate the spectrum of possible land use/land cover change scenarios for the years 2020 and 2050. The application of these results into the broader scale climate and health impact study is discussed, as is the general role of land use/land cover change models in climate change studies and associated environmental management strategies.

Keywords: Climate change scenarios; SLEUTH; Urban land use

The objective of this paper is to describe and examine the process through which climate change scenarios were downscaled into a computer-based land use change model. The land use model utilized in the project is the SLEUTH program (developed by Clarke; see Clarke et al., 1997) which includes the Urban Growth Model (UGM) and the Land Cover Deltatron Model (LCDM). The Intergovernmental Panel on Climate Change (IPCC) regional greenhouse gas (GHG) emissions scenarios (Special Report on Emissions Scenarios [SRES] A2 and B2 scenarios) were used to define the potential conditions of future land use change. The land use change scenario experiments developed for the study represent an innovative application of the SLEUTH program. The case study region of the project is the 31-county ($35,568\ km^2$.) New York Metropolitan Region (NYMR) that includes New York City and portions of the states of Connecticut, New Jersey and New York and includes a population of 21.5 million residents (US Census 2000).

1. The role of urban land use modeling in a climate change study

A key rationale for this paper is to illustrate the role and effectiveness of computer-based urban land use modeling activities in broader scale interdisciplinary climate change studies. As global change science emerged in the past decade there has been a concurrent growing appreciation of the importance of the land use/land cover measures in the understanding of global environmental change

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and the generation of GHG. The recent publication of the IPCC SRES narratives (Nakićenović et al., 2000) and similar reports (e.g. US EPA, 2003) have helped increase the focus on the role of urban settlements and associated urban land use in the GHG emissions. Different urban land use patterns and population densities have been used as measures and indices of different GHG profiles (Gaffin, 1998). Low density, urban sprawl communities are often defined as relatively high-per capita GHG emissions sites (Liu et al., 2003). Cellular automata models have been effectively utilized to illustrate differing urban land use scenarios (Yeh and Li, 2003, 2001; Li and Yeh, 2001; Wu, 1998).

In this study, the SLEUTH model results are part of a three-year integrated study (the New York Climate & Health Project) that attempts to define the impact on public health from a series of potential global and regional climate changes, land use changes and air quality changes in the New York Metropolitan Region in the 21st century. Anticipated global climate change is expected to combine with continued suburban sprawl and associated land cover change to amplify potentially hazardous climate-elated conditions in urban areas. More precisely, these conditions include the increased threat from an augmented urban heat island effect (defined as increased surface and air temperatures in urban areas relative to outlying rural/peri-urban sites) and associated heat stress (Rosenzweig and Solecki, 2004), and air quality shifts resulting from an increase in primary and secondary air pollutants (i.e. ozone and particulate matter [PM2.5]).

The project is designed to utilize a set of models and a cascade of their results. One set of model results will be utilized as the input for a next set of models. While each one of these models have and can be run separately, linking them together enables the researchers to receive more refined data, either temporally or spatially, and in turn define enhanced projections. See Hogrefe et al. (2003) for more discussion of the project.

Within this larger project, the specific research objectives of the land use modeling work involving the SLEUTH program were threefold:

1. Define the projected conversion probabilities and the amount of rural-to-urban land use change for the NYMR as derived by the UGM and LCDM for the years 2020 and 2050, as defined by the pattern of growth for the years 1960–1990;
2. Down-scale the IPCC SRES A2 and B2 scenarios as a narrative that could be translated into alternative growth projections;
3. Create two alternative future growth scenarios: A2 scenario which will be associated with more rapid land conversion than found in initial projections, and a B2 scenario which will be associated with a slower level of land conversion. The modeling would be done for the years 2020 and 2050.

2. Land use modeling and the sleuth program

SLEUTH is a probabilistic cellular automata model that defines future land use change as a product of a set of growth inducing variables (e.g. slope, land cover, exclusion zones, land use, transportation, and hillshading), a set of growth parameters (defined by the past patterns of urbanization), and growth rules. The software structure enables one to define future growth as a projection of past growth, as well as define alternative growth scenarios (e.g. slowed conversion, more rapid conversion). See Jantz et al. (2003), McGinnis (2002) and Silva and Clarke (2002) for recent examples of land use modeling utilizing SLEUTH.

SLEUTH is comprised of the Urban Growth Model (UGM) and the Land Cover Deltatron Model (LCDM). The UGM simulates land class change, or more specifically, the probability that a non-urban cell will be converted to an urban cell. The LCDM, which is driven by the UGM, include land cover data in the simulation and therefore, can specify the nature of the non-urban to urban changes (e.g. the amount of agricultural land to urban land change, the amount of forest land to urban land change, etc.). The UGM may be run independently of the LCDM, but the LCDM must be run with the UGM.

In order to create the range of possible climate outcomes, a number of land use change scenarios utilizing the SLEUTH program were developed. The analysis first examined past changes in urban land cover and then applied these trends to construct a range of scenarios for future land use changes in the NYMR for the years 2020 and 2050. The researchers used both the SLEUTH UGM and LCDM programs and a set of land use and land cover data from the 1960s–1990 to create the scenarios of land use/land cover change. Before future land use scenarios were generated, model results for the 1960–1990 period were compared against observed data of land use change for the same period in order to validate the model structure.

2.1. SLEUTH growth protocol

Executing the SLEUTH model entails running a series of Monte Carlo simulations, where the initial conditions (input data) and starting coefficients are reset at the beginning of each simulation. There are five coefficients, each of which may have a value between 1 and 100, inclusive. The five coefficients are:

1. *Dispersion*. Controls how many times to attempt spontaneous urban growth.
2. *Breed*. Probability of a spontaneous growth cell to become a spreading center.
3. *Spread*. Probability that any cell in a new spreading center will have another neighboring cell urbanized.

4. *Slope*. Affects the probability that a cell will be urbanized based on the percentage slope.
5. *Road gravity*. Controls the maximum search distance to find a road near a selected cell.

A single simulation is composed of a number of growth cycles, where a growth cycle represents a year of growth. A growth cycles begins by setting the coefficient values, applying growth rules, and finally evaluating the growth rate to determine if self-modification of the coefficients are to be performed. Each of the growth rules is affected by the coefficient values set at the beginning of a growth cycle, as well as the slope, land cover (in the case of the LCDM), and exclusion data layers (e.g. land such as parks that cannot be developed). The growth rules are applied in the following order:

1. *Spontaneous growth*. Simulates the random urbanization of the land, is controlled by the dispersion coefficient. It directly affects the number of times a pixel will be selected at random for possible spontaneous growth. An increase in the dispersion coefficient results in a more diffuse pattern of urban growth.
2. *New spreading centers*. Simulates the development of new urban areas, is controlled by the breed and slope coefficients. A random value is generated for each newly urbanized cell from the previous step. If the value is less than the breed coefficient, up to two neighboring cells will be urbanized, dependent on availability and topography (slope). An increase in the breed coefficient will result in more spreading centers, while an increase in the slope coefficient will result in higher resistance to growth as the measured slope in the input data layer increases.
3. *Edge growth*. Simulates infilling around new and existing urban centers, is controlled by the spread and slope coefficients. For each interior urban cell, if a generated random value is less than the spread coefficient, and two of its neighbors are also urban, then, dependent on availability and topography, a non-urban neighbor will be urbanized.
4. *Road-influenced growth*. Simulates the transportation layer's influence, is controlled by the dispersion, breed, slope and road gravity coefficients. For newly urbanized cells, if a generated random value is less than the breed coefficient, and if a road is found within a maximal radius (determined by the road gravity coefficient), a temporary urban cell is created on the road nearest the selected cell. This temporary urban cell conducts a random walk along connected roads. The length of the walk is determined by the dispersion coefficient. The final location of the temporary urban cell becomes the location of a new spreading center, and up to two neighbors are urbanized.

LCDM simulates land cover change as a result of urbanization, and is an optional additional component of the SLEUTH program. The Land Cover Deltatron Model simulates urban expansion produced in the UGM onto the landscape and other land cover or land class changes via a transition matrix. A basic distinction between LCDM and UGM, besides the use of differing land use data sets (UGM uses a simple binary urban–non-urban data set and LCDM uses a land cover data set), is that the Deltratron Model can define cell as harbingers of change. More specifically, it utilizes data on land conversion among the cells surrounding a specific cell from previous growth cycles (i.e. years) to define change probabilities of that specific cell.

Overall, the LCDM operates as follows:

1. *Initiate change*. *n* Transitionable cells (non-urban, non-water, non-deltatron) are selected at random, where *n* equals the number of newly urbanized cells created in the UGM. A probability of transition is then computed based on the weighted average slopes for each land class type, the historical land class changes, and the slope of the current cell. If a transition does occur, a new deltatron is created.
2. *Create change cluster*. Neighboring cells of the new deltatrons are randomly selected and tested for transition. The cell can only change to the same land class as the associated deltatron or remain unchanged.
3. *Propagate change*. All non-deltatron cells that are neighbors to at least two deltatron cells that were created in the previous year are tested against the same weighted probability of transition to one of the neighboring deltatron's land class type.
4. *Age the deltatrons*. All deltatrons are aged one year, if they exceed a user set age, they 'die' and can potentially again become new deltatrons in the next year or a following year.

For both the UGM and LCDM, SLEUTH also maintains an optional self-modification protocol. Self-modification (if used) alters the dispersion, breed, and spread coefficient values to simulate accelerated growth (boom condition) or depressed growth (bust condition). At the end of a year, the amount of growth is compared to a set of limits (critical_high, critical_low). If the amount of growth exceeds the critical_high limit, the three coefficients are multiplied by a value greater than one, increasing growth. If the amount of growth is less than the critical_low limit, the three coefficients are multiplied by a value less than one, depressing growth. The coefficient changes take effect during the next year of growth. The critical_high, critical_low, and multiplier values for boom and bust are defined in a scenario file.

Within the basic SLEUTH program, one also can define several additional growth parameters. For example, one could adjust the slope layer making urban growth on lands with varying slopes more or less likely. In this study presented here, the transportation layers were modified to use a weighted classification. Main thoroughfares (limited access roads), interstate highways and state roads were given a value of 100. Secondary roads were given a value of 50, while non-road cells had a value of 0. These weighted roads, and the original non-weighted roads were used in separate calibration sets with both the boom and bust cycle turned on and the boom and bust cycle turned off.

In Section 2.2 below, we present details of the calibration process and the results of the scenarios which performed the best during validation. The weighted roads, with the boom-bust off, scenario was defined as the most valid.

2.2. Model calibration

The SLEUTH program requires several data sets in order to calibrate the models. Of primary importance are coverages of past land use and land cover. SLEUTH requires a minimum of four land use coverages (which distinguish between urban and non-urban land) and two land cover coverages (defining the Class 1 Andersen categories of urban, agricultural, forest, grassland, wetland, water, and barren land). In this analysis, four land use coverages (1960, 1970, 1980 and 1990) and two land covers (1975 and 1992) were utilized. The data were calibrated to a 70 m resolution. Other required surface data coverages included the slope, transportation (i.e. road networks at least at two time periods), hillshade, and exclusion areas (typically defined as existing park and other conservation land). Fig. 1 show the shift in urban land extent from 1960 to 1990 and the relative location of the region's road network.

The SLEUTH model must be calibrated to the unique characteristics of the study area. This is accomplished by determining the appropriate control parameters, or coefficients, that affect the growth rules of the model. The model simulates growth over the range of known historical data, comparing the historical data to simulated growth. The starting coefficients are measured using Pearson r^2 statistics generated during calibration. Once a set of 'best fit' coefficients are found, a final prediction run

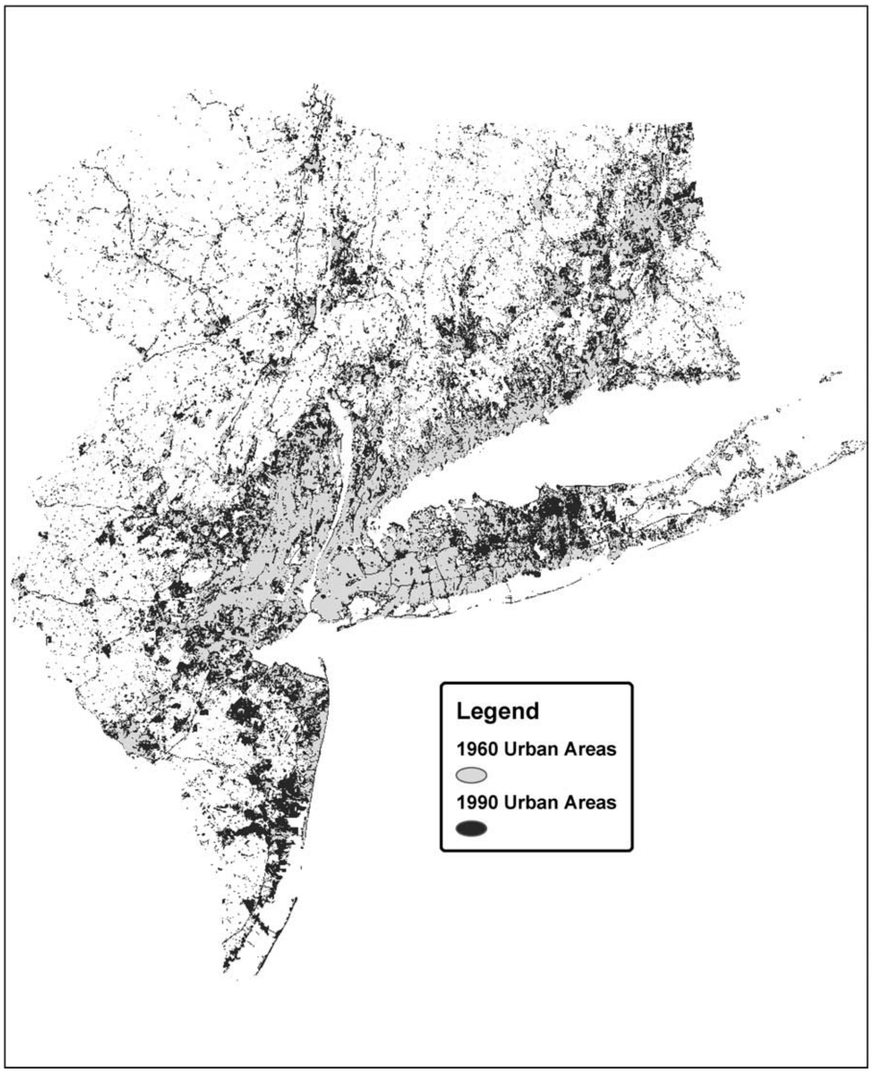

Fig. 1. Illustration of the 31 county New York Metropolitan Region showing the historical urban extent 1960 and 1990 and roads in the 1960 and 1980 (the most recent available).

over the historical data using those starting coefficients is performed. The resulting log file is examined to determine the starting coefficients for prediction into the future.

We score each set of coefficients by calculating the product of several key statistics generated during calibration. The selected statistics are:

1. *Compare*. The modeled population for final year/actual population for final year, or if $P_{\text{modeled}} > P_{\text{actual}}$, then $1 -$ (modeled population for final year/actual population for final year).
2. *Pop*. Least squares regression score for modeled urbanization compared to actual urbanization for the control years.
3. *Edges*. Least squares regression score for modeled urban edge count compared to actual urban edge count for the control years.
4. *Clusters*. Least squares regression score for modeled urban clustering compared to actual urban clustering for the control years.
5. *Mean_cluster_size*. Least squares regression score for modeled average urban cluster size compared to actual average urban cluster size for the control years.
6. *Leesalee*. a measurement of spatial fit between the model's growth and the known urban extent for the control years.

The highest collective coefficient score was selected as the best fit calibration. Within the SLEUTH user group community there has been extensive discussion regarding how to interpret the coefficient values and their relative importance. (Candau, 2002 and http://www.ncgia.ucsb.edu/projects/gig/project_gig.htm website for more general information about the SLEUTH program).

2.3. SLEUTH results for the New York metropolitan region

The results of the UGM and LCDM modeling illustrate that there could be significant land use and land cover change in the NYMR during the first half of the 21st century Given the past rate of development, the vast majority of remaining developable forest and agricultural land in the region, excluding protection areas such as parks and wetlands or steep slope zones, will be built-on by the 2030s. The current peri-urban suburbs become fully developed. The UGM results state that from 1990, 950, 379 ha will be converted from non-urban uses to urban by the year 2020 and a total of 1, 162, 695 ha by 2050 (Fig. 2a). This represents a loss of 47% and 67%, respectively, of the total non-urban land present in 1990. If one excludes conservation lands existing in 1990 and lands with relatively steep slopes, which are difficult to build on, the urban land conversion represents a far greater percent of non-urban land loss. The rate of conversation slows significantly during the 2020–2050 period because the number of available sites (i.e. pixels) for spontaneous and new breeding centers becomes limited and instead an increased proportion of the new growth takes place as slower edge growth or transportation corridor related growth.

The LCDM results illustrate a very similar process (Fig. 2b). The LCDM results state that 1,580,458 ha will be converted from non-urban uses to urban by the year 2020 and a total of 1,785,770 ha by 2050. This represents a loss of 60% and 80%, respectively, of the non-urban land present in the 1992 land cover data set used by the LCDM. It should be noted that the absolute amount of urban land conversion vary for UGM and LCDM because the baseline data of urban land extent was different for each model (the UGM uses a GIS layer which distinguishes between urban and non-urban land for 1990; while the LCDM uses a US Geological Survey land cover GIS layer for 1992 which distinguishes the primary Andersen land use classes (i.e. urban, agriculture, grazing, forest, water, wetland, and barren).

In both models, the overall spatial distribution of the urban land conversion is similar. Projected rapid conversion takes place where significant conversion had occurred during the period 1960–1990 and where the development potential was high (e.g. areas with relatively flat terrain, access to highways, etc.). As a result, conversion was particularly extensive in eastern Long Island and central New Jersey. The more mountainous and isolated northern parts of the region incurred less development during the study period.

3. Using emissions scenarios as land use change protocol

A key objective of the New York Climate & Health Project was the definition of several scenarios of future climate and land cover conditions. In response to the project demand for several land cover conditions, a set of land use change scenarios were created. It was important for the larger project that land cover conditions associated with more rapid land use conversion, and less rapid land use conversion were specified. The objective was to determine what impact these differing qualities might have on the regional climate conditions, and in turn on the regional air quality and associated public health impacts. In the analysis, the IPCC SRES (Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios), A2 and B2 regional GHG emissions scenarios (in comparison to the A1 and B1 global scenarios) were used as the meta-narrative to define future regional development patterns and associated land use change.

The IPCC has been a source of numerous influential reports on the state of climate change and climate change impact science since 1990 (see http://www.ipcc.ch/ for more information). In 2000, the IPCC produced the Special Report on Emissions Scenarios (SRES) that presented two narratives detailing possible regional (i.e. continental-scale) emission futures. One narrative describes the situation of increased rates of CO_2 emissions, derived from a variety of developed and developing country sources. For example, the A2 scenario is associated with increased automobile dependence and greater reliance on fossil fuels as a source of energy. The A2 scenario can be generally described as a pessimistic future. The alternative scenario includes conditions under which CO_2 emissions are steadily reduced throughout this century, and focuses on a conversion to alternative sources of energy and a focus on sustainable lifestyles. The B2 scenario is commonly described as an optimistic future.

A multi-step process was developed to translate the A2 and B2 scenarios into SLEUTH defined modeling experiments. First, the broad narrative of each scenario was examined within the context of metropolitan growth and change in developed country settings such as the New York Metropolitan Region. From these narratives, specific growth parameters were defined in the second step of the process.

It is important to state that the A2 and B2 scenarios did not detail specifics, but instead focused on potential trends of key drivers of GHG emission (e.g. pattern and intensity of metropolitan region land development) that were applicable to conditions in urbanized regions. From these broad descriptions of change, the researchers in this study developed narratives of potential change in the NYMR. They are as follows:

A2 Scenario. Overall there will be rise in per capita land use conversion and per capita automobile vehicle miles traveled in the NYMR. Road corridor growth and growth associated with new suburban, peri-urban employment centers will become increasingly important drivers of land use/land cover change. These new centers will be more often located in agricultural and forested areas than in existing suburban areas as had been the case in the recent past. A new loop highway will be built approximately 75 km from the region's center (i.e. mid-town Manhattan).

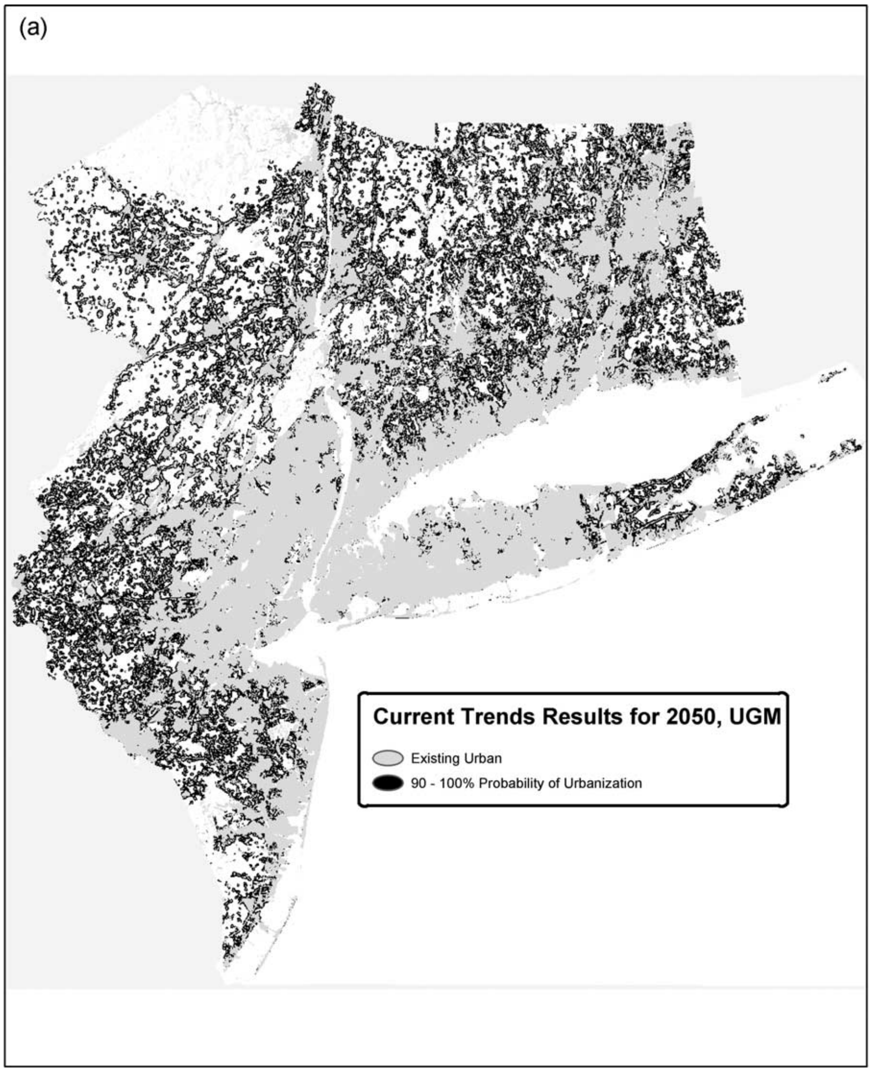

Fig. 2. (a) Current trends results for 2050, UGM Output. Illustration of the 31 county New York Metropolitan Region showing the predicted urban extent for the year 2050. (b) Current trends results for 2050, LCDM Output. Illustration of the 31 county New York Metropolitan Region showing the predicted urban extent for the year 2050.

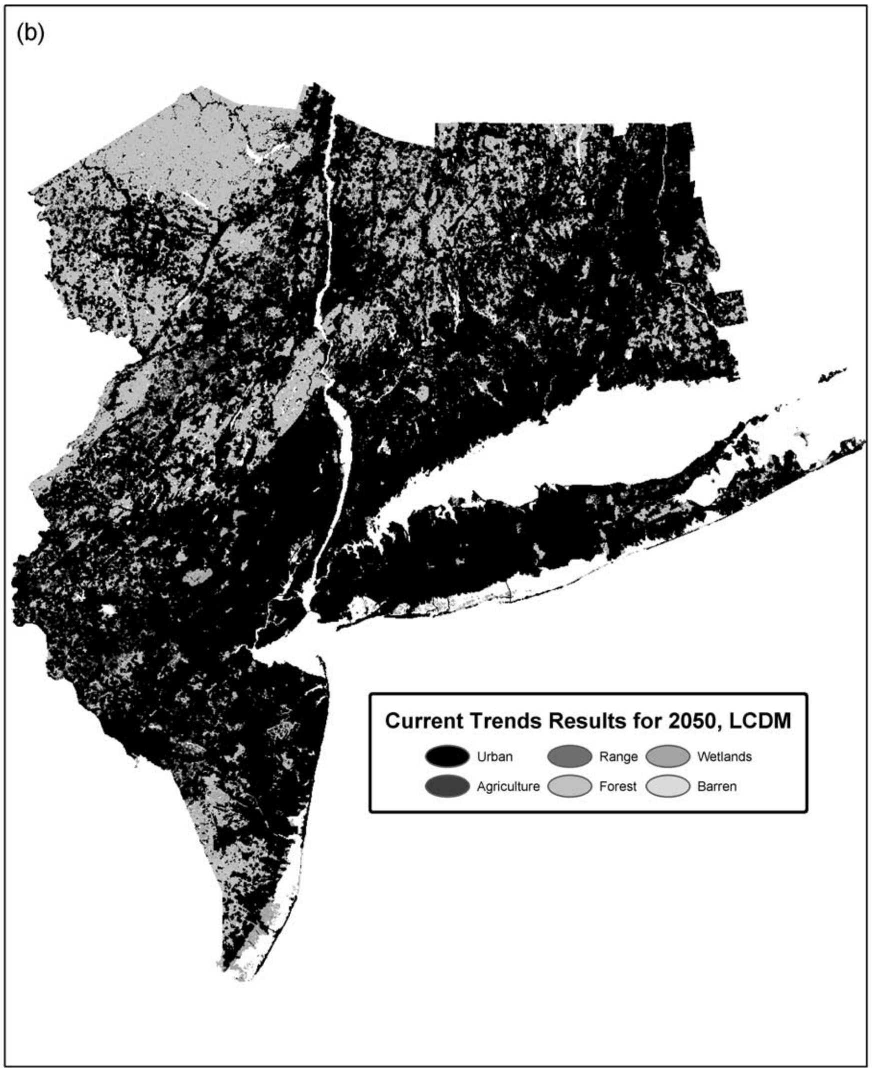

Fig. 2 (*continued*).

There will be minimal infilling and minimal increase in existing urban and/or suburban densities. A small amount of urban land abandonment and conversion of land from urban industrial/commercial/residential land use to green space (e.g. weed filled lots) will take place (Note: SLEUTH as currently constructed cannot illustrate the conversion of urban land to non-urban land (green space).

From this A2 Scenario narrative, a set of potential future growth parameters were defined:

1. New growth centers as sites of new residential and employment growth;
2. New limited access highway loop road throughout the ex-urban part of the region;
3. Increased road corridor growth and growth associated with new suburban, peri-urban employment centers;
4. Minimal infilling and minimal compact growth.

B2 Scenario. Overall there will be a decrease in per capita land use conversion in the NYMR, as well as a decrease in per capita automobile vehicle miles traveled. Road-influenced growth will continue to be important along certain existing corridors, however, no new roads will be built. The use of public transportation will increase, encouraging growth along railroad corridors. There will be minimal spontaneous growth, as well as fewer new spreading centers. Increased rates of infilling, compact growth and edge growth will take place in existing urban and/or suburban areas, especially in areas where sprawl already has taken place. Conservation buffers between existing urban/suburban areas and rural, environmentally sensitive areas will be created. Environmental resources protection will be enhanced through the rezoning of large contiguous areas of land, and active re-greening and afforestation.

A set of B2 scenario growth parameters also was defined. The parameters include the following:

1. Increased growth along public transportation corridors;
2. Minimal spontaneous, leap-frog sprawl growth;

3. Infilling, compact growth, and edge growth;
4. Increased protection of environmental resources;
5. Active re-greening and afforestation.

A critical question not addressed in the scenario narratives was the shift in the absolute amount of land conversion. While it is clear that the A2 scenario would be associated with a greater amount of conversion, and the B2 scenario with a lower amount of conversion, the relative percentiles were not defined in the narrative development process. After reviewing literature on the expected impact of land conservation strategies (e.g. growth management policies) and on highway development impact (and other activities associated with more rapid land conversion), it was decided that an overall growth variance of $\pm 20\%$ was an appropriate range to define. Therefore, the A2 scenario would be defined as having 20% more conversion than the current trend projection, and the B2 scenario would have 20% less conversion than the current trend projection.

The final step in the process was to translate the scenario growth parameters into specific SLEUTH program applications. For example, a decrease of the amount of edge growth was determined to be an effective way to minimize the amount of infilling as specified by the A2 scenario. In most cases, either data layers conditions were changed (e.g. the exclusion layer values were altered or new computer code was added to define the scenarios. SLEUTH open source code facilities the addition of new code and associated algorithms. See Table 1 for an overview of each scenario and the necessary model adjustments. Details of this application for each scenario are presented below.

3.1. A2 Growth scenario

Three steps were performed to produce the A2 growth scenario. First, a new transportation layer for the year 2015 was created from the 1980 transportation layer. A new ring road at a radius of 75 km from New York City was placed into this layer. Using existing highways and through roads, this new major roadway arced from Trenton, New Jersey to Bridgeport, Connecticut.

Table 1
Growth scenarios and SLEUTH modeling adjustments

A2 Growth scenario	
New Growth	Increased breed and spread coefficients
New limited access highway	New transportation layer for 2015 with ring road added
Increased road corridor growth	Highways given increased weighting
Minimal infilling	Dynamic exclusion layer increases percent exclusion around existing urban centers
B2 Growth scenario	
Increased road corridor growth	Highways given increased weighting
Minimal spontaneous growth	Dispersion and breed coefficients decreased
Increased infilling	Dynamic exclusion layer increases percent exclusion around large non-urbanized areas
Increased protection of environmental resources	Increased percent exclusion of protected areas in exclusion layer

Second, to encourage the development of more spreading centers away from existing urban areas, code was added to the UGM to generate a dynamically changing exclusion layer which increases the percentage of cells for exclusion the closer they are to urban areas. The code works by examining each cell of the exclusion layer and base urban layer. An $n \times n$ window centered over each urban cell is examined for urban fill and the exclusion value of the corresponding cell in the exclusion layer is adjusted accordingly. The greater the fill ratio, the greater the increase in the exclusion value will be. This effectively discourages growth near existing urban areas. The new exclusion layer is generated before the start of the first growth cycle. The percentage of exclusion of the modified cells in the exclusion layer is reduced by an equal amount in 10 year intervals until they have returned to their initial (unmodified) values.

Finally, the dynamic exclusion layer defined in step two was found to depress overall growth, therefore it is necessary to modify the coefficients such that the appropriate amount of growth occurs. In this case, the desired amount was 20% more conversion (or approximately 0.61% increased growth per year) for the years of interest 2020 and 2050 than defined in the initial growth simulation based on past trends.

3.2. B2 growth scenario

Two steps were performed to produce the B2 growth scenario In order to encourage growth near existing urban areas and discourage growth in large, open areas, code was added to the UGM to generate a dynamically changing exclusion layer that increases the percentage of exclusion of cells the further away they are from urban areas.

The code works in much the same way as that of the A2 scenario. A window centered over each urban cell is examined for urban fill and the corresponding cell in the exclusion layer is adjusted based on the fill ratio. For the B2 scenario, the key difference is that the lower the fill ratio, the greater the increase in the exclusion value will be. Growth will take place primarily near existing urban cells, where there is little to no increase in the level of exclusion.

As in the A2 scenario, it was found that the dynamic exclusion layer depressed overall growth beyond the desired goal of 20% reduced growth. It was necessary to modify the coefficients such that the appropriate amount of growth would occur over the predicted years.

3.3. A2 and B2 scenario-based land use modeling results

The A2 and B2 Scenario-based land use modeling experiments were successfully constructed. The results of the UGM model for each scenario illustrated two widely divergent patterns of growth (Fig. 3a and b). While both scenarios represent significant landscape transformation, the A2 scenario as designed showed more significant conversion than the extrapolation of current trend model and the B2, 'smart growth'—type scenario. The A2 scenario illustrated a dramatic increase in the amount of urban land use and decrease in the amount of agricultural and forest land during the study period. The B2 scenario reflected a much slower process of urban land conversion and corresponding slower decline in the amount of agricultural and forest land (Table 2).

As with the current trend scenario, in both the A2 and B2 scenarios rapid conversion is projected to take place. In a closer, sub-regional analysis however, it is evident that the A2 and B2 scenarios maintain distinct spatial patterns of growth in response to the specified growth protocols. The A2 scenario is characterized by extensive growth throughout much of the region except areas that are at very high slope and/or very remote. In the case of the B2 scenario, urban land conversion is concentrated as infill development adjacent and/or within pre-existing heavily urbanized areas. Overall, however, in both cases conversion is particularly extensive in eastern Long Island and central New Jersey and less in the more mountainous and isolated northern parts of the region.

4. Discussion and conclusions

In keeping with the structure of the New York Climate & Health Project, the results of the completed land use change scenarios became part of the foundation for the next stage of analysis The results served as input for a remote sensing specialist, who will use the change in the areal extent of urban land to redefine the estimates of the surface

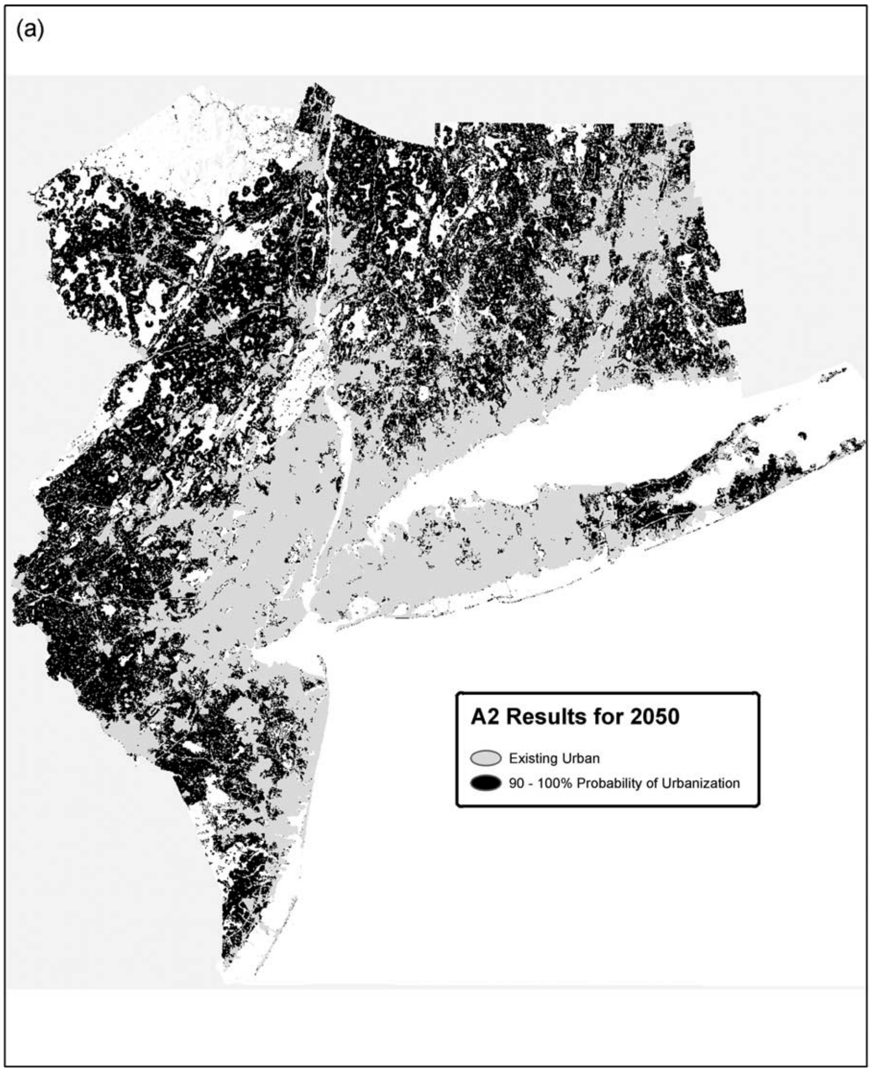

Fig. 3. (a) A2 Results for 2050, Urban Extent. Illustration of the 31 county New York Metropolitan Region showing the predicted urban extent for the year 2050 using the A2 scenario. (b) B2 Results for 2050, Urban Extent. Illustration of the 31 county New York Metropolitan Region showing the predicted urban extent for the year 2050 using the B2 scenario.

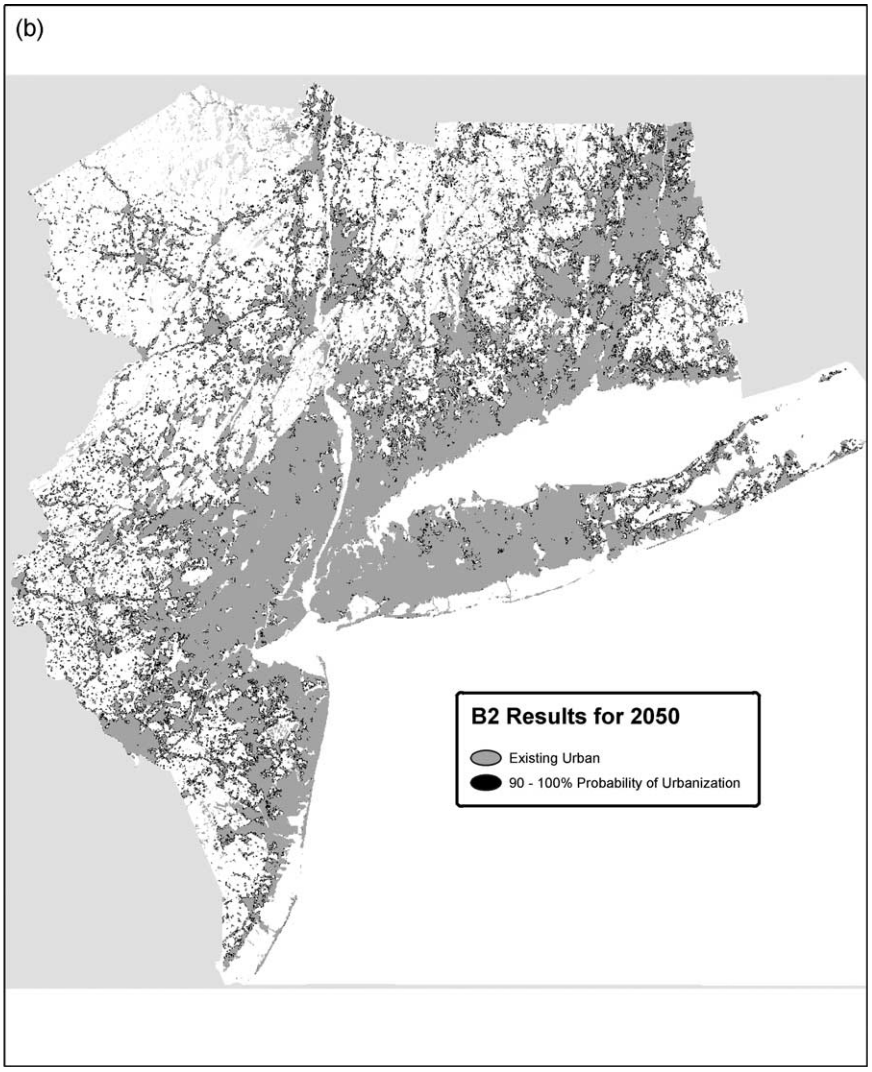

Fig. 3 (*continued*).

characteristics of the NYMR landscape. The results of the three basic scenarios (current trend, A2, and B2 scenarios) are to be utilized.

The reconfigured landscapes will be analyzed to calculate the future vegetative fraction, albedo and soil moisture properties of the region. These revised surface condition measures then serve as input into the regional climate models and air quality models, the next phase of the project study. The initial results of this analysis indicate that the difference in urban extent and, in turn, in the vegetative fraction could have a significant impact on possible future air quality conditions in the New York Metropolitan Region particularly with respect to ozone concentrations (Hogrefe 2003, 2004).

Overall, the modeling exercise illustrates the utility of the SLEUTH program for this type of application. Together, the downscaling of the SRES scenarios, the construction of narratives of regional development shifts, and models adjustment provided opportunities for the researchers to develop and test a set of 'best guess' approximations of what future land use conditions in the NYMR might be like. The scenario results indicate a conversion of approximately 50% of the open space land present in 1990 to urban land by 2020, and a conversion of roughly 75% of such land during the period from 1990 to 2050.

Table 2
Percent urban, agricultural, and forest land for 1960, 1990, 2020, 2050: Scenario A2 and Scenario B2 UGM results with weighted roads and boom-bust option off

	Historical data[a]		A2		B2	
	1960	1990	2020	2050	2020	2050
Urban	20.3	25.6	77.2	89.9	51.3	62.2
Agricultural	–	10.4	1.9	0.03	7.1	4.8
Forest	–	55.5	20	9.8	38.9	31

[a] 1960 data from urban extent layer, 1990 data from land use layer.

For the A2 and B2 scenario development, the multi-faceted structure of the SLEUTH program enabled the researchers to test and refine their modeling regime until it approached the desired output goals. Model adjustments, including changing the data layer properties and addition of new code, enabled the researchers to alter the pace (faster or slower), type (more diffuse or more compact growth) and location (by adjusting the spatial extent and character of the exclusion layer) of where land use change could take place.

Access to the SLEUTH source code was crucial in development of the A2 and B2 scenarios. Manipulation of the model's input parameters (coefficients) and data layers was insufficient to meet all of the goals for the scenarios. By adding the previously discussed dynamic exclusion layer code, we were able to reach our desired goals with a minimum of modification of the original SLEUTH code. Another advantage of having the source code was our ability to improve upon the existing brute force calibration method by developing a parallel genetic algorithm that drastically reduced the amount of computing time required during the calibration phase.

In this regard, future code modification work is now planned to focus on attempting to adapt the SLEUTH program to define the probability of interurban shifts, or more specifically conversion from low density urban land uses to high density urban land uses. This would be quite useful for further understanding the potential development of other regional climate changes such as urban–rural temperature regime shifts associated with urban heat islands.

5. Disclaimer

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