Modeling the Interactions Among Urban Development, Land Cover Change, and Bird Diversity

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Project Description

The interactions between urban development and ecological processes are extraordinarily complex. Urban development evolves over time and space as the outcome of microscopic interactions of individual choices and actions taken by multiple agents. These decisions affect ecosystem structures and functions through the conversion of land, fragmentation of natural habitat use, disruption of hydrological systems, and modification of energy flow and nutrient cycles. Environmental changes at local and regional scales affect human well-being and preferences as well as the decisions people make. Our project is developing an integrated model of urban development and land-cover change in the central Puget Sound region that can interface with models representing a large set of ecosystem processes (Figure 1). The focus of our project is on linking urban development to bird diversity through land cover as a test case for an integrated modeling approach. This approach builds on model traditions in urban economics, landscape ecology, bird population dynamics, and complex system science, each of which offers different perspectives on modeling urban ecological interactions. The project explores Bayesian networks and a multi-agent microsimulation approach for their potential to support complex inference modeling in problem domains with inherent uncertainty.

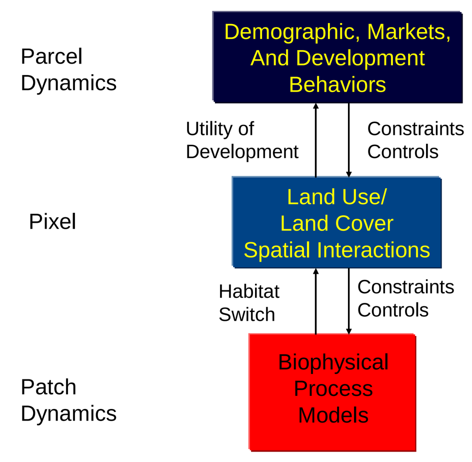

Figure 1. Integrated Modeling Scheme

Philosophy

Instead of separately simulating urban growth and its impacts on habitat for birds, this project is developing a framework to simulate metropolitan areas as they evolve through the dynamic interactions between urban development and ecological processes and link them through a spatially explicit representation of the urban landscape. Land development is modeled using UrbanSim, a behavioral explicit model that simulates demographic, market, and real estate development behaviors at the parcel level. The biophysical process model, here limited to the dynamics of bird species richness, is based on habitat patches, and is defined by the species or species-group under consideration. The land cover change model is the link in our system between human development events and land use changes, to the biophysical model, providing bi-directional feedback and interactions between socioeconomic and biophysical processes.

Urban Development Component

UrbanSim is a simulation system to model multiple interacting aspects of urban development. It interfaces with external macroeconomic and transportation models, and predicts the changes over time in the spatial distribution of households, jobs, and real estate quantities, types and prices. The core models are summarized below, and the architecture is shown in the figure that follows. The system is implanted as Open Source Software and is available at www.urbansim.org.

Demographic and Economic Transition

The *Demographic Transition Model* simulates births and deaths in the population of households. Externally imposed population control totals determine overall target population values and can be specified in more detail by distribution of income groups, age, size, and presence or absence of children. The *Economic Transition Model* is responsible for modeling job creation and loss. Employment control totals determine employment targets and can be specified by distribution of business sector.

Mobility and Location

The *Household Mobility Model* simulates households deciding whether to move based on historical data. The *Employment Mobility Model* determines which jobs will move from their current locations during a particular year using a similar approach to the Household Mobility Model. The *Household Location Choice Model* chooses a location for each household that has no current location. A sample of vacant land is evaluated for its desirability to the household through a multinomial logit model calibrated to observed data. The *Employment Location Choice Model* is responsible for determining a location for each job that has no location. The variables used in the Household Location Model include attributes of the housing in the grid cell (price, density, and age), neighborhood characteristics (land use mix, density, average property values, and local accessibility to retail), and regional accessibility to jobs. Variables in the Employment Location Model include real estate characteristics in the grid cell (price, type of space, density, and age), neighborhood characteristics (average land values, land use mix, and employment in each other sector), and regional accessibility to population.

Real Estate Development

The *Real Estate Development Model* simulates developer choices about what kind of construction to undertake and where, including both new development and redevelopment of existing structures. Each year, the model creates a list of possible transition alternatives (representing different development types), including the alternative of not developing. Variables included in the developer model include characteristics of the grid cell (current development, policy constraints, and land and improvement values), characteristics of the site location (proximity to highways, arterials, existing development, and recent development), and configuration of neighboring cells.

Land Market and Price

The *Land Price Model* simulates land prices of each grid cell as the characteristics of locations change over time. The model is based on urban economic theory and is calibrated from historical data using a hedonic regression to include the effect of site, neighborhood, accessibility, and policies on land prices. It also allows incorporating the effects of short-term fluctuations in local and regional vacancy rates on overall land prices.

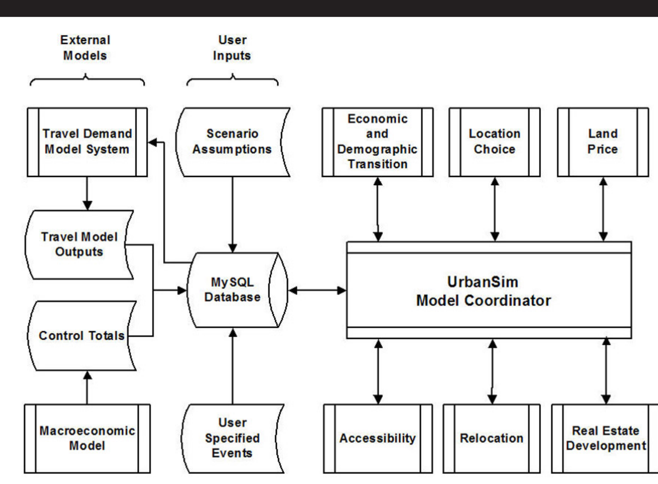

Figure 2. UrbanSim Model Architecture

The data used for estimating the model system includes land parcels describing the real estate inventory and prices, household and business locations, business locations, and environmental and planning features that influence urban development.

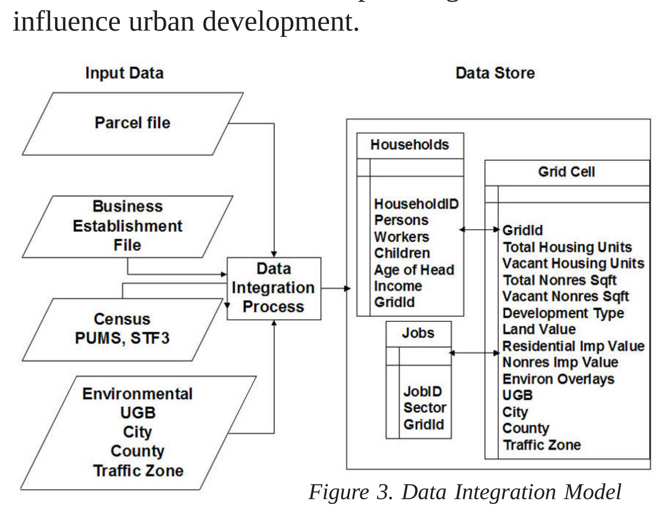

Figure 3. Data Integration Model

The model development effort in the Puget Sound is in final stages of database review, and model estimation is underway. It has been previously applied and validated in other settings, including Eugene-Springfield, Oregon, Honolulu, Hawaii, Houston, Texas and Salt Lake City, Utah.

Biodiversity Component

Our research on biological responses to land cover change has focused on birds with some additional work on plants and small mammals. Land conversion and age since development on Seattle's fringe reduced native plant (native forb and tree diversity: Figure 4a), bird, and small mammal diversity, and increased exotic ground cover. Small mammal communities exhibited threshold changes from primarily native to mixtures of natives and exotics as landscapes were converted from exurban to suburban or urban (Figure 4b, Donnelly and Marzluff, in press).

We are linking bird populations to land cover changes by modeling the response of bird communities and populations to local and landscape land cover variables. Birds appear most responsive to local attributes of land cover, especially the amount and composition of ground, shrub, and canopy cover (Table 1, Donnelly and Marzluff, in press). Bird community diversity decreases with the amount of urban land cover within a 1 km^2 survey area. Bird community diversity also decreases with development age (Figure 4c). Bird species richness in combined samples of forest fragments and settled areas stayed level with decreasing forest down to a threshold of approximately 20% forest, at which richness dropped dramatically (Figure 4c). Species richness was also related to age of development, with bird species richness decreasing from ~35 at time of development to below 15 by 80 years after, a drop likely explained by fewer nests and not increased predation levels.

We will use the decline in diversity associated with increasing urban land cover and the progressive decline in diversity with development age to link bird community changes to predicted (modeled) land cover changes. We are also preparing a spatially-explicit model of 10 focal bird populations. To accomplish this we have banded over 2000 songbirds to estimate survival and reproductive success, and we are currently using radio telemetry to monitor dispersal in the larger species. Together these data will allow us to better understand how some species respond to land cover change and how these population responses determine the more easily modeled community responses.

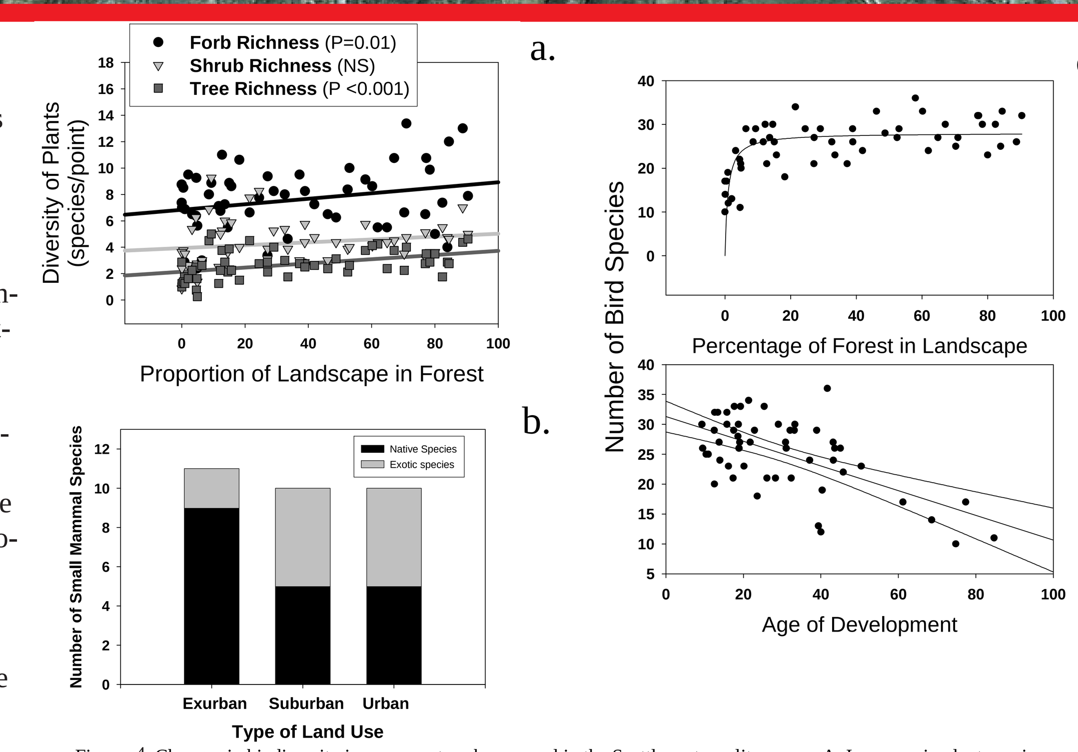

Figure 4. Changes in biodiversity in response to urban sprawl in the Seattle metropolitan area. A. Increases in plant species richness with increasing forest land cover. B. Shifting composition of small mammal communities. C. Correlation of bird species richness with amount of forest and age of development. Plant and bird data were derived from sampling at 54 1km2 study sites (Methods in Donnelly and Marzluff in press). Small mammals were sampled at 35 sites (12 exurban, 18 suburban, 5 urban) during a single summer for a total of 96 trapnights per site.

Table 1. A. Average regression models of bird community metrics for settlements and forest. Retention refers to retention of native species; gain refers to addition of synanthropic species. B. Some example equations for individual species in settlements.

A. Settlement	Average Model	R^2
Richness	23 - 0.13 Urban land cover + 9.8 Tree density - 0.20 Canopy closure	0.59
Evenness	62 - 2.9 Urban patch size - 0.037 Exotic trees	0.53
Retention	37 - 0.20 Urban land cover + Tree density	0.66
Gain	17 + 0.12 Exotic ground cover - 0.13 Canopy closure	0.01
Forest		
Richness	24 - 0.13 Canopy closure	0.17
Evenness	74 - 2.6 Ground diversity	0.10
Gain	5.1 - 0.11 Canopy closure + 2.9 Ground diversity	0.32

B. Species	Model	R^2
House finch	-0.089 + 0.025 Urban land cover + 0.011 Exotic tree cover	0.53
E. Starling	-0.73 + 0.041 Urban land cover + 0.044 Exotic shrub cover	0.47
Spotted towhee	-0.041 - Urban patch size	0.40
Winter wren	-0.56 + 0.0085 Forest aggregation – 0.0086 Exotic shrub Cover + 0.0046 Ground cover + 0.0022 Evergreen tree	0.70

Land Cover Change Modeling Component

Land cover change is driven by both biophysical and and human agents, each operating through different mechanisms measured through different proximate variables (Table 2). The land cover change model component consists of a set of spatially explicit multinomial logit models of site-based land cover transitions. We build on previous efforts in land cover change modeling to simulate land cover change as influenced by spatially explicit dynamic interactions between socio-economic and biophysical processes. The probability of transition of a 30-m pixel from one discrete land cover class i to another cover class j is influenced by the intensity of a development event predicted by the development model, a set of attributes of the pixel, and the land cover composition and configuration of the neighboring pixels. The transition probability equations are estimated empirically as a function of a set of independent variables comparing land cover data ever two years from 1986 to 2001.

We use MonteCarlo simulation to determine whether each pixel of a specified land cover changes to another cover type or remains in its current state. Land cover change equations are used to estimate the transition probabilities for each cell and the changes implemented by comparing the probability to a random number chosen from a uniform distribution between 0 and 1. If the transition probability to a different land cover exceed the random value, the transition takes place. Otherwise, the grid cell maintains its current land cover. The result of this procedure is the simulation of land cover change events that represent any observed transitions between land cover.

Three types of variables are considered: 1) Biophysical; 2) Land use; and 3) Change variables (Table 3). We consider three different spatial effects: 1) attributes of the site; 2) site location along various gradients, including proximity to the most recent land conversion and most recent development event; and 3) landscape patterns, both landscape composition and configuration of neighboring cells.

The effects of the spatial context are captured by a number of pattern metrics. We measure spatial patterns with a variable moving window of 150-m, 450-m, and 750-m resolution centered on the 30-m pixel depending on the variable of interest measured. Land cover characteristics are currently measured at 150-m resolution while land development characteristics are measured at 450-m and 750-m. The appropriate spatial resolution however is still to be determined using empirical estimation of the effect of specific variables at various scales and consideration of spatial autocorrelation.

We measure land cover composition and configuration using four indices: pland, dominance, mean patch size, and the aggregation index. Four indices are computed for each Landsat image: *pLand*, the proportion of the landscape area occupied by each cover type; *dominance*, the deviation from the maximum possible landscape diversity; *mean patch size*, the sum of the areas of all patches divided by the number of patches; and the *aggregation index*, the number of like adjacencies divided by the maximum possible number of like adjacencies involving a specified class. The probability of transition from one land cover type to another is higher if the surrounding cells are highly dominated by the same land cover class as the terminal transition. The transition from non-urban classes to urban classes is more likely at the urban fringe where dominance, mean patch size and aggregation of both urban and non-urban classes are low.

Table 2. Agents, mechanisms, and related proximate variables for both biophysical- and human-related processes.

AGENTS	MECHANISM	PROXIMATE VARIABLE
Biophysical Agents		
Physical	Climate/Energy&Material Hydrology/Topography/Soil	Mean Annual Rainfall Flooding/Erosion Slope/Soil quality
Biological	Species Viability Competition/Succession	Habitat type Land cover
Disturbance	Spread (i.e. diseases)	Landscape pattern
Human Agents		
Households/Retails	Location choice	Housing/Commercial Sqft
Developers	Land development	Development type
Farmers	Land conversion	Land use
Loggers	Forest harvesting	
Governments	Regulations/Infrastructure	Zoning/UBG Infrastructure

Table 3. Variables potentially entering land cover change models.

	Biophysical Variables	Land Use Variables	Change Variables
Site Attributes	Land cover Slope of cell Aspect of cell Soil quality Floodplain (in) Wetland (in) Riparian (in)	Parcel size Parcel ownership Land use Housing density Commercial density Land value Zoning UGB	Devtype transition 1…30 Land cover transition 1…7
Site Location	Distance to forest source area Distance to agricultural area Distance to floodplain Distance to wetland Distance to riparian	Distance to CBD Distance to nearest highway Distance to nearest arterial Distance to water infrastructure	Distance to nearest land cover transition Distance to nearest development event
Landscape Pattern Composition	% Land cover (each type) Dominant land cover in ½ mile % Slope > 25% % High erodible soil % Flood plain % Wetlands % Riparian	Dominant land use in ½ mile Built-up density % prime farmland Road intersection density in ½	% recent land cover transitions % recent land use transitions
Configuration	MPS of land cover in ½ mile Contagion of land cover in ½ mile	MPS of parcels in ½ mile	MPS LC change MPS parcel change

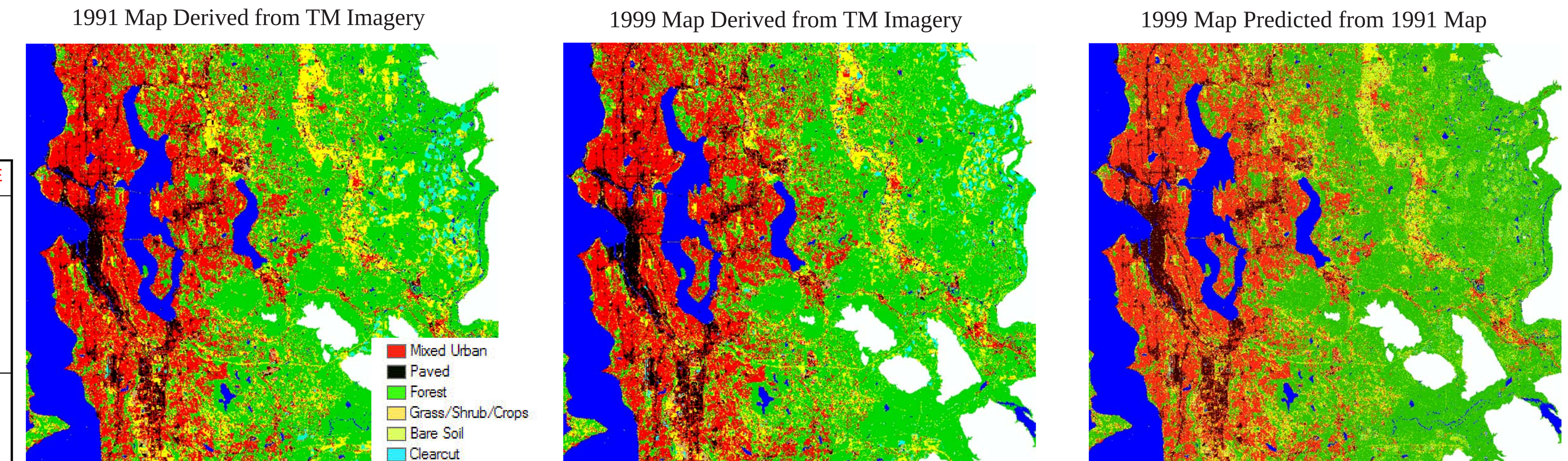

Figure 5. Land Cover maps of Seattle area derived from Landsat Thematic Mapper (TM) imagery for (1991, 1999) and predicted for 1999 from the 1991 map.

We have implemented a preliminary model specification using land cover maps of the Puget Sound for 1991 and 1999 interpreted from Landsat Images and ancillary GIS data for King County to develop multinomial logit equations for seven land cover classes (Paved, Mixed Urban, Forest, Grass/Shrub/Crops, Bare Soil, and Clearcut). Preliminary model results (Table 4) indicate good agreement between observed and predicted for Mixed Urban, Paved, and Forest classes with lower agreement for Grass/Shrubs/Crops and Bare Soil. Our predicted new Clearcut class had only 10% agreement with the observed Clearcut, with most of the Clearcut observed in 1999 being predicted as Forest or Grass.

Predicted	Observed: Mixed Urban	Paved	Forest	Grass/Crop	Bare Soil	Clearcut
Mixed Urban	**88.7**	6.5	0.8	2.8	8.7	6.0
Paved	2.0	**86.4**	0.1	0.6	6.0	1.8
Forest	4.5	2.6	**92.2**	19.4	9.9	60.1
Grass/Crop	3.5	2.2	6.4	**74.9**	8.7	20.9
Bare Soil	1.0	1.8	0.1	0.6	**66.1**	1.3
Clearcut	0.3	0.5	0.4	1.8	0.7	**9.9**
Total	100.0	100.0	100.0	100.0	100.0	100.0

Table 4. Percent agreement between land cover mapped in 1999 and land cover predicted in 1999. Table shows where the predicted model deviated from the observed land cover map.

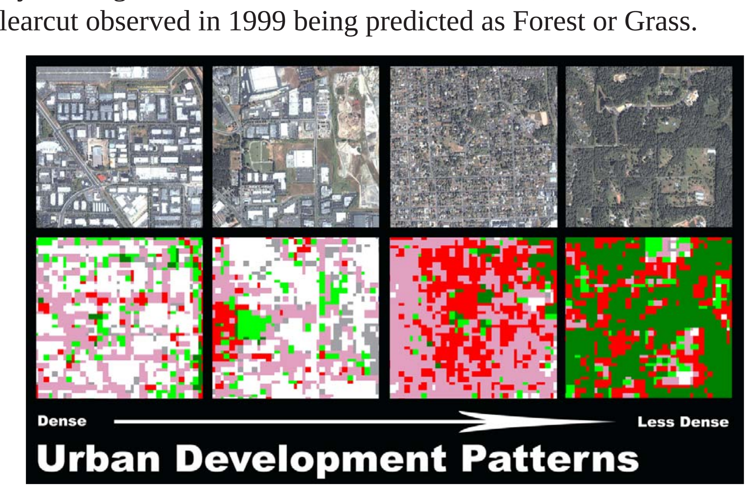

Figure 6. Urban Landscape Patterns

The results of our preliminary analysis suggests that the seven land cover classes mapped in 1991 and 1999 may not produce stable models for some classes because of insufficient class resolution (e.g., too few classes to adequately relate current land cover classes to potential future class and class confusion of mapped classes). We have developed a much more detailed land cover classification including 18 classes and are working to classify a seasonal (leaf-on, leaf-off) and yearly time series (approximately every three years from 1985-2002) of Landsat Thematic Mapper imagery for the Puget Sound. We are also developing various rules to better constrain the model spatially.

Future Challenges

A major challenge in our project is to realistically represent the complexity of human behaviors influencing urban development and land cover change as well as the biological responses and feedbacks in a unified modeling system. A second major challenge is developing an integrated spatial database of both socioeconomic and biophysical processes for the Central Puget Sound Region. In particular, creating a real estate development dynamics using parcel databases from the four counties in the Central Puget Sound and other GIS data layers representing several biophysical processes is a complex task. Another challenge is to develop a land cover change analysis over a 15 years period at a high spatial (30m) and temporal resolution (2-3 years) using a 18-class land cover protocol. Integrating three highly complex models is perhaps the greatest challenge of this project. We have developed a series of options for model integration of our three modeling efforts into a seamless, integrated model and are exploring the use of Bayesian updating to integrate UrbanSim and the land cover model components.

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