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# MULTI-TEMPORAL LAND USE GENERATION FOR THE OHIO RIVER BASIN

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# FINAL REPORT

# MULTI-TEMPORAL LAND USE GENERATION FOR THE OHIO RIVER BASIN

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# ABSTRACT

A set of backcast and forecast land use maps of the Ohio River Basin (ORB) was developed that could be used to assess the spatial-temporal patterns of land use/land cover (LULC) change in this important basin. This approach was taken to facilitate assessment of integrated sustainable watershed management (SIWM) planning in the ORB at various spatial scales by providing information on historical LU patterns, future LU trends, and LU legacy maps illustrating spatial and temporal changes in LULC in relation to groundwater travel time. The latter information, combined with water resource-related information on water quality, quantity and ecosystem service values, is expected to provide a quantitative basis for scenario exploration and optimization in support of SIWM over short and longer periods of time. Interest into SIWM on a watershed scale, and supporting research, has increased recently within EPA and other organizations active in monitoring water quality and quantity, water use, and watershed management planning.

The overarching purpose of this study was to develop a set of backcast and forecast land use maps for the ORB that could be used to assess the spatial-temporal patterns of LUC in this basin. The Land Transformation Model (LTM), an artificial neural network and GIS-based tool, was used to conduct this study. This tool has been designed to forecast LU changes into the future and simulate LU patterns in the past. The USGS's National Land Cover Database (NLCD) was used to develop a forecast and backcast set of GIS maps at 30-m resolution. Simulations back in time included the transformation of land into and out of agriculture, and the loss of urban LU. Backcast LU maps were generated using a training of two time periods (NLCD 2001 and 1992) with the amount of agriculture and urban change scaled to data from the USDA Land In Farms database and the US Census Bureau's decadal Year Built statistic as reported in the 2000 housing census. A recent version of the LTM (2012) was ported to a super computer and recoded to perform the backcast simulation for the ORB. A GIS was used to create spatial inputs for both models. A separate urbanization model was merged with the backcast models. Model simulations at 3-km spatial resolution were considered acceptable.

Backcast results indicated that: (1) approximately 90% of the ORB has remained in the same LULC class since 1930; (2) agriculture was the dominant LULC class from 1930 to the mid-1960s; and (3) significant amounts of agriculture have been lost over the last 60 years, largely to forest. Consequently, LU legacies should be considered in forest management plans for this basin. Forecast results indicated that: (1) metropolitan areas are likely to have the greatest amount of LU legacy locations, and (2) the spatial variability of LU legacies across the ORB is significant. Greatest LU legacies were found in areas nearest to the Ohio River proper and least LU legacies in the northwestern part of the Basin. The potential impacts of historical LUC on sensitive areas of watersheds, in particular areas that potentially recharge streams (i.e., riparian zones of permanent streams and rivers), were examined in the Upper White, the Sugar, the Tippecanoe, and the Upper Wabash River watersheds. LU persistence was found to be greater within the entirety of these watersheds than within their riparian zones (83 to 93% versus 74 to 88%, respectively), suggesting that riparian zones have a greater potential for LU legacies than upland areas. Finally, an analysis of all HUC-8s in the ORB showed that many have surpassed the regional thresholds for stream water quality health of > 10% urban or > 38% agricultural LU since 2010, most of which are located in the northern part of the Basin, and increases in urban LU and associated negative impacts on water quality are expected by 2050.

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# EXECUTIVE SUMMARY

A flurry of research in land change science over the last several years has found that historical land uses significantly shape current ecosystem structure and function. These historical land uses, often referred to as land use legacies, have been shown to affect plant community structure, animal abundances and distributions, water quality and biogeochemical fluxes at a variety of spatial and temporal scales. Historical land use transition pathways at any given location can be complex. Many areas in the Eastern United States were cleared for agriculture over a century ago, then abandoned and converted into forest; recent urban sprawl has resulted in a significant amount of forested landscapes – including the relatively recently developed forests- transforming to urban use. Knowing the extent and pattern of land use change over time can provide natural resource managers with valuable information for developing sustainable management plans.

At the same time, considerable work in land change science has focused on simulating current trends as impacts from certain futures which may require mitigation or adaptation to the effects of these land use changes. Currently, about 3-4% of the nation's land area is in urban use, and this amount of land use is predicted to grow, perhaps twice as much, by 2050. If current trends continue, how might these changes impact ecosystem structure and function?

The overarching purpose of this study was to develop a set of backcast and forecast land use maps for the Ohio River Basin (ORB) that could be used to assess the spatial-temporal patterns of land use change (LUC) in this important basin. Specific objectives of this project included: (1) quantifying land use/land cover (LULC) changes over time for the major LULC classes; (2) producing historical, future and LU legacy maps for use in GIS; (3) quantifying the spatial distribution of similarity between historical, current and future LU maps; (4) characterizing the distribution of LU and legacies in watersheds of the ORB; and (5) assessing the distribution of LU legacies in high impact surface/ground water areas within four demonstration watersheds. We employed an artificial neural network and GIS-based tool, called the Land Transformation Model (LTM), which has been designed to forecast LUC into the future and simulate LU patterns historically. The USGS's National Land Cover Database (NLCD) was used to develop a forecast and backcast set of GIS maps at 30-m resolution, the native resolution of the NLCD. Simulations back in time included the transformation of land into and out of agriculture, and the loss of urban LU (as described in the reverse direction, as the model simulates in time backwards). As in previous work with the LTM, backcast LU maps were generated using a training of two time periods (NLCD 2001 and 1992) with the amount of agriculture and urban change scaled to data from the USDA Land in Farms database and the US Census Bureau's decadal Year Built statistic as reported in the 2000 housing census.

Due to the massive size of the ORB (31,644 columns by 31,191 rows representing over $1.0 \times 10^8$ cells), a recent (2012) version of the LTM, ported to a high performance computer cluster (i.e., super computer), was recoded to perform the backcast simulation. A GIS was used to create spatial inputs for both models, including distance to urban, distance to roads, density of agriculture and slope. Calibration and validation of the model were conducted using standard land change modeling statistics reported in the literature and those developed and published by the Purdue research team. A stable neural network was achieved after about 100,000 training cycles. Backcast maps for 1930 through 1990 were produced at ten year time steps and a set of forecasts, 2010 through 2050, were also produced. A LU legacy map was generated that contained codes for LULC for each decade between 1930 and 1990. Analysis of LULC by an 8-digit hydrologic unit was performed on LULC forecast maps and summary tables of these were created along with percent area in urban and agriculture.

A separate urbanization model was merged with the backcast models. Previously published as a national scale simulation, the urbanization model uses a new spatial-temporal statistical routine that is coupled to state and national population projections and historical per capita urbanization rates. New calibration techniques used for the urbanization model were applied to the backcast simulation model.

We found that the forecast and backcast model performed adequately well at 3-km spatial resolution. Both location and quantity errors were less than 10%, at 3-km, across the ORB. Using the model, we estimated that (1) approximately 90% of the ORB has remained in the same LULC class since 1930; (2) that agriculture historically was the dominant LULC class in the ORB until about the mid-1960s when forest overtook it as the dominant LU class; and (3) significant amounts of agriculture have been lost over the last 60 years, a majority of it by transitioning into forest; and, thus, LU legacies should be considered in forest management plans for the region. With regards to historical LUC compared to current, we found that (1) metropolitan areas are likely to have the greatest amount of LU legacy locations, and (2) the spatial variability of LU legacies across the ORB is significant. We also noted that areas nearest the Ohio River proper have some of the greatest (measured in area) LU legacies and areas to the northwest have some of the least amount (measured in area) of LU legacies.

Four demonstration watersheds were selected to examine the potential impact of historical LUC on sensitive areas of these watersheds – in particular, areas that potentially recharge streams. To accomplish this, we examined LU legacy patterns in riparian zones of permanent streams and rivers in these four watersheds. We found that LU persistence was between 83 to 93% within the entirety of these watersheds, but slightly less within riparian zones (74 to 88%), suggesting that riparian zones have a greater potential for LU legacies than the upland areas of watersheds.

Finally, an analysis of all 8-digit hydrologic units in the ORB showed that many of these watersheds have surpassed what we consider as thresholds for stream water quality health (>10% urban or >38% agriculture). The distribution of watersheds that exceeded either threshold is similar; much of the northern areas of the ORB have exceeded urban or agriculture amounts that might lead to decreased stream health. Currently, 32% (38/12) of the 8-digit hydrologic units surpass 10% urban, and by 2050, more than half (64/120) will surpass this threshold. We also predict that the ORB will have 11.83% of its area in urban use by 2050, a 32% increase from the 8.98% appearing in the 2001 NLCD map.

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# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ANN | Artificial Neural Network |
| BLTM | Backcast Land Transformation Model |
| DEM | Digital Elevation Model |
| GIS | Geographic Information System |
| GWTT | Ground Water Travel Time Model |
| HPC | High Performance Compute cluster which is the cyber infrastructure used to run the backcast and forecast LTM |
| HUC | Hydrologic Unit Code |
| LIF | Land In Farms, a USDA NASS statistic that provides the total amount of land, by county and reported in acres, that is in cropland and pasture. Dates of reporting vary over time, but the USDA generally has reported on these data approximately every 5 years since 1900 |
| LTM | Land Transformation Model |
| LTM-MC | Multiple-Class Land Transformation Model (more than one class is simulated for change at each time step) |
| LTM-HPC | High Performance Compute LTM (version that runs on a HPC cluster) |
| LU | Land use |
| LUC | Land Use Change |
| LULC | Land Use/Land Cover |
| MC | Multiple-Classification output node structure used to train artificial neural networks where two or more changes are being quantified at the same time |
| MSE | Mean Square Error |
| NASS | National Agricultural Statistics Service of the USDA |
| NHDPlus | National Hydrologic Database Plus of the USGS |
| NLCD | National Land Cover Database produced by the USGS, for years 1992, 2001 and 2006 |
| ORB | Ohio River Basin |
| QSPP | Quality Assurance Project Plan |
| PCM | Percent Correct Metric which is the proportion of correctly predicted cells divided by the number of observed changes occurring between two time steps |
| QAPP | Quality Assurance Project Plan |
| SIWM | sustainable integrated watershed management |
| $t_1$ | time step number 1 or the first time step |
| $t_2$ | time step number 2 or the second time step |
| USGS | United States Geological Survey |
| USDA | United States Department of Agriculture |
| YB | Year Built, a U.S. Census Bureau housing statistic |

# 1 INTRODUCTION

## 1.1 Project Background

Historical land use/land cover (LULC) maps are useful for sustainable management and restoration planning because understanding how landscape structure and ecosystem services are linked provides valuable information about baseline (or reference condition) as well as legacy signals from the past. Land use legacy maps provide natural resource managers with information about the role that slow hydrological processes, such as groundwater travel time, have on current water quality in surface water bodies such as rivers and streams. This is especially true when management and restoration need to consider ecosystem services that are directly tied to water quality and the dynamics of the hydrologic cycle. Future land use maps assist natural resource managers to determine areas that might be under risk to land transformation and provide early warnings to them about potential deleterious impacts to ecosystems.

Interest into sustainable integrated watershed management (SIWM) on a watershed scale, and supporting research, has increased recently within EPA and other organizations active in monitoring water quality and quantity, water use, and watershed management planning. A recently (2011) initiated EPA study to evaluate integrated sustainable watershed management planning in the Ohio River Basin at various spatial scales requires information on historical land use patterns, future land use trends, and land use legacy maps illustrating spatial and temporal changes in LULC in relation to groundwater travel time. The latter information, combined with water resource-related information on water quality, quantity and ecosystem service values, is expected to provide a quantitative basis for scenario exploration and optimization in support of SIWM over short and longer periods of time. We intend to produce basin-wide maps of historical land use patterns (at decadal time steps from pre-settlement to current), future land use trends (also decadal, from current to 2050) and demonstrate the application of land use legacy maps in a small portion of the Ohio River Basin (ORB).

This effort is expected to provide information on the potential impacts of dynamic land use patterns for sustainable watershed management planning and contribute to the 'Safe and Sustainable Water Research Program' focus areas, 'Sustainable Water Resource Flows' and 'Sustainable Natural and Engineered Water Infrastructure Systems'.

## 1.2 Project Objectives

The objectives of this project are to generate land-use legacy maps for watershed management from historical and recent land-use maps for the ORB and to provide a proof of concept for the use of the land use legacy concept in a smaller watershed (e.g., within the basin such as portions of the Wabash or White River watersheds) where these patterns are likely to impact water quality. Areas with karst topography cannot be reliably modeled for groundwater patterns and are beyond the scope of this project.

Once developed, these land use legacy maps may serve as a valuable example that greatly facilitates collaboration in water resources management research and encourages undertaking of similar activities by EPA colleagues and non-EPA collaborators.

The results of this project are subject to the Quality Assurance Project Plan (QAPP) ID no W-16753-QP-1-0 (Approval date: 03/12/2012).

## 1.3 Report Outline

The rest of this report is structured as follows. Section 2 describes the planned approach as outlined in the project QAPP. Section 3 presents an overview of the data sources used in this study. Section 4 summarizes the approach used to develop the land change model simulations. Model calibration and validation approaches are presented in Section 5. Section 6 contains the results of the simulations. Our discussion of the results as related to the QAPP is provided in Section 7.

Contents of each section are summarized as follows:

2.0 Planned Approaches

We summarize the objectives of the modeling study with regards to the larger project goals. A work flow of the modeling steps is provided here.

3.0 Data Sources

Here we summarize briefly the study area and primary data sources used in the modeling and analysis.

4.0 Simulation Approach

We describe how we prepared the backcast land transformation model (BLTM) for simulating backwards in time and the land transformation model high performance compute (LTM-HPC) for the forecasts and the approach used for simulating in both directions. We describe the topology of the artificial neural network used, how GIS was used to prepare inputs and the transition rules that were applied in the Backcast version of the land transformation model (LTM).

5.0 Calibration and Validation Approach

We describe here the calibration and validation approaches used for the backcast and forecast LTM and the metrics generated for the ORB and nation (for the forward LTM).

6.0 Simulation Results

The results of the simulations for backcast and forecast LTMs are provided. These backcast summaries examine LULC change as a sequence of LULC classes (at ten year time steps between 1930 and 1990) across the entire ORB, by 8-digit hydrologic unit (i.e., watershed) and then for riparian buffers for four selected demonstration watersheds. The forecast results are examined for the ORB in its entirety and for 8-digit hydrologic units as percentage of urban and agriculture as a function of a water quality threshold.

7.0 Discussion

Our discussion presents an overview of the simulation results as related to the five main objectives outlined in the QAPP and Section 2 of this report.

# 2 PLANNED APPROACH

The Backcast Land Transformation Model (BLTM) was used to generate legacy land use maps for a large part of the Ohio River Basin (ORB), i.e., the part included into the only existing basin-wide conservation plan, the ORB Fish Habitat Partnership Strategic Plan (cf. Stark 2011).

The BLTM is based on a widely used land change model the 'Land Transformation Model' (LTM) which has been used to forecast land use change in a variety of areas around the world (US, Europe, and east Africa). The LTM model is an approach by which large-scale land use change is predicted with a Geographic Information System (GIS) and artificial neural networks. Future land use maps are also generated through to 2050 from the current year (in ten year time steps). Methods for projecting large, basin-wide land use maps with the LTM have been recently described by Tayyebi et al., (2012). The BLTM is often coupled to a Groundwater Travel Time (GWTT) model (Pijanowski et al., 2007) or a spatial-temporal summary routine that quantifies land use legacies at a point or within watersheds over time. Previous land uses are well known to influence soil quality (Foster et al., 2003), water quality (e.g., Allan, 2004), species composition (e.g., Wallin et al., 1994) and invasive ability (Brudvig et al., 2011).

The BLTM is a spatial-temporal model that uses current land use maps and historical data from the agricultural census and U.S. population to construct historical land uses. One use of this model has been its coupling to a groundwater travel time model to develop land use legacy maps. By quantifying the differences between current land use and legacy land use, a more accurate representation of linkage between LULC and current water quality is provided than by current land use alone, in areas dominated by groundwater. Historical signatures of land use impact current water quality with an extent that depends on landscape geography and should be considered in land use and watershed management planning.

Basin-wide historical and future land use projections and demonstration site legacy maps provide quantitative information about the:

1. Changes over time of the major classes of the 7 Anderson level-I land-use/cover categories (urban, agriculture, forest, shrubland, open water, wetland, and barren);
2. Historical, future and legacy land use/cover maps as digital maps for use in a GIS;
3. Spatial distribution of similarity between historical, current and future land use maps;
4. Distribution of land use legacies as a function of the surface and groundwater watersheds (riparian zones) and surface watershed subbasins and major rivers in the ORB; and,
5. Distribution of current land-use/cover patches in high-impact groundwater recharge areas (riparian zones) for demonstration. Demonstration sites are the Upper Wabash Watershed, Upper White Watershed, Tippecanoe Watershed and the Sugar Watershed.

# 3 DATA SOURCES

## 3.1 Study Area

Data used to build and validate the backcast LTM covered the entire Ohio River Basin (ORB), which included counties that wholly or partially fall within the basin borders (Figure 3-1). The ORB includes 456 counties in Illinois, Indiana, Ohio, Pennsylvania, West Virginia, Kentucky and Tennessee, the size of the area including counties is 515,818 km$^2$ (the ORB covers 421,962 km$^2$). We also selected four demonstration watersheds to examine land use legacy patterns in more detail and within the context of known human development patterns. These watersheds included: (1) the Upper White watershed, which contains much of the Indianapolis, Indiana metropolitan area; (2) the Sugar Watershed, a rural Indiana watershed that contains a lot of forested riparian zones; (3) the Tippecanoe Watershed, which has been historically a rural, agricultural watershed and the (4) Upper Wabash watershed, an agricultural watershed that is currently undergoing transitions to large-scale livestock production, all located in Indiana.


**Figure 3-1. Study area showing ORB boundaries and counties included in the simulation. Modeling was performed for all counties with land area partially or wholly within the ORB boundary**

## 3.2 Land Use Data Processing

We used the National Land Cover Database (NLCD) to obtain land use data for the ORB for 2001 and 1992 at 30-m resolution. We reclassified NLCD for both years from Anderson Level 1 to four main land use classes (e.g. urban, forest, agriculture and other classes; Figure 3-2). In order to accomplish this, the four developed NLCD classes (e.g. 21, 22, 23 and 24) were combined to create a single urban land use class. All forest (e.g. 41, 42 and 43), shrubland (e.g. 51, 52), and herbaceous vegetation classes (e.g. 51, 52) were combined to create a single natural vegetation cover class referred to as forest from here on. The agricultural land use classes included pasture (e.g. 81) and cultivated crops (e.g. 82). Urban, agriculture and forest land use classes occupied 8.90, 37.39, 51.55% of the landscape, respectively, in the ORB in 2001; however, these proportions were 8.57, 37.34 and 52.12% in 1992, respectively. Little land use change has occurred overall in the ORB between 2001-1992; however, this does not indicate to what extent different counties in the ORB transitioned from one land use class to another.

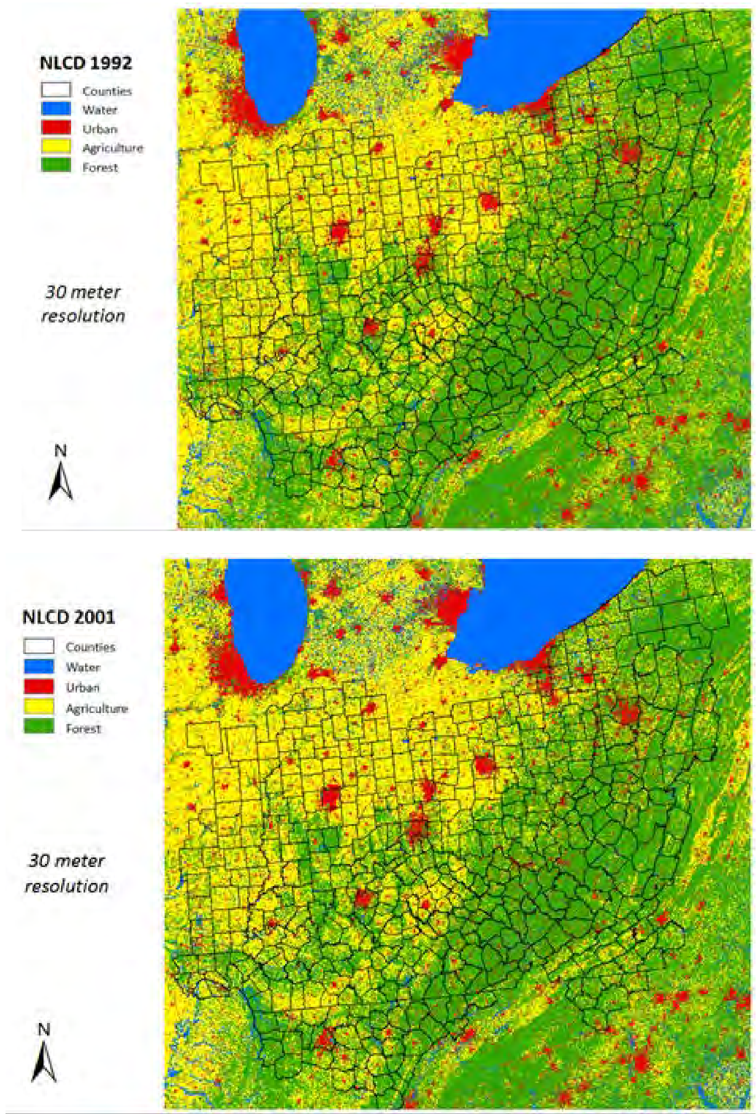



**Figure 3-2. Land use maps used for training of the Artificial Neural Network**

# 4 SIMULATION APPROACH

## 4.1 Model Inputs

We applied distance and density functions in ArcGIS10 to calculate the distance of each cell from the nearest land use category and density of land use category around (e.g. urban, forest and agriculture) the central cell, respectively. The Euclidean distance tool in ArcGIS10 was used to create separate raster maps that stored in each cell the distance from the nearest (1) urban, (2) forest and (3) agriculture cell. Focal statistics in the neighborhood tool were used to calculate the density of each main land use class around the central cell. Slope was calculated from the DEM using the ArcGIS10 Spatial Analyst tool. Spatial drivers (Figure 4-1; Table 4-1) used as input for the backcast LTM-MC simulation included: DEM, slope, distance to town, distance to road, distance to water, distance to urban, distance to forest, distance to agriculture, distance to capital, density of agriculture in 10, 50 and 250 m windows, and density of urban in 10, 50 and 250 m windows.

**Table 4-1. Drivers included in the backcast LTM and their rationale**

| Driver | Description of Rationale |
|---|---|
| Distance to nearest road | Road construction has been found to be one of the strongest drivers of urbanization in the U.S. |
| Distance to nearest town | People live and work near towns and proximity to cities, towns and villages strongly influences urbanization |
| Slope | Built environment cannot occur on steep slopes; crops are difficult to manage large scale using mechanized management. Generally, slopes > 8% are not farmed in the U.S. |
| Distance to nearest urban pixel | Previous urban cells are well known to create new urban cells in future time steps because infrastructure for urban use likely exists |
| Density of urban within a fixed window size | Urban cells tend to fill in once a certain density of this use is reached |
| Density of agriculture within a fixed window size | Large homogeneous agricultural plots are more sustainable over time |
| Distance to nearest surface water body | People like to place built structures (e.g., houses) next to lakes and rivers and are, thus, drivers of urbanization |

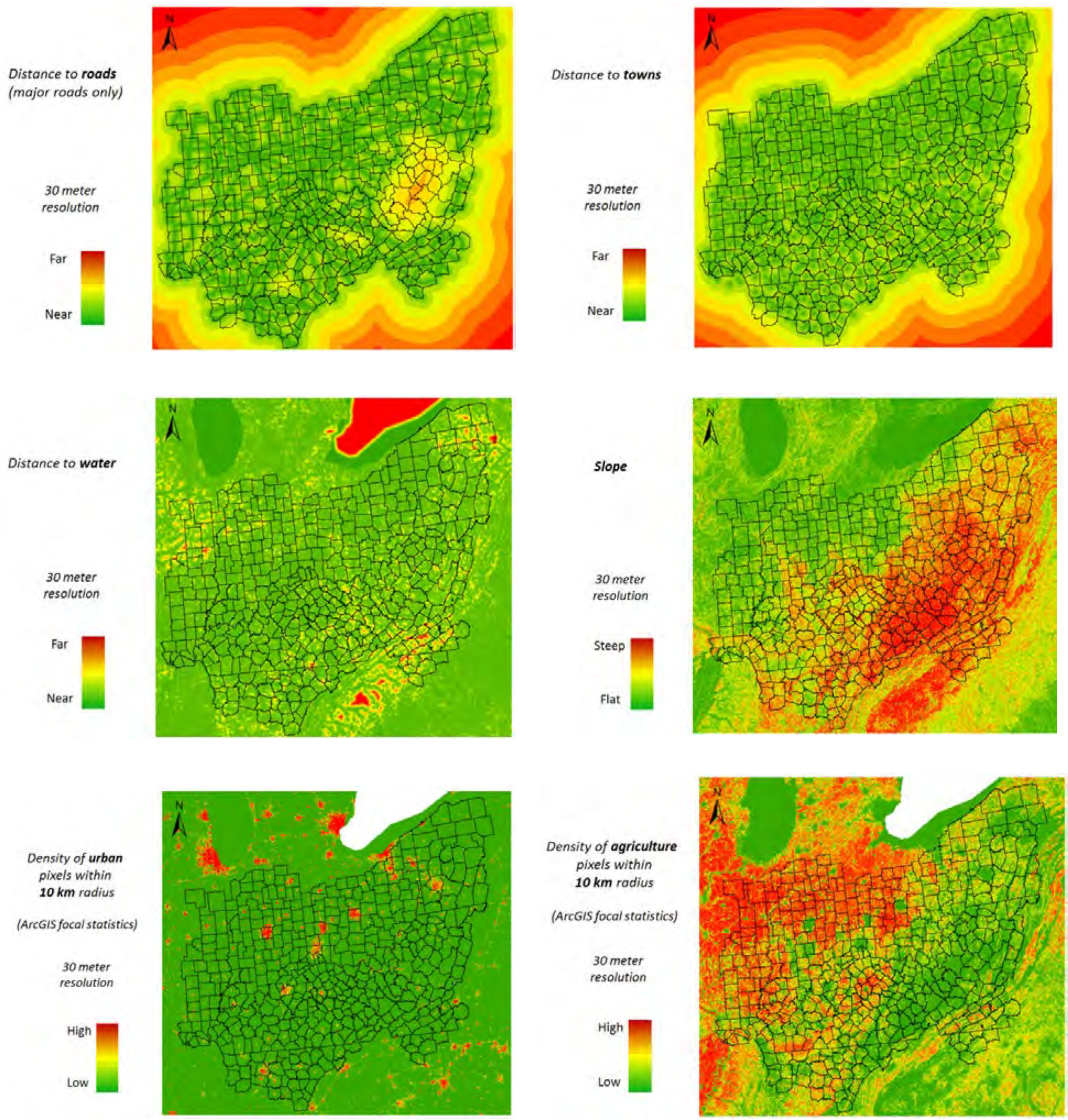



**Figure 4-1. Maps of drivers (6 samples) used for training of the Artificial Neural Network**

## 4.2 Artificial Neural Network Topology

The backcast model artificial neural network (ANN) topology includes two outputs that have been coded using two digit codes (Figure 4-2): (1) the cells that experience agriculture gain (e.g. transition from other LULC classes to agriculture) have been coded (e.g. 1, 0) as the first model outcome, (2) the cells that experience urban loss (e.g. transition from urban to other LULC classes) have been coded (e.g. 0, 1) as the second model outcome, and (3) other cells that experience other types of transitions have been coded as 0, 0.

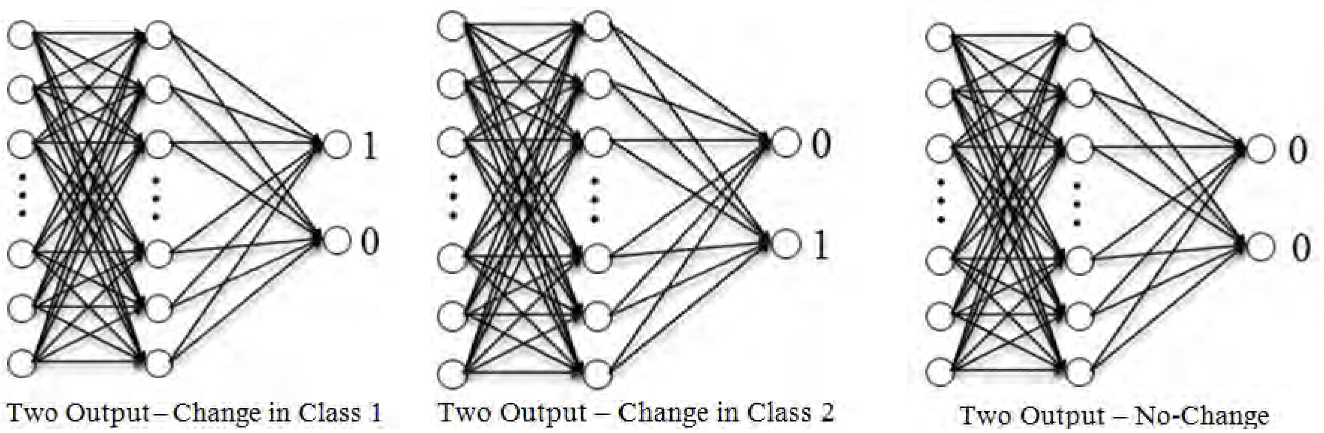



**Figure 4-2. Multiple-class output Artificial Neural Network topology illustrating the three possible outcomes for change or no change**

## 4.3 LTM Using Meso-Scale County Drivers of Urban and Agriculture Quantities

Most of the land use change models incorporate a separate module to determine the quantity of land use change and to locate the cells in the map that experience land use change properly. The drivers of change for quantity and location can differ from each other (Tayyebi et al., 2012). For example, the meso-scale subcomponents in LTM are responsible for the determination of the quantity of change in LTM, but the locations of change still have to be determined based on the suitability of the cells within the spatial units. The ANN component of the LTM is a location-based driver. The suitability map produced by the model contains the probability of cells in the region for land use change. Cells with higher probabilities are more likely to convert to land use change than cells with lower probabilities (Pijanowski et al., 2002 and 2010; Tayyebi et al., 2011).

The amount (i.e., quantity) of each particular land use was determined using county-based historical data on agriculture for the National Agricultural Statistics Service (NASS) Land In Farms (LIF) database for agricultural land use (Figure 4-3) and the Year-Built (YB) statistic (Table 4-2) of the 2000 U.S. Census Bureau Housing Data (http://dataferrett.census.gov/). The YB statistic reports the number of houses built, per county, within each 10-year census period after

1940. The NLCD and the county statistics for urban and agriculture were proportionately scaled to YB for 1992 (NLCD) and LIF for 1990, respectively, following procedures outlined by Ray and Pijanowski, 2010, and Pijanowski et al., 2010. These standardized values were then changed over time according to historical estimates of proportional changes in urban and agricultural land uses, by county, between 1930 through 1990.

**Table 4-2.Sample of year built statistics from the 2000 U.S. Census Bureau Housing Data (U.S. Census Bureau 2000). Units are houses per county.**

| County | State | Built 1939 or earlier | Built 1940 to 1949 | Built 1950 to 1959 | Built 1960 to 1969 | Built 1970 to 1979 | Built 1980 to 1989 | Built 1990 to 1999 |
|---|---|---|---|---|---|---|---|---|
| Summit | Ohio | 51890 | 20128 | 41815 | 31997 | 31537 | 19882 | 27875 |
| Franklin | Ohio | 62590 | 31277 | 74719 | 73952 | 79490 | 64208 | 78070 |
| Marion | Indiana | 69454 | 28309 | 59414 | 61713 | 57714 | 48380 | 52015 |
| Jefferson | Kentucky | 52813 | 26344 | 53711 | 51206 | 50796 | 26704 | 3607 |
| Davidson | Tennessee | 20084 | 15472 | 34148 | 42919 | 50935 | 46263 | 35359 |
| Allegheny | Pennsylvania | 188469 | 64840 | 111591 | 69263 | 61424 | 38700 | 29664 |
| Rutherford | Tennessee | 3024 | 1549 | 4165 | 6457 | 12070 | 16141 | 26714 |
| Cambria | Pennsylvania | 2420 | 7787 | 9932 | 4827 | 8830 | 4857 | 3388 |
| Hamilton | Ohio | 104533 | 30545 | 64819 | 5792 | 46385 | 29518 | 27246 |
| Williamson | Tennessee | 2303 | 896 | 1632 | 3724 | 9008 | 9785 | 19244 |
| Wabash | Indiana | 5218 | 722 | 1660 | 1553 | 1585 | 1250 | 1516 |

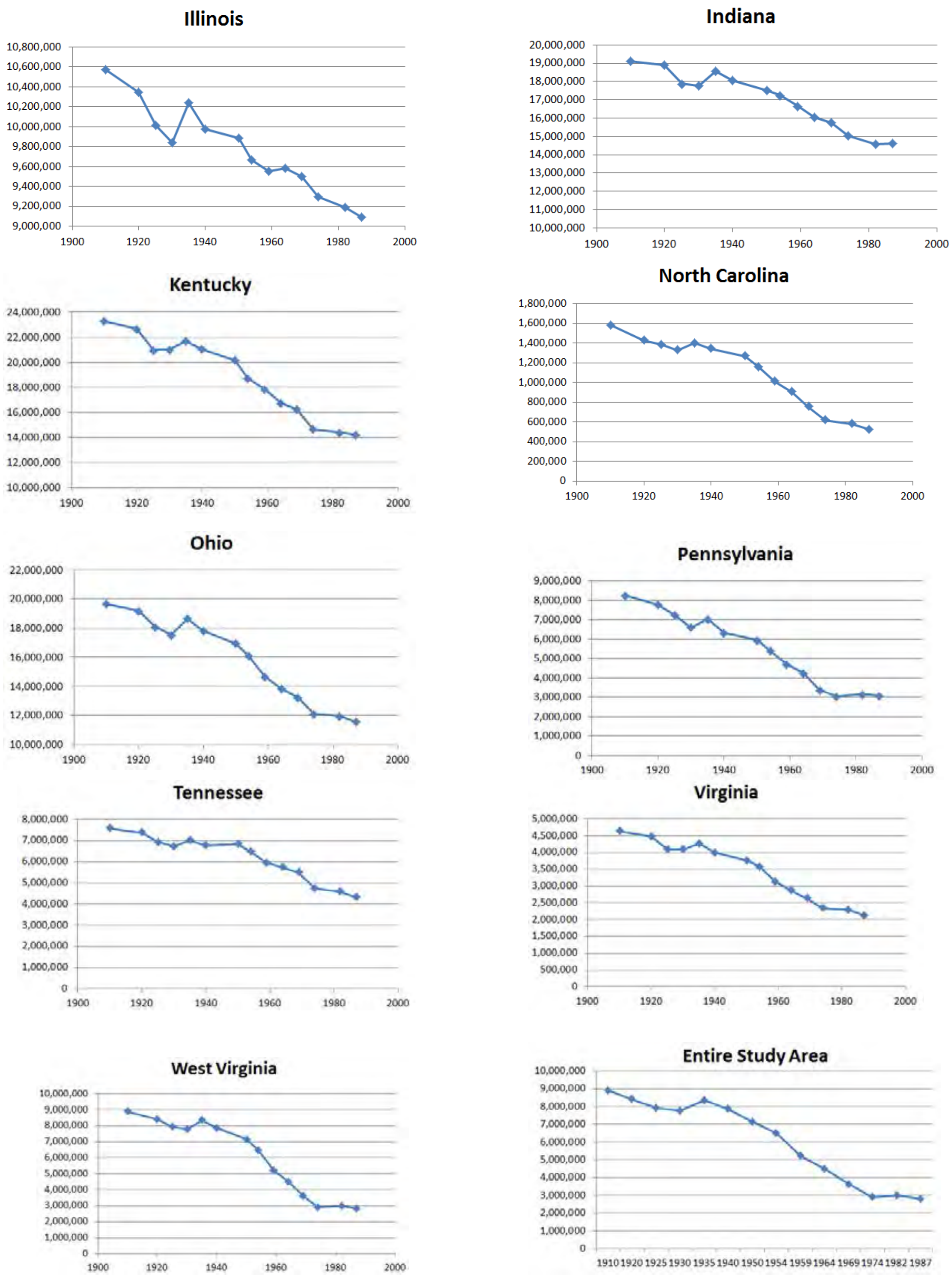



**Figure 4-3. Land in Farms statistics summarized by state (in acres, as reported by the USDA NASS (2002))**

## 4.4 Running the Backcast LTM-MC on an HPC

Scaling up a land use change simulation often requires re-engineering the model so that it may handle larger datasets. We recently redesigned the LTM for running at continental scales with fine (30-m) resolution using a new architecture that employs a windows-based HPC cluster computer (Pijanowski et al., 2014). We configured the LTM-HPC as a backcast LTM for both MC with the HPC to run the backcast LTM model at a national scale (Figure 4-4). Simulations in the forward direction occurred at the level of place polygons. Briefly, place polygons are created in the GIS using the Delany polygon routine with U.S. Census place locations (i.e., cities, town and villages) as points for inputs. The Delany polygon represents the largest area of influence for any place. Urban forecasts for these locations where made using state population forecasts from the U.S. Census Bureau following the statistical procedure outlined in Tayyebi et al., 2012. Simulations in the reverse direction occurred at the county level as historical USDA NASS (2002) and U.S. Census Bureau (2000) are distributed at this scale. In some cases (e.g., Cincinnati), metropolitan counties were merged to avoid artifacts that arise with back casting of large areas where urban/population ratios vary considerably from rural areas to inner city locations. The LTM-HPC was configured so that the ORB was split into these meso-scale regions using the GIS. ANN routines were then applied and output for each meso-scale region created. The GIS was then used to integrate these back into one ORB-wide map.

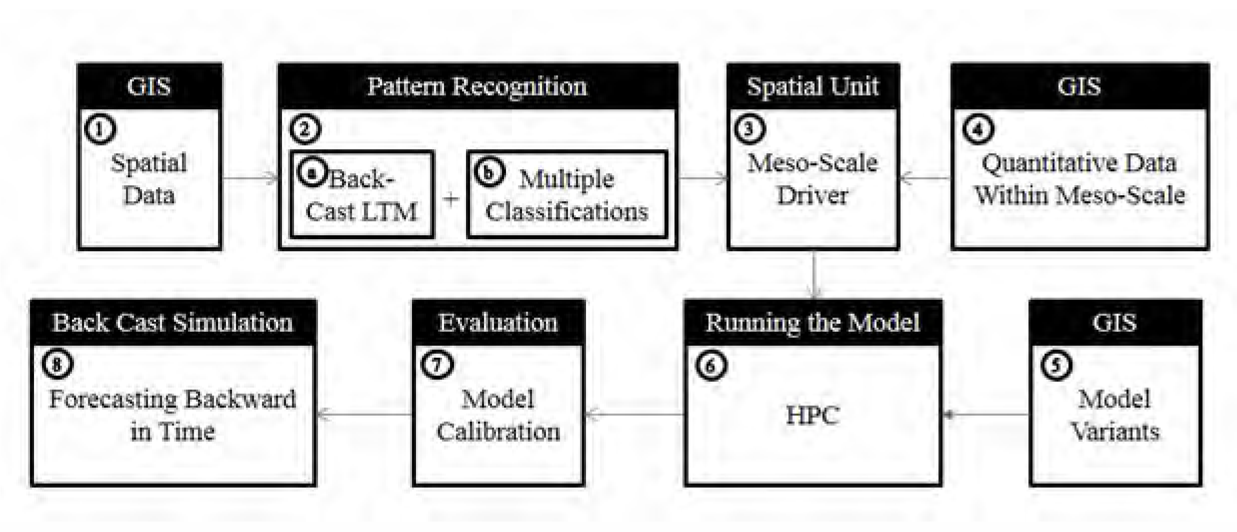



**Figure 4-4. Steps in model development and underlying technologies**

## 4.5 Transition Rules Applied

Extensive urbanization has occurred over the past decades in the U.S. for a variety of economic, technological, and population-growth related reasons (Pijanowski and Robinson, 2011). Thus, it is to be expected that urban areas decrease in backcast land transformation simulation results. Many agricultural lands have been converted into urban areas (e.g. agricultural land use loss) because agricultural land is usually conveniently located in the periphery of urban areas and forest areas have been converted into agricultural lands (e.g. agricultural land use gain) to meet the demand for agricultural goods. Thus, for a given area where agriculture can be gained or lost, there are two pathways for land use to transition in a backward manner (Figure 4-4):

> (1) Agriculture gain: Agricultural gain quantity is less than urban loss quantity within the meso-scale boundary, and urban cells at $t_1$ (e.g., 2001) are the first candidates to turn into agriculture. The urban loss suitability map exhibits the locations of urban cells expected to go to agriculture first, while the rest of the urban loss goes to forest. Thus, urban loss is equal to agriculture and forest gain in this case.
>
> However, if the total quantity of urban cells in $t_1$ cannot satisfy the quantity of agriculture gain, the rest of the cells (e.g. forest cells first) are ranked based on the urban loss suitability map and turn into agriculture cells until the total number of agriculture gain cells is met. Thus, agriculture gain is equal to urban and forest loss in this case.
>
> (2) Agriculture loss: Agriculture cells at $t_1$ are the first candidates to turn into forest, and the agriculture gain suitability map decides the locations of those agriculture cells that should go to forest first within the meso-scale boundary. The urban cells at $t_1$ could also convert into forest, with the urban loss suitability map deciding the locations of the urban cells that go to forest first. Thus, forest gain is equal to agriculture and urban loss in this case.

These model variants are exclusive, and, thus, conflicts resulting from multiple classifications are prevented (Tayyebi and Pijanowski, 2014). Because barren, open water, wetlands and shrubland are very minor LULC classes in the ORB and much of it does not change (open water, barren), we collapsed these into an umbrella “Other Class” in reporting in order to focus on the reporting of the spatial-temporal dynamics of the major LULC classes (urban, agriculture and forest) located in the ORB.

## 4.6 Training Goodness of Fit Statistics

We conducted multiple training cycles with the LTM to identify a training cycle that would generate model results that deviated to an acceptable extent from observed values. We used the MSE per cycle and followed these values during training. Briefly, MSE calculates the difference between observed change (value of “1”) and no change (value of “0”) and simulated change (value of “1”) and simulated no change (value of “0) for the entire ORB. An MSE value of 0.0 means that there is a perfect fit between the observed map of change and the simulated map of change (likewise a value of 1.0 means there is ~~not~~ a fit whatsoever between observed and predicted maps of change and no change). Early training produced an MSE of 0.182 but the MSE sharply fell after several hundred cycles (Figure 4-5). We halted the training at 100,000 cycles where the MSE reached a stable minimum of 0.172. After training the model, the entire dataset in 2001 was used to generate urban loss and agriculture gain suitability maps (a suitability map contains “probabilities” or likelihood of change). The urban loss suitability map shows that the cells around the cities have higher values, and are, thus, the first cells to be converted to other LULC classes (Figure 4-6). In contrast, the agriculture gain suitability map shows that the cells around the cities have lower values while the cells around the agriculture or close to the forest cells in 2001 are the first to be converted to agriculture classes from other LULC class (Figure 4-6). NLCD data between 2001-1992 were used to calculate and fix the amounts of urban, agricultural and forest transitions within the meso-scale boundary (areas that define place Delany polygons).

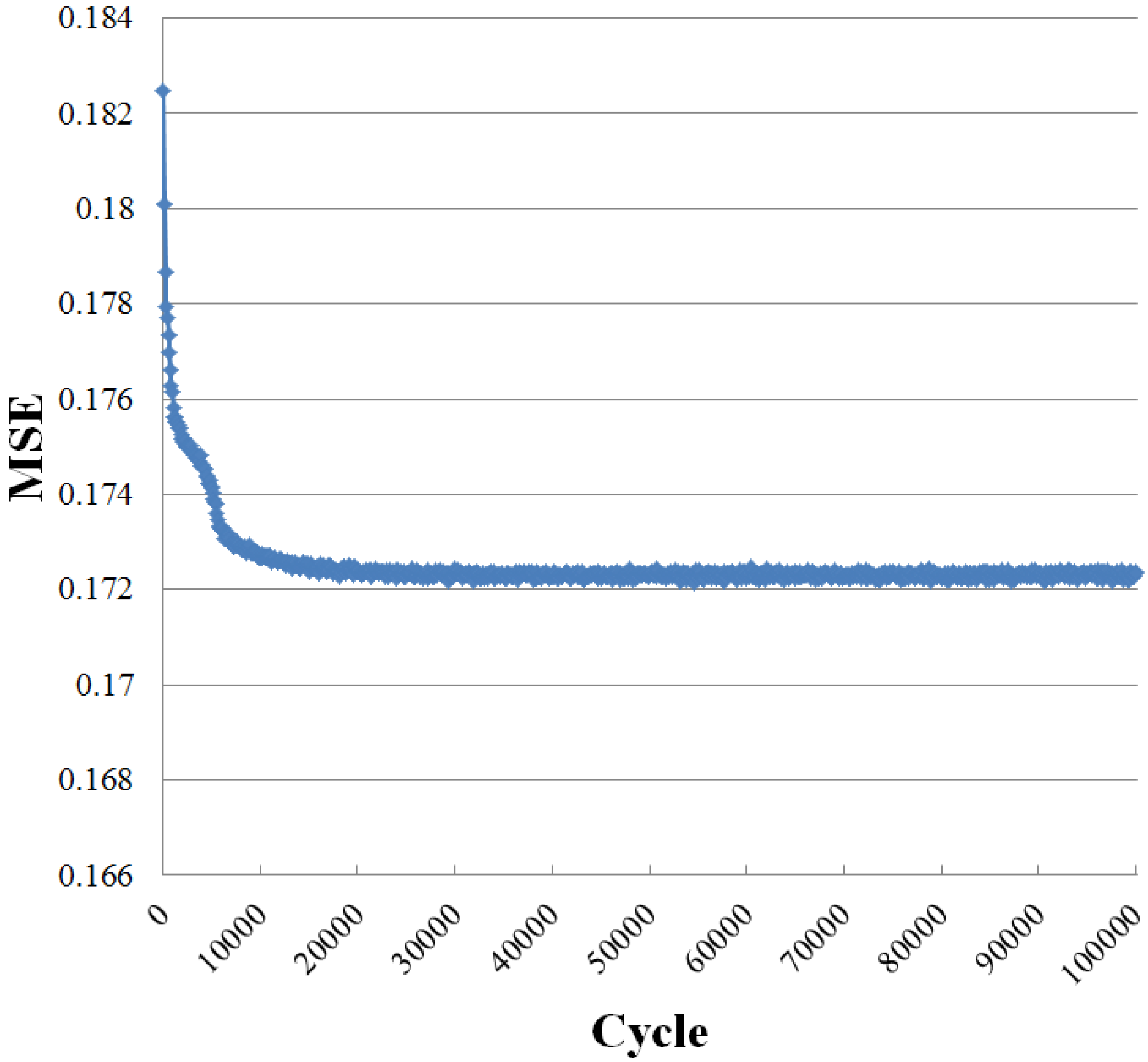
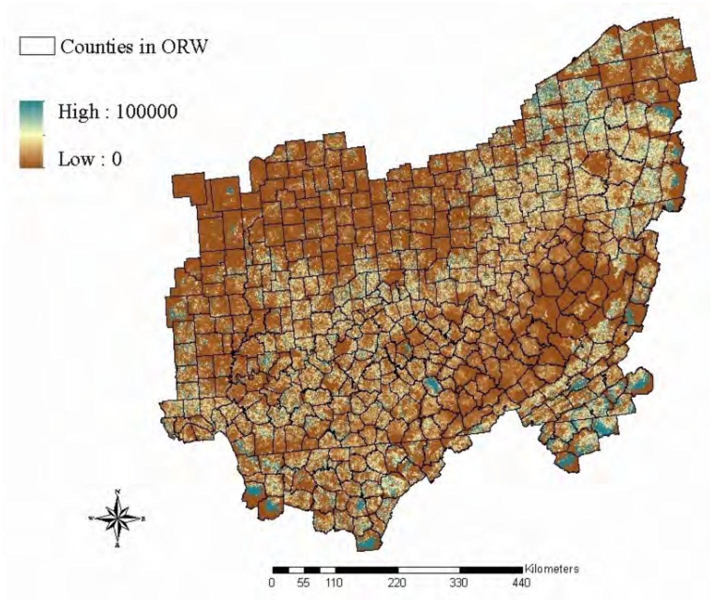



**Figure 4-5. Mean Square Error saved from training run across training cycles**



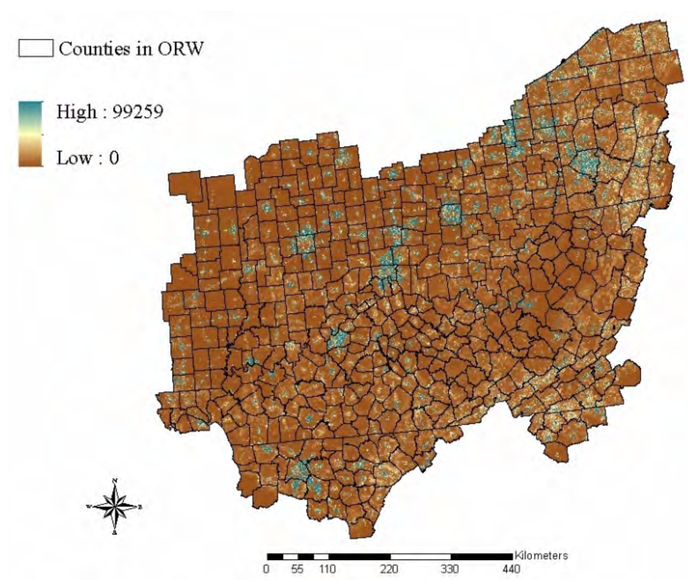




**Figure 4-6. Suitability maps produced in the training/testing phase of the modeling application: top - agricultural change; bottom - urban change. Suitability values range from 0 to 100,000 (0.0 to 1.0 multiplied by $10^5$)**

## 4.7 Hydrologic Sensitivity and Transition Pathway Analyses

We extracted the USGS National Hydrologic Database Plus (NHDPlus) hydrography for the entire Ohio River Basin and used the ArcGIS buffer command (at 150-m) to delineate riparian zones for the four study site watersheds (Sugar, Tippecanoe, Upper Wabash, Upper White watersheds). These areas are commonly (cf. Ray et al., 2012) the most sensitive areas affecting water quality in a watershed (Allan, 2004).

Land use maps from 1930 through 1990 were used to create one raster map with each cell coded with land use class sequences (e.g., a code of 44433322 represents three decades of forest, followed by three decades of agriculture and then two decades of urban). We calculated the total percentage of area falling into each possible land use transition pathway; we totaled the percentage of the watershed and riparian zone that was in the top five most common transition pathways (this followed previous work by Pijanowski and Robinson, 2011). Finally, we report the percentage of the watershed or riparian zone that did not change between 1930 through 1990 (this is termed land use persistence).

Current work by the Purdue team has determined that land use tipping points exist that significantly negatively impact watersheds or riparian zones, and that these land use category intensities should not be exceeded if stream macroinvertebrate community structure is to remain healthy. These tipping points are for watersheds >10% urban or >38% agricultural use (Pijanowski in preparation).

# 5 MODEL CALIBRATION AND VALIDATION

Model evaluation is needed to ensure that underlying patterns apply to new data (Pontius et al., 2004; Tayyebi et al., 2012) or that the model can be used for past or future predictions (Ray and Pijanowski, 2010). The model generated from the training run was applied to the entire dataset in $t_1$ to simulate LUC in $t_2$ using observed (NLCD) data between two times (1992 and 2001) as a comparison. We then merged simulated LUC maps (e.g. from reference and non-reference data) in $t_2$ to the observed map in $t_2$ to create a map of correctly and incorrectly predicted locations.

Following standard land change modeling practices, we calculated location and quantity errors from this error map (Pontius et al., 2004). Location errors exist when the model does not predict the correct cell to transition; two types of related location errors exist, omission (did not predict it to change) and co-mission (predicted it to change but in reality it did not change). We followed Pijanowski et al., (2002, 2005, 2006 and 2014) and matched omission/co-mission error pairs at 100 x 100 window sizes (3 km x 3 km) and then reported average values at 4000 x 4000 pixel window sizes (which we call a simulation tile; dimensions are 30 m/pixel x 4000 pixel length = 120 km x 120 km). The correct location prediction rates for each simulation tile are mapped in Figure 5-1. In general, the average goodness of fit for urban change ranges from 0.80 to 0.90 (80-90% accurate at 3 km).

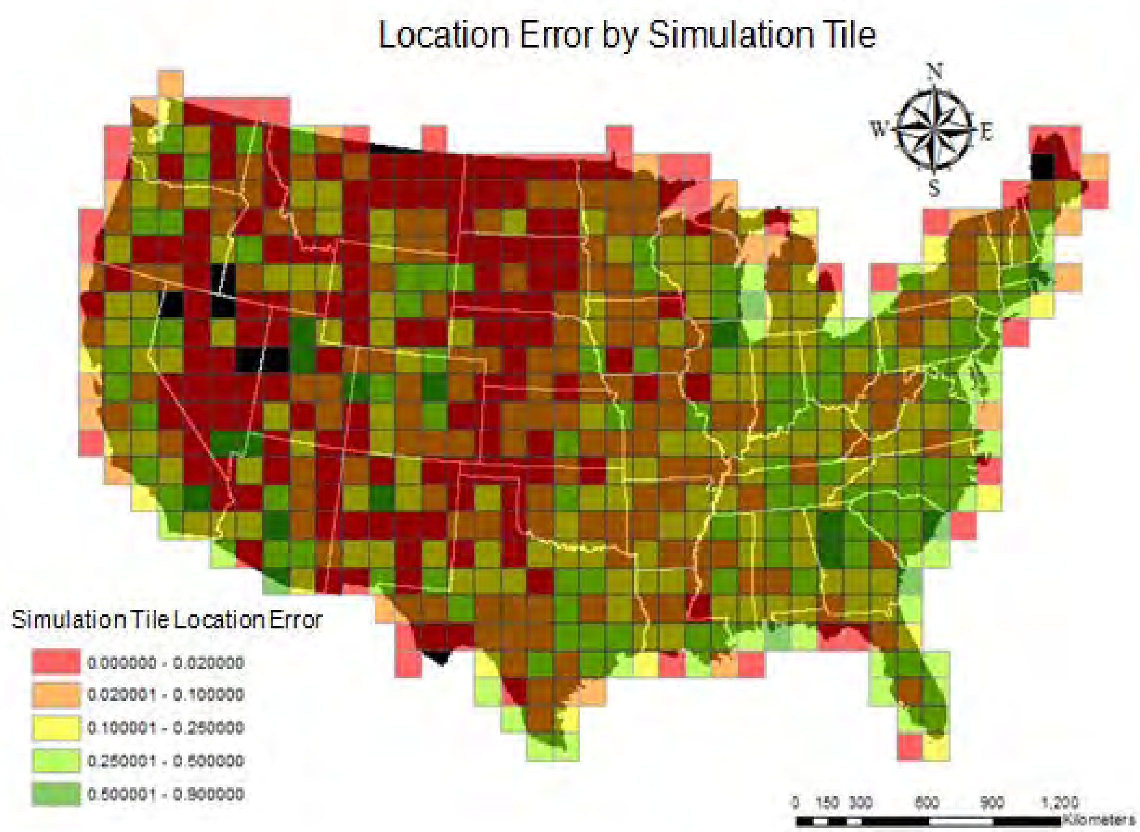



**Figure 5-1. Goodness-of-fit statistics of location-change results of the model when applied to the entire 48 states. As measure for goodness of fit the correctness, on a scale of 0 to 1, of 3 x 3 km simulation tiles relative to observed values was used**

Quantity errors exist when the model either under-predicts or over-predicts the amount for LULC change. To test the quantity error of the backcast model and determine which counties our model under-estimates and/or over-estimates for three scenarios (versions 1, 2 or 3 in Figure 5-2) with using non-reference data, we followed the steps listed below. We first compared the classified NLCD (e.g. with the four land use classes: urban, agriculture, forest and other) between $t_1$ and $t_2$ using a contingency table to generate the NLCD change map. We also compared NLCD at $t_2$ with the simulated map at $t_1$ using a contingency table to generate a NLCD simulated change map. We then used the tabulate function in ArcGIS10 to summarize the NLCD change map and NLCD simulated change map for each county in a separate table. Comparing the corresponding tables for the NLCD change map and the NLCD simulated change map enabled us to find where our model under-estimated and over-estimated each scenario within each county. After model evaluation, the model could be used for simulating past scenarios.

The quantity errors for urban change for the national simulation (see Pijanowski et al., 2014 for details) are reported and visualized in Figure 5-2, and illustrate that quantity errors for the ORB are some of the smallest in the lower 48 states. Past simulations suggest values that are less than 0.5 are satisfactory at this scale of simulation (Pijanowski et al., 2005), this is particularly important for areas where there is a lot of urban change.

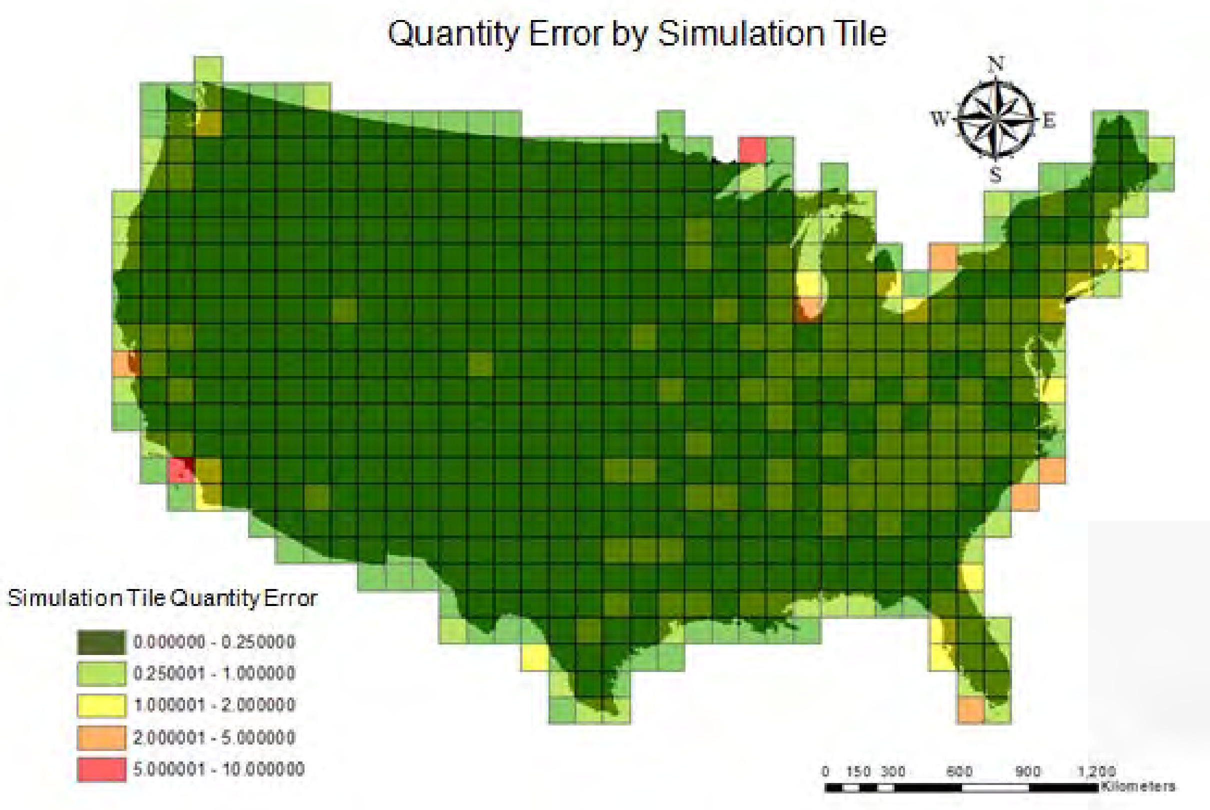



**Figure 5-2. Goodness of fit statistics of quantity-change results of the model when applied to the entire lower 48 states. As measure for goodness of fit the correctness, on a scale of 0 to 1, of 3 x 3 km simulation tiles relative to observed values was used**

# 6 SIMULATION RESULT

## 6.1 Backcast Results

Maps of the historical changes in land use by decade (relative to the calibration period of 1990-2001) were created by the LTM, from 1930 to 1980 (Figure 6-1). Three general trends emerge from these simulations: an increase in urban, an increase in forests and a decrease in agriculture. The increase in forest occurs in the southeastern portion of the study area in large, homogenous patches. Forests tend to increase in smaller amounts and in a more fragmented pattern in the northeastern and central regions of the study area. Urban growth is prominent throughout the region with obvious increases in the major metropolitan areas of the ORB. Urban use in 1930 was estimated to be 6.9% (a major part of this was in roads) growing to 8.9% by 2010 (36% increase in the urban use footprint). Nearly one third (33.5%) of the agriculture from 1930 was lost by 2010 (agriculture went from 55.6% in 1930 to 37.0% in 2010). Forest cover gained between these time periods, representing 35.1% of the land cover in 1930 and 48.8% in 2010. Agriculture was the dominant land use/cover in 1930 and through gradual loss, forest became the dominant LULC in the mid-1960s and thereafter.

The GIS was also used to create a time series map of land uses and estimate the proportion of the map involved in each land use legacy pathway. A land use legacy pathway is a sequence of land uses in set decadal time steps. For example, one land use legacy pathway is a location staying forest for 10 years, then converting to agriculture for 20 years and then finally converting to urban and remaining urban for 30 years. Theoretically, $4^7$ (i.e., 16,384) land use transition pathways are possible (in all likelihood, fewer than 16,384 of urban is an ‘end land use’). We found (Table 6-1) that 36.7% of the map (ORB) remained agriculture for 60 years (1930 through 1990), 33.5% remained forest and 6.9% remained urban. As for urban, we classified all roads as urban, and, since most of the secondary roads in the basin were developed around the early 1900s, a majority of the urban footprint for 1930 are considered roads. About 2.6% of the map remained other (open water, barren, shrubland). The most common transition land use legacy pathways was the conversion of agriculture to forest (16.4% of the transition pathways in the basin), followed by the conversion of agriculture to urban (1.11% of the transition pathways basin; Table 6-1).

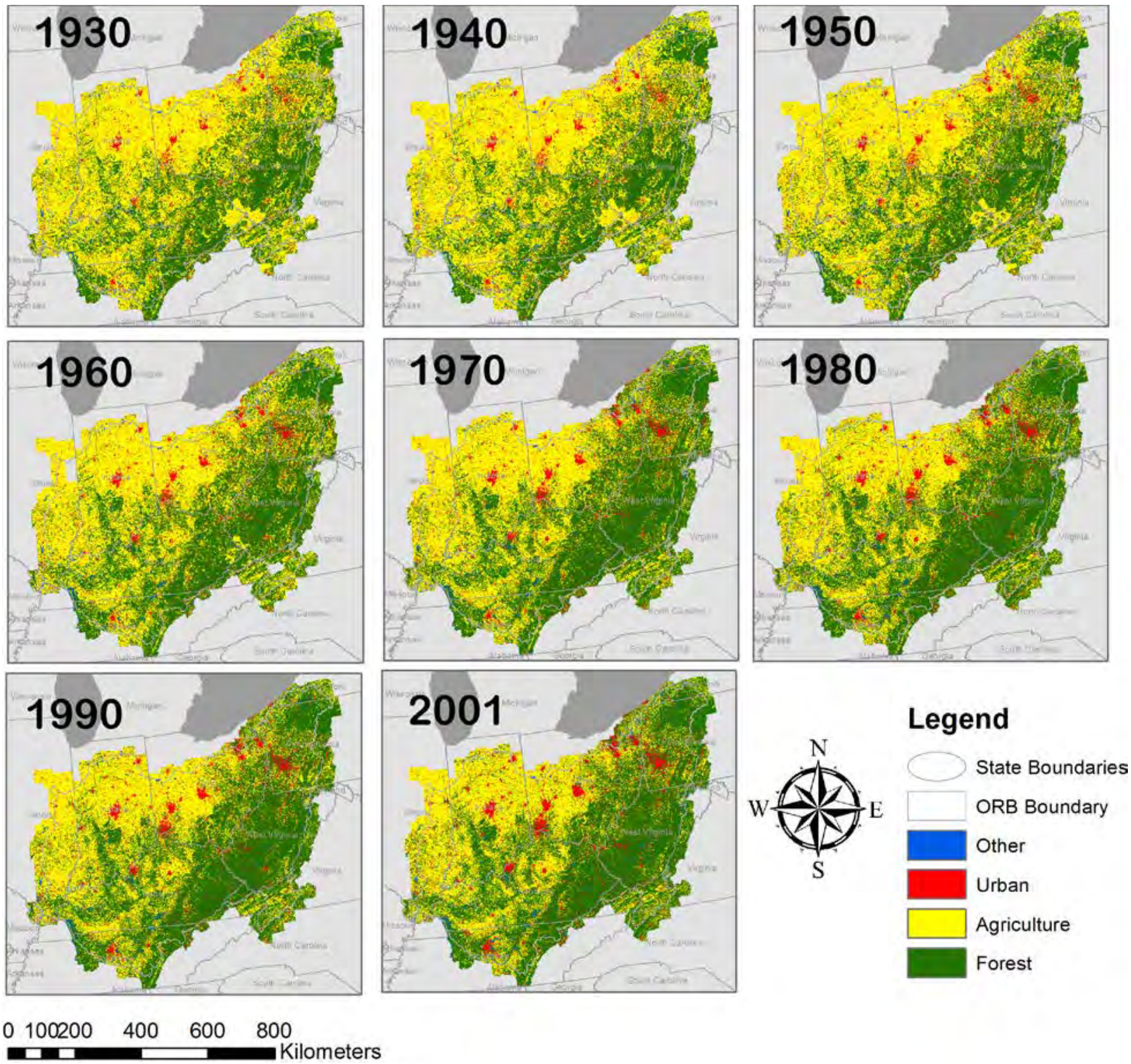



**Figure 6-1.The most common BLTM land use transition pathways occurring between 1930 and 1990 for the ORB**

**Table 6-1. The most common BLTM land use transition pathways occurring**

| Percentage of Pathways in Specific Transition Pathway | Status 1 | Change To | Status 2 | Change To | Status 3 |
|---|---|---|---|---|---|
| 36.7703 | Stay Ag for 60 Years | ---- | ---- | ---- | |
| 33.5545 | Stay Forest for 60 Years | ---- | ---- | ---- | |
| 6.9823 | Stay Urban for 60 Years | ---- | ---- | ---- | |
| 5.2397 | Ag for 30 Years | Forest | Forest for 30 Years | ---- | |
| 4.3761 | Ag for 40 Years | Forest | Forest for 20 Years | ---- | |
| 2.4097 | Ag for 60 Years | Forest | Forest in 1990 | ---- | |
| 2.2673 | Ag for 50 Years | Forest | Forest for 10 Years | ---- | |
| 2.1635 | Stay Other Classes for 60 Years | ---- | ---- | ---- | |
| 1.4411 | Ag for 20 Years | Forest | Forest for 40 Years | ---- | |
| 0.6978 | Forest for 10 Years | Ag | Ag for 10 Years | Forest | Forest for 40 Years |
| 0.6953 | Ag for 10 Years | Forest | Forest for 50 Years | ---- | |
| 0.3773 | Ag for 10 Years | Urban | Urban for 50 Years | ---- | |
| 0.3397 | Forest for 10 Years | Ag | Ag for 20 Years | Forest | Forest for 30 Years |
| 0.2711 | Ag for 50 Years | Urban | Urban for 10 Years | ---- | |
| 0.2405 | Ag for 30 Years | Urban | Urban for 30 Years | ---- | |
| 0.2387 | Forest for 20 Years | Ag | Ag for 10 Years | Forest | Forest for 30 Years |
| 0.2236 | Ag for 40 Years | Urban | Urban for 20 Years | | |

Approximately 90% of the area in our four demonstration watersheds (Figure 6-2) remained in a single land use over the 1930 to 1990 simulation period. The Upper White watershed had less area (83.4%) that persisted in a single land use during the 60-year period; this also means that over 16% of the watershed has experienced at least one land use change. Of the four watersheds, it is the only one to contain a large city (Indianapolis). We also examined land use persistence in riparian zones and found that these areas have undergone more change than the watersheds as a whole, suggesting that these are more dynamic locations. Of the four demonstration watersheds, the Upper White had a quarter of its riparian zone transformed during the 1930 to 1990 period. The Sugar Watershed had the greatest amount of forest cover (~12%) that persisted over the backcast simulation period.

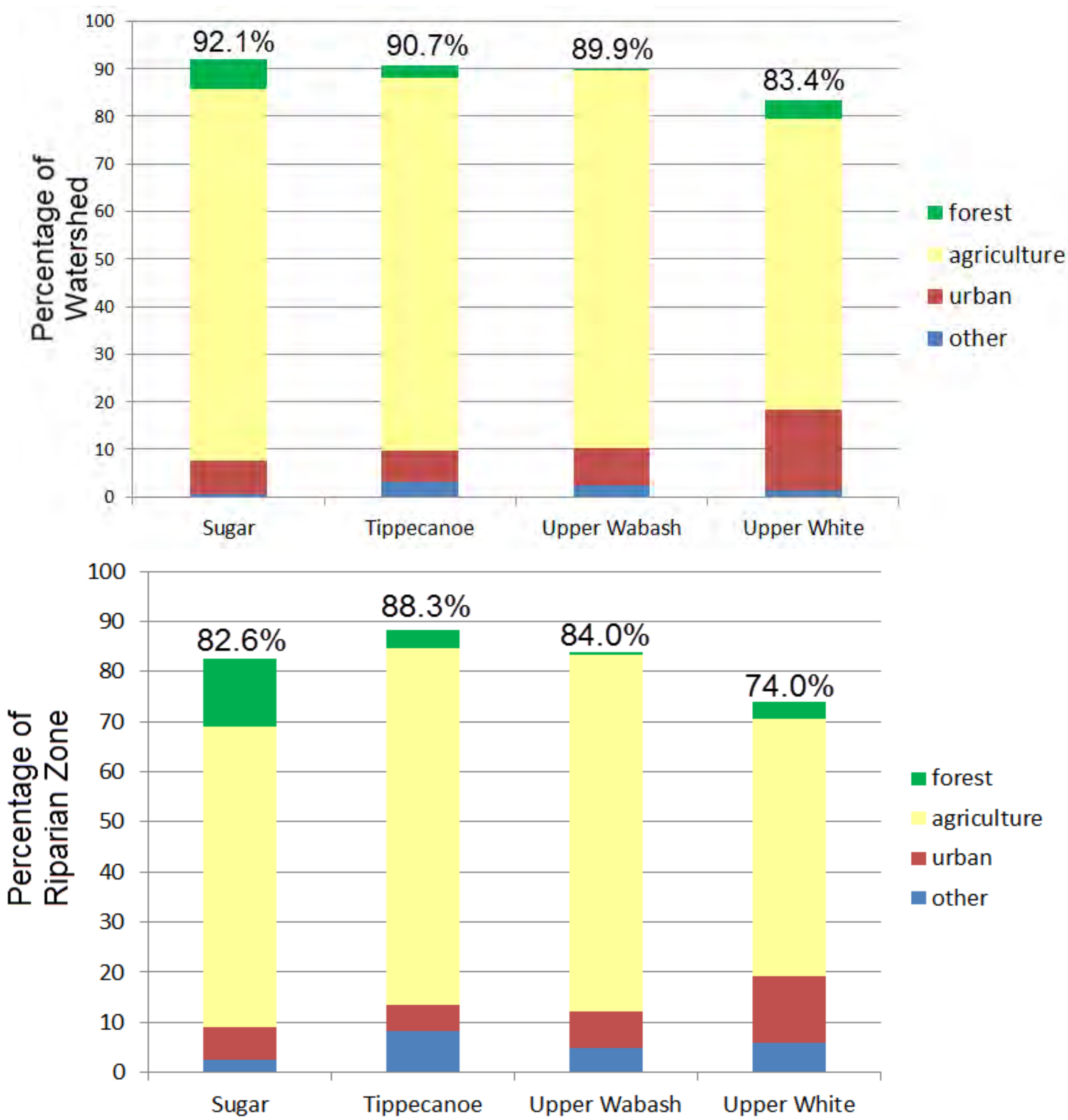



**Figure 6-2. Percentage of each case study watershed (top) and within permanent stream riparian zones (bottom) that persisted in a land use class from 1930 to 1990. Percentage value over each aggregated bar indicates the total area that persisted in a single land**

The land use transition pathways for all four of our demonstration watersheds are relatively similar. The top 5 most frequent long-term pathways are shown in Table 6-2 for entire watersheds (A) and for riparian zones (B). Between 2 to 6 percent of these watersheds were in agricultural land use for 3 to 6 time steps. In three of the four watersheds, agriculture for one time period (1930) followed by urban (1940 and thereafter) was among the top 5 transition pathways. When examined within riparian zones, compared to values for entire watersheds, there were larger proportions of land use in agriculture followed by forest for each of the four demonstration watersheds. For example, the Sugar Watershed had 7.58% of the riparian zone in agriculture for 5 time steps and forest for 2; only 2.71% of the entire watershed exhibited this exact transition pathway. Only the Upper White Watershed had a transition pathway for its riparian zone that included urban.

**Table 6-2. Transition pathways for the selected demonstration watersheds (A) and their riparian zones (B). Only the top 5 most common transition pathways are listed here and their percent area for the watershed and riparian zone. Totals are percentage total area.**

A. Top Five Transition Pathways for All Areas within Demonstration Watersheds

| **Sugar** | **Percent** | **Tippecanoe** | **Percent** | **Upper Wabash** | **Percent** | **Upper White** | **Percent** |
|---|---|---|---|---|---|---|---|
| AAAAAFF | 2.71 | AAAAAAF | 2.07 | AAAAAAF | 4.24 | AAAAAFF | 2.83 |
| AAAAAAF | 1.13 | AAAAAFF | 1.57 | AAAAAFF | 1.94 | AAAAAAF | 2.48 |
| FAFFFFFF | 0.82 | FAAAAFF | 0.78 | AAAAFFF | 0.99 | AAAFFFF | 1.88 |
| FAAFAFA | 0.46 | AAAAFFF | 0.67 | AUUUUUU | 0.59 | AAAAFFF | 1.78 |
| AUUUUUU | 0.25 | FFAFFFF | 0.47 | FFFFFAFFF | 0.34 | AUUUUUU | 1.35 |
| *total for top 5* | *5.36* | | *5.56* | | *8.11* | | *10.31* |

B. Top Five Transition Pathways within Riparian Zones of the Demonstration Watersheds

| **Sugar** | **Percent** | **Tippecanoe** | **Percent** | **Upper Wabash** | **Percent** | **Upper White** | **Percent** |
|---|---|---|---|---|---|---|---|
| AAAAAFF | 7.58 | AAAAAAF | 2.60 | AAAAAAF | 7.19 | AAAAAFF | 6.68 |
| AAAAAAF | 2.88 | AAAAAFF | 2.01 | AAAAAFF | 2.83 | AAAAAAF | 6.45 |
| FAFFFFF | 1.83 | FAAAAFF | 1.26 | AAAAFFF | 1.45 | AAAAFFF | 2.99 |
| FAAFAFF | 1.05 | AAAAFFF | 0.84 | FAAAFFF | 0.48 | AAAFFFF | 2.32 |
| AAAFAFF | 0.56 | FFAFFFF | 0.59 | AAAFFFF | 0.27 | AUUUUU | 1.24 |
| *total for top 5* | *6.32* | | *7.31* | | *12.23* | | *19.69* |

The spatial distribution of persistence and land use change in the ORB between 1930 and 1990 varies considerably spatially. Many areas, such as those in the northeastern portion of the ORB (Figure 6-3, area labeled A), have a very scattered distribution of persistence. The northwestern portion of the watershed (area labeled B) has few locations of change; much of the land use that was in place in 1930 persists today. Areas along the Ohio River proper, especially north of the river, have clumped areas of change and persistence (labeled C). Finally, one area in southern West Virginia (labeled D) experienced large homogeneous amounts of change. Inspection of the time series maps from Figure 6-1 indicates that the latter area used to be largely agricultural in the 1930s and 1940s but it transitioned to forest in later years, possibly as a result of farm failures during the Great Depression.

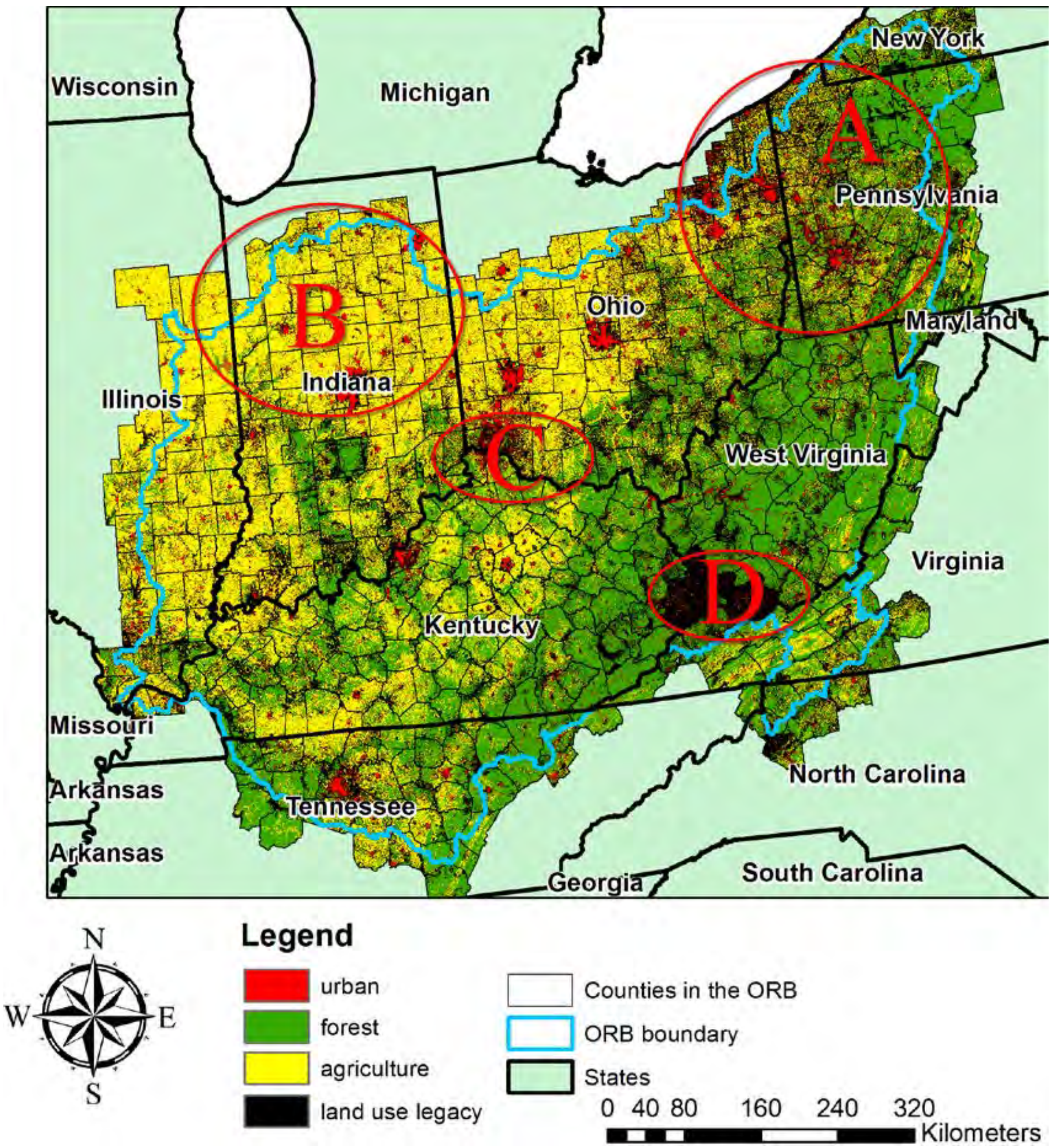



**Figure 6-3. Map of land use persistence from 1930 through 1990 and locations of change (i.e., locations where land use legacies may impact ecosystem dynamics). See Section 6.1 for explanations of areas indicated by letters A-D. ArcGIS file name is *legacy_all***

## 6.2 Forecast Results

The same training approach was used to forecast land use change into the future at 10-year time steps (2010-2050). The decadal maps of land use change are presented in Figure 6-4, and show that metropolitan areas will continue to expand at historical rates (Pijanowski and Robinson, 2011, Pijanowski and Plourde, unpublished) and these are reflected in our estimates. We predict that the entire study area will reach 11.83% urban in 2050 with agriculture decreasing to 35.8% and forest decreasing to 47.6%. Figure 6-5 shows a complete trend for all major land use classes from 1930 through 2050. Note that in 1930, a majority of the ORB was in agriculture but over time there was a steady decline in agriculture with an increase in forest cover. Urban land use increases gradually over time and by 2050 we estimate that urban should be almost half the footprint of agriculture in 2050.

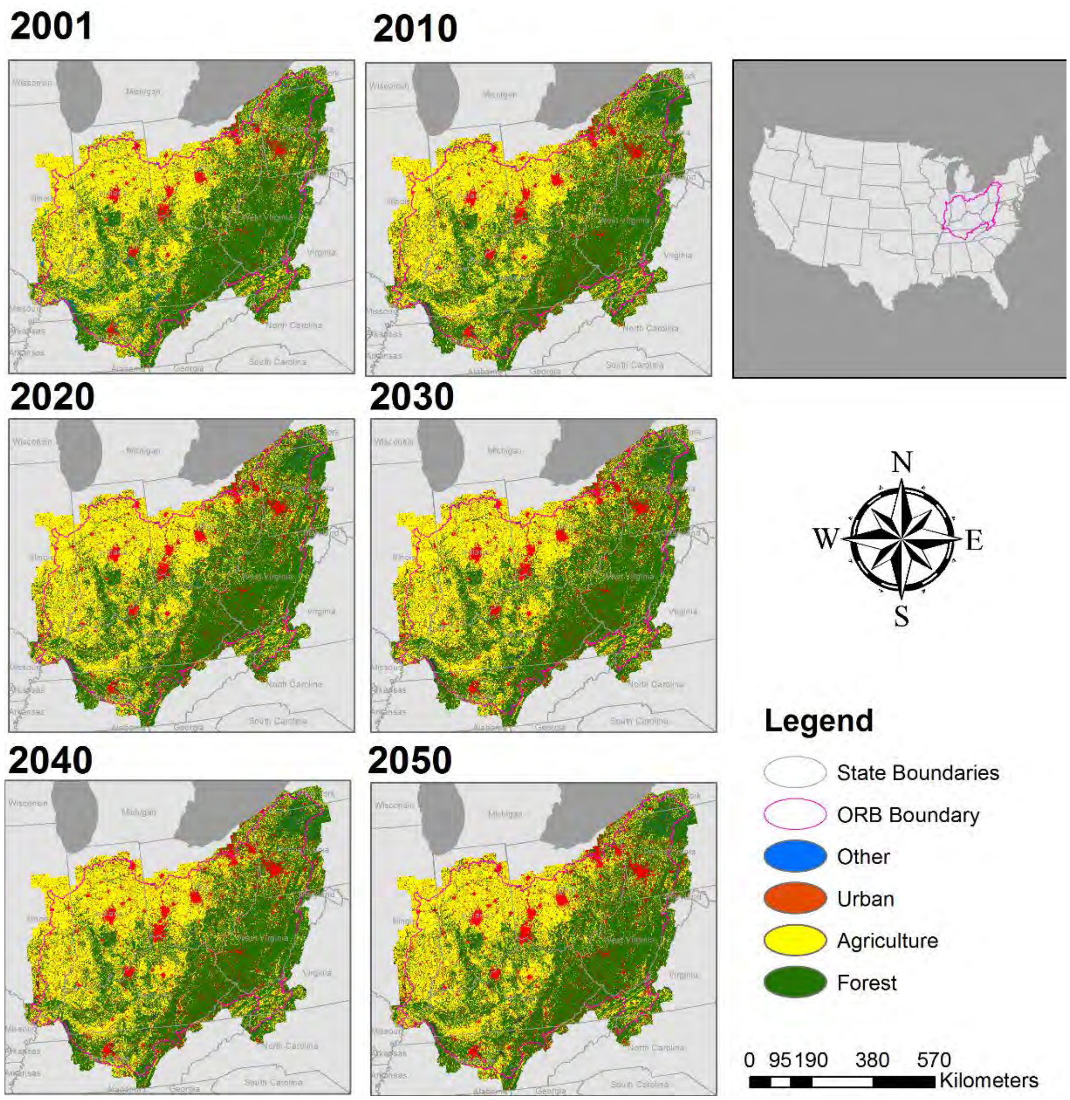



**Figure 6-4. Land Transformation Model projections summarized by decade**

In 2010, a majority of the areas converted to urban are from forest (51.7%), followed closely by agriculture (41.2%). Only 7% of the "other" LULC class was converted to urban in 2010. These rankings stay the same but the trends differ slightly, as less forest and more agriculture is converted to urban with each successive decade (Figure 6-6). By 2050, 48.4% of the new urban in that decade is from forest and 45.5% is from agriculture.

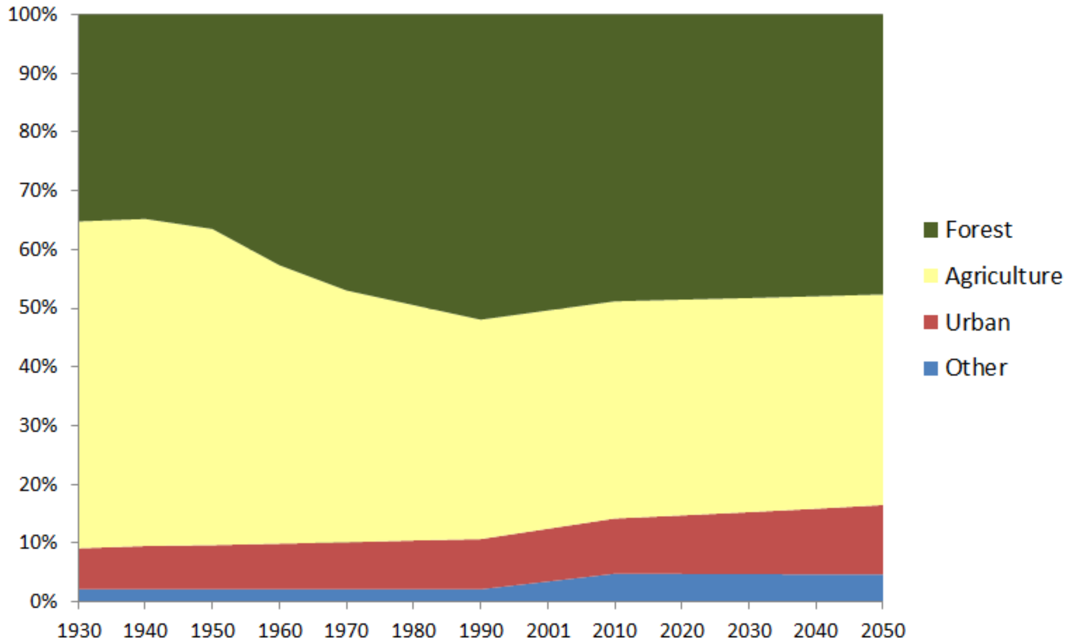



**Figure 6-5. Percentage of land use/cover classes simulated over time for the ORB from 1930 through 2050 with 10-year time steps**

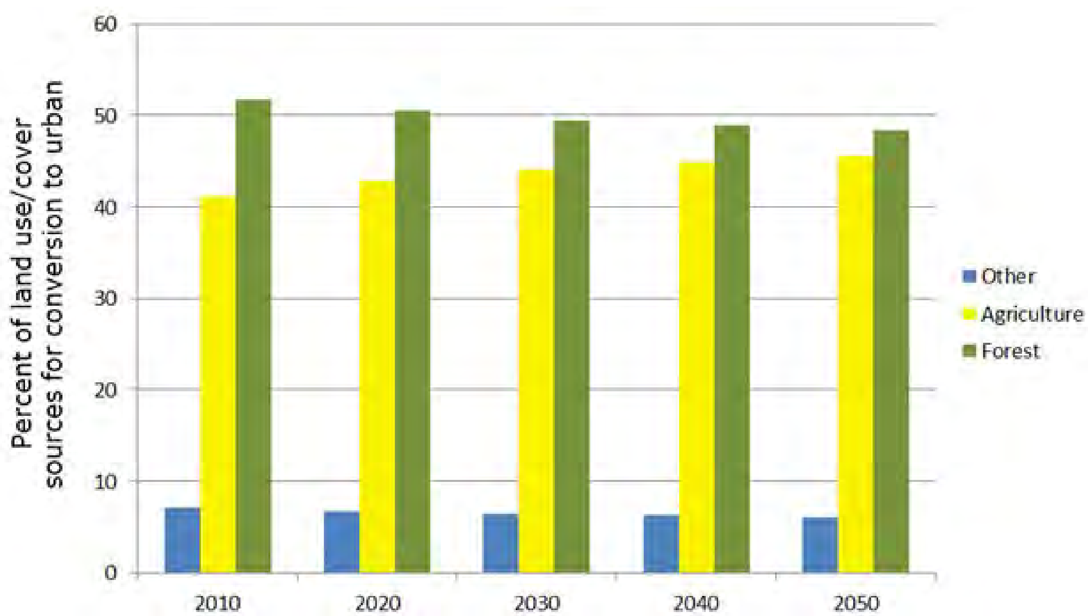



**Figure 6-6. Percentage of land use/cover classes that are predicted to be converted into urban land use during each decade**

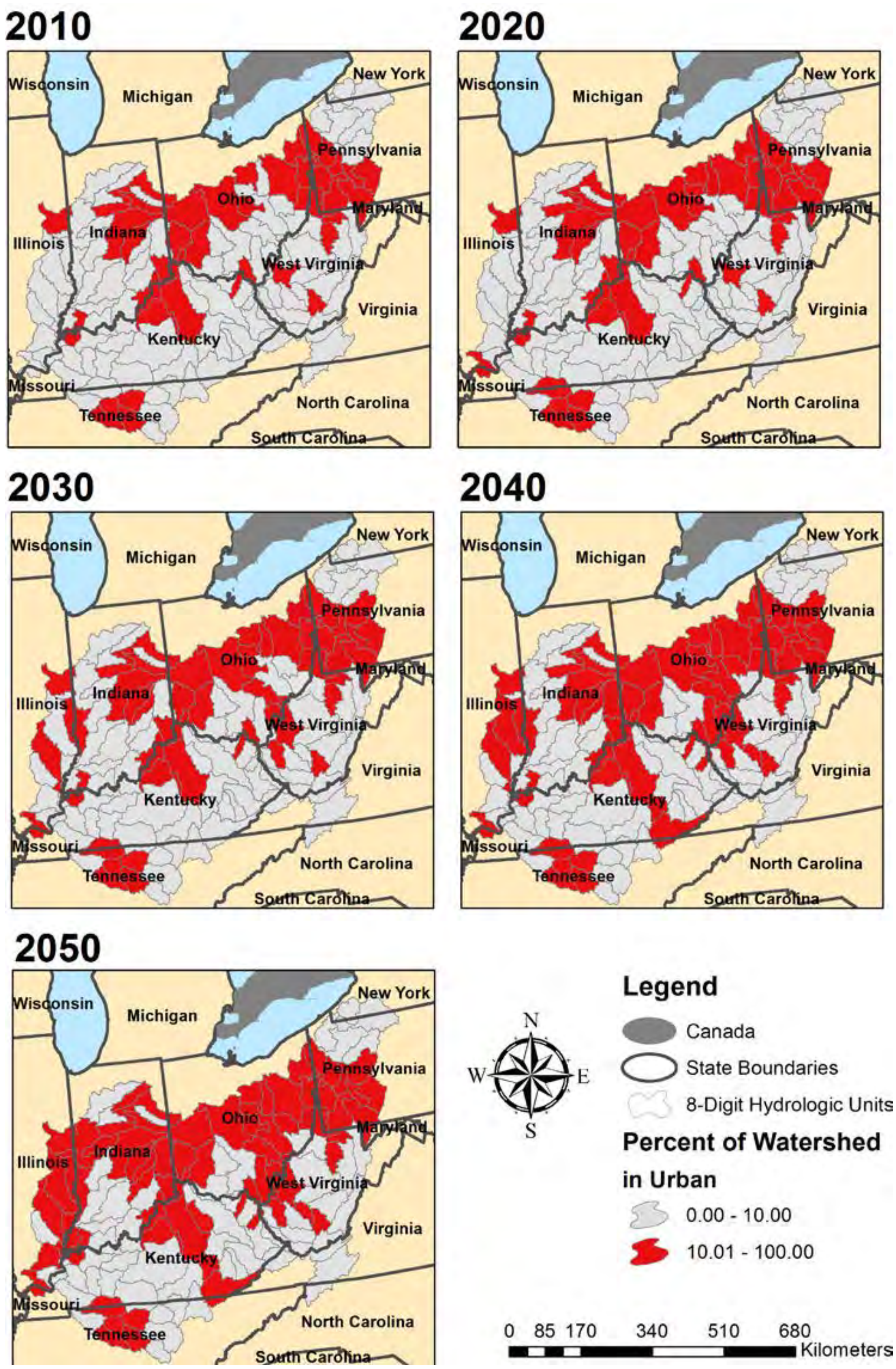



**Figure 6-7. Locations where potential urban-water quality thresholds have been met at the scale of an 8-digit hydrologic unit (i.e., watershed) for years 2010 through 2050. Watersheds with a red color have exceeded 10% urban land use by the year indicated**

Almost one third of the ORB watersheds exceeded 10% urban in 2010 (Figure 6-7). Much of these watersheds (we call these threshold watersheds) in 2010 are located in the northern portion of the ORB and along the Pennsylvania-West Virginia border. By 2050, the distribution of these "threshold" watersheds have spread further east, south and north. By 2050, over half (64/120) of the 8-digit hydrologic units have more than 10% urban (Figure 6-8).

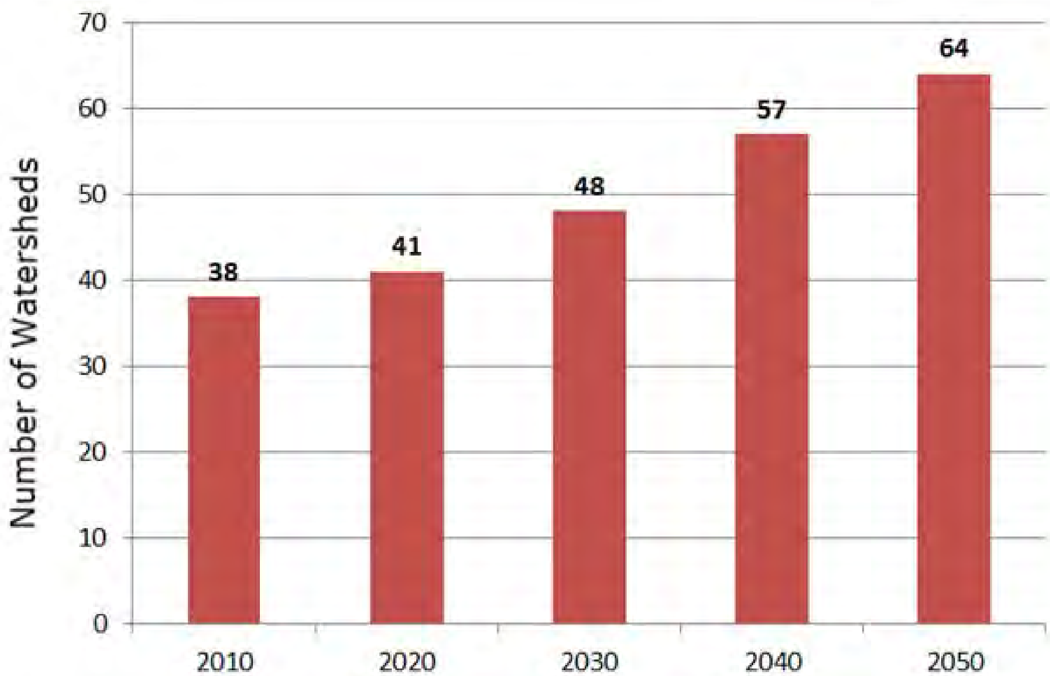



**Figure 6-8. Number of 8-digit hydrologic units (watersheds) that have exceeded 10% urban land use by the year indicated. There are 120 8-digit hydrologic units within the ORB**

Most of the watersheds in Indiana, Illinois and Ohio have also exceeded 38% agriculture (Figure 6-9) by 2010. Between 2010 and 2040, fifty 8-digit hydrologic units have more than 38% agriculture; by 2050 one of these is predicted to have enough agriculture transitioned to urbanization that it is no longer a member of this threshold condition.

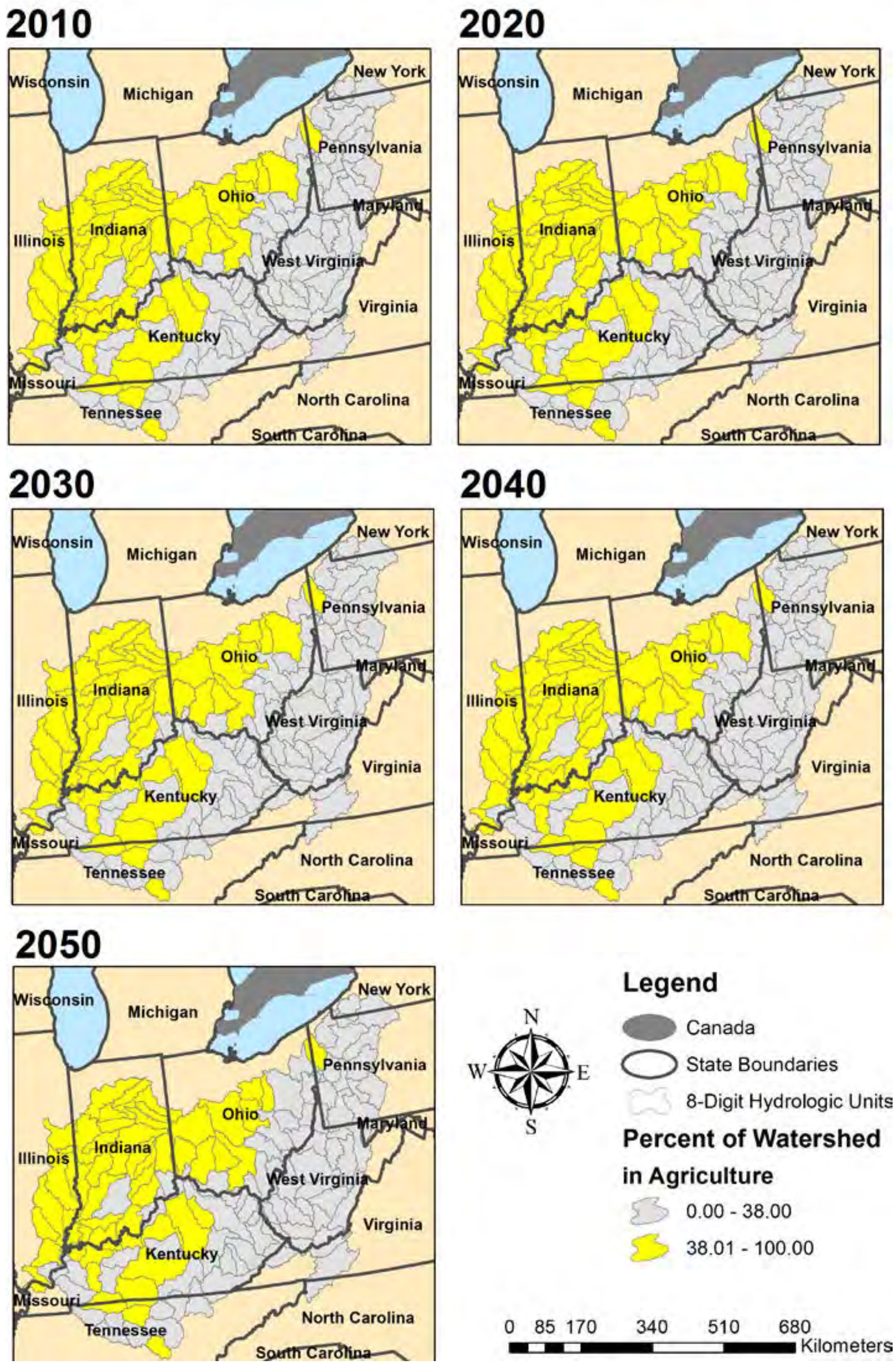



**Figure 6-9. Locations where potential agriculture-water quality thresholds have been met at the scale of an 8-digit hydrologic unit (watershed) for the years 2010 through 2050. Watersheds with a red color have exceeded 38% agricultural land use by the year indicated**

### 6.3 Model Output

We are distributing five sets of files that are output from the simulations. The first set contains seven backcast results at 10-year time steps from 1930 through 1990. Maps are in ArcGIS 10 raster file format in 30-m resolution. Land use codes are urban, agriculture, forest and an "other" class that collapses four minor LULC classes. The second set contains LULC maps for the forecasts from 2010 through 2050, also at 10-year time steps. One version contains urban forecasts coded as 1XX where XX is the original Anderson level 2 LULC code from the 2001 NLCD. Locations from 2001 that are not predicted to change contain the original LULC codes. We have also collapsed the LULC classes to the major four classes and will distribute these as well as they corresponded to the same LULC class codes as the backcast maps. The fourth database distributed is a raster legacy map that contains a sequence of codes for LULC for years in the sequence 1930, 1940, 1950, 1950, 1970, 1980 and 1990. We coded "other" = '0', urban='1', agriculture='2' and forest ='3'; a value in this database that is 2223331 is a location that has had a sequence of agriculture for three decades (1930-1950), forest for three more decades (1960-1980) and urban for the final decade (1990). The fifth database we are distributing is a shape file with the summary of the percentage of urban and agricultural land use by 8-digit hydrologic unit. We used the *tabulate area* command in ArcGIS 10 Spatial Analyst to summarize the area for each land use and Excel to calculate the percentage areas for urban and agriculture. All raster files contain grids of 31,644 columns by 31,191 rows (slightly more than $1.0 \times 10^8$ cells) and are being distributed in the simulated projection of Albers Equal Area (the North American standard datum).

**Table 6-3. List of model simulation outputs distributed to EPA by Purdue University**

| Output | Naming | Description | Data Format |
|---|---|---|---|
| Backcast maps 1930-1990 | Orb_xxxx_v1_1 where xxxx is year | Maps of LULC for urban, agriculture, forest and other category | Seven ArcGIS 10.0 raster maps at 30 x 30m resolution (31,644 columns by 31,191 rows) |
| Forecast maps 2010-2050 | Orb_xxxx_urb where xxxx is year | Maps of land use/cover for native NLCD 2001 LULC classes. Urban forecasts are included in maps as 100 + original code (e.g., 182 is future urban from agriculture class of 82) | Five ArcGIS 10.0 raster maps at 30 x 30m resolution (31,644 columns by 31,191 rows) |
| Forecast maps 2010-2050, collapsed classes | Orb_xxxx where xxxx is year | Maps of LULC for the four major LULC classes of urban, agriculture, forest and other. | Five ArcGIS 10.0 raster maps at 30 x 30m resolution (31,644 columns by 31,191 rows) |
| Legacy map | Legacy_orb | Map of LULC change sequences for each location. Code contains the land use for year sequences as seven sequential digits, the first is the LULC code for 1930 and the last is the LULC code for 1990 | One ArcGIS 10.0 raster data at 30 x 30m resolution (31,644 columns by 31,191 rows) |

| | | | |
|---|---|---|---|
| Land Use/Cover Percent by 8-Digit Hydrologic Unit | HUC_ORB_future urb_ag_percents_ Final.shp | Percentage of each land use class summarized by 8-digit hydrologic unit for years 2010-2050 | One shape file with 8-digit hydrologic units, codes and percent land use/cover classes as attribute table |

There are 120 8-digit hydrologic units in the ORB and the attribute table for the shape files contains summary information for each hydrologic unit. Table 6-3 summarizes these simulation output files.

# 7 DISCUSSION

The Ohio River Basin (ORB) has undergone tremendous changes in land use from 1930 to current, and, if contemporary trends continue, it is likely that the entire ORB will reach 10% urban by 2050. Historical patterns are not unlike other areas of the Midwest (see Pijanowski et al., 2007; and Pijanowski and Robinson, 2011). In 1930, the dominant land use was agriculture, but afforestation patterns between 1950 to current have "greened" portions of the ORB yielding forest as the dominant land use/land cover (LULC) class today. The return of some of the landscapes to forests has been well characterized by Brown et al. (2005), who showed that many landscapes east of the Mississippi River from 1970 to present have increased forest cover. However, these new forested landscapes exist today with land use legacies that include past agriculture. Areas that have had agriculture in the past are known to retain the biogeochemical signature of the inputs from cropping, most notably phosphorus and herbicides (Dupouev et al., 2002; Flinn and Vellend, 2005; Standish et al. 2006; Baeten et al., 2010; Christiansen et al., 2010; Brudvig et al., 2013), which can be retained in the soil for long periods of time. Past agricultural use influences plant community structure through processes such as germination (Flinn and Vellend, 2005; Hermy and Verheven, 2007; Feurdean et al., 2009) or facilitates the colonization and spread of invasive species (Vila and Ibanez 2011). Water quality of streams has been shown to harbor the "ghost" of previous land uses (Harding et al. 1998) through biogeochemical signatures that remain from historical land use management practices, such as fertilizer application.

Our model shows that the spatial patterns of land use persistence vary considerably across the ORB. A highly fragmented pattern of land use persistence exists in the northeastern portion of the ORB, a large homogenous distribution of agriculture to the north and west and one "patch" of almost exclusive agriculture conversion to forest exists in southern West Virginia. Areas just to the north of the Ohio River proper contain large, but dispersed, areas which have had a history of change in land use. We also observed that many metropolitan areas have undergone more land use change and, thus, have more frequent occurrences of land use legacies than rural areas. The most common land use transition pathway that occurred throughout the ORB was for land to remain agriculture for 30 years, then to transition to forest, and stay forest at the current time step. The next most common land use transition pathways were (1) agriculture for 40 years and then forest, (2) agriculture for 60 years and then forest, and (3) agriculture for 50 years and then forest. Thus, agricultural abandonment leading to forest represents the most common land use pathway even when urbanization is accounted for. Three-phase land use transition pathways, such as agriculture to forest and then to urban, accounted for some pathways but these were only 1/10th as frequent as the two-phase agriculture to forest pathway. Thus, land use legacies have tremendous implications for forest management in the ORB and, based on recent literature on the topic (Vila and Ibanez 2011), for invasive plant species management.

Analysis of four demonstration watersheds was conducted so that we might examine trends that reflect different human histories. The Upper White watershed contains much of the Indianapolis, Indiana metropolitan area representing a highly urbanized watershed. The Sugar Watershed is a rural watershed and contains a lot of forested riparian zones. The Tippecanoe Watershed is historically a rural, agricultural watershed. Finally, the Upper Wabash watershed is an agricultural watershed that is currently undergoing transitions to large-scale livestock production. We found three of the four watersheds (the Upper White with some differences) to have very similar land use persistence patterns historically. Nearly 90% of these watersheds stayed in the same land use from 1930 to 1990. The most common transitions were agriculture to forest. The Upper White watershed had less land use persistence and the most common land use transition pathway involved urban. Interestingly, land use persistence was less in riparian zones for all four watersheds as compared to the watersheds as a whole. As the most common land use transition pathways involved the conversion of agriculture to forest, conservation efforts by groups and land owners may have created situations where stream health was a concern and planting of trees or agriculture abandonment may have resulted in more forested landscapes along the riparian zones. An analysis of historical photographs along different portions of these rivers could verify the model outcome. Restoration efforts along streams and rivers should examine historical patterns of land use transition pathways as the model suggests that they are more common there than in the upland portions of the watershed.

Calibration of the forecast and backcast models suggest the model performed satisfactorily in the forward and backward directions at about 3-km spatial resolution, making the output suitable for larger scale coupled simulations to hydrologic and/or climate at this resolution or larger. Describing general trends at coarser resolutions is possible as we have done.

The future of the size of the agricultural footprint for the ORB remains uncertain. Two factors may lead the agricultural footprint to remain the same despite the need for a large area of cropland in the U.S. to be used for biofuels. First, as Plourde et al. (2013) recently found, much of the ethanol production occurs west of the ORB. Cropland there is also being changed to monoculture inter-annual planting of corn (i.e., corn-soybean rotation is not occurring) with a majority of the corn-soybean rotation in the U.S. occurring in the ORB. It is uncertain as to whether monocultural corn cropping would move east and into the ORB as a result of increased ethanol demand. The second factor contributing to an unknown future of the agricultural footprint for ORB is the economics of energy; the relatively low price of fossil fuel relative to the cost of ethanol production makes ethanol less profitable. However, if fossil fuel prices rise dramatically then pressure to grow more corn could result and corn-soybean rotation in the ORB may be dropped in favor of monocultural corn. Such corn-corn crop rotation practices are known to increase the need for fertilizer, thus, potentially reducing water quality of streams and rivers (Plourde et al. 2013). Current work in the Purdue lab has focused on how to incorporate crop rotation patterns into the LTM so that crop-type patterns can be accounted for in land-hydrologic simulations.

The ORB watersheds currently contain levels of land use, particularly the percentages of urban and agriculture, which are known to threaten water quality and stream macroinvertebate community structure in the Great Lakes watersheds (Pijanowski in prep.). Our analysis suggests that a majority of the 8-digit hydrologic units to the north have exceeded 10% urban already. Likely, nearly all of the 8-digit hydrologic units in the north and some in the central (e.g., Kentucky) watersheds have exceeded 38% agriculture.

The modeling approach here differs from similar efforts to simulate future and historical land use/cover at large scales. A notably similar effort has recently been undertaken by Sohl and colleagues (Sohl et al. 2012a, 2012b) with a model called FORE-SEC. Both models use a “demand” and “allocate” structure where the demands for each use are constrained by scenario and allocation is driven by spatial pattern characterization. Both approaches also use historical NLCD data to parameterize and calibrate the models.

Very recently, the 2011 NLCD maps have become available and having a fourth time step to determine how well these models perform will help support their use and further development. Using two maps from different time steps to parameterize a model and then another two time steps is likely to lead to more insight on how we could improve models that simulate these very complex phenomena.

In summary, the ORB has been a dynamic basin historically. An agriculturally dominant land cover has given rise to a forested landscape which in turn may become mostly urban in the future. Land use legacy patterns in the ORB are complex and are likely to be key factors in consideration of forest and water quality management.

**Disclaimer**

The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

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# 9 APPENDIX

## 9.1 Metadata for the Backcast LTM output

Metadata:

- Identification_Information
- Data_Quality_Information
- Spatial_Data_Organization_Information
- Spatial_Reference_Information
- Entity_and_Attribute_Information
- Distribution_Information
- Metadata_Reference_Information

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*Identification_Information:*

*Citation:*

*Citation_Information:*

*Originator:*

Human-Environment Modeling and Analysis (HEMA) Laboratory, Department of Forestry and Natural Resource, Purdue University

*Publication_Date:* December 31, 2013

*Title:* Historic Land Use for the Ohio River Basin 1930 - 1990

*Geospatial_Data_Presentation_Form:* ESRI GRID

*Description:*

*Abstract:*

Past land cover predictions were created for 1990 to 1930 in 10-year increments for the Ohio River Basin. The 2001 National Land Cover Dataset version 2 served as the basis for all predictions. Change in land use between 2001 and 1992 along with topography, infrastructure accessibility, proximity to water, and land use density were used to determine the probability of change for a given area. Rates of agriculture change were based on "land in farm" from the U.S. Census of Agriculture, and "year built" from the U.S. Census for urban areas.

*Purpose:*

Past land cover is meant to serve as an example of one possible scenario of past conditions.

*Supplemental_Information:*

This metadata applies to all data from 1930 to 1990. The backcast year can be determined based on the file name (e.g. ORB_1930 is the Ohio River Basin data for 1930).

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*Time_Period_Information:*

*Range_of_Dates/Times:*

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*Ending_Date:* 1990

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*Status:*

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*Contact_Organization:* Department of Forestry and Natural Resources, Purdue University
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*City:* West Lafayette
*State_or_Province:* IN
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*Contact_Facsimile_Telephone:* 765-496-2422
*Contact_Electronic_Mail_Address:* bpijanow@purdue.edu
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Human-Environment Modeling and Analysis Laboratory, Department of Forestry and Natural Resources, Purdue University
*Native_Data_Set_Environment:*
ArcGIS Desktop 10.1
*Cross_Reference:*
*Citation_Information:*
*Originator:*

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*Citation_Information:*
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The 2001 National Land Cover Dataset version 2 served as the basis for all predictions. Change in land use between 2001 and 1992 along with topography, infrastructure accessibility, proximity to water, and land use density were used to determine the probability of change for a given area. Rates of agriculture change were based on "land in farm" from the U.S. Census of Agriculture, and "year built" from the U.S. Census for urban areas.

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2: Agriculture (81 – Pasture/Hay and 82 – Cultivated Crops)
3: Forest and Rangeland (41 – Deciduous Forest, 42 – Evergreen Forest, 43 – Mixed Forest, 52 – Scrub/Shrub, and 71 – Grassland/Herbaceous)
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*Contact_Electronic_Mail_Address:* jdoucett@purdue.edu
*Distribution_Liability:*
The Human-Environment Modeling and Analysis Laboratory, Department of Forestry and Natural Resources, Purdue University assumes no liability for results or conclusions drawn from use of this data.
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