Appendix 2: Details of map generation

Maps for each scenario were generated using custom land cover change models. Details of these models varied by scenario, but, following the methods of Thompson et al. (2011), all simulations used regression tree (RT) models to distinguish among zones with different probability of land cover change and conservation during the 1996 to 2011 interval. Population and impervious cover maps were generated by combining these maps with the accompanying population trajectories. Details of model construction are presented below, beginning with an overview of the use of RTs and the general approach for producing population and impervious cover maps. Subsequent subsections present the model details for the *Linear*, *Backyard*, and *Community* scenarios.

General methods

RTs are non-parametric models used to relate a single response variable to categorical and numeric independent variables by recursive binary partitioning of input data into more homogeneous groups (De'ath and Fabricius 2000). The predictor variables supplied to the the RTs varied somewhat by scenario, but generally included: 1996 land cover categories, elevation, slope, soil drainage classification, prime farmland classification, and distances from major roads, developed land, conserved land, surface water, and the population centers of different sized communities (Table A2.1). Size classes for communities were determined from visual inspection of natural breaks in the distribution of town sizes in the state. We excluded predictor variables that were likely to change over the interval from 2010-2100 but which could not be simulated as a simple function of changing land cover. For instance, because some of our scenarios include the construction of new roads in residential subdivisions, we excluded distance from minor roads as a driver in our analyses. We also deliberately excluded population densities and population growth rates as possible driving variables in our statistical models because of the difficulty of disentangling the degree to which population drives development from the degree to which development drives population growth.

Following the methods of Thompson et al. (2011), we generated RTs in the software package R version 3.2.2 (R Core Team 2015), using the conditional inference tree toolset implemented in the R package PARTY (Hothorn et al. 2006). Spatial coverages for all input variables were derived from the GRANIT database (NH GRANIT 2016), and all spatial analyses were conducted using the R packages RASTER (Hijmans 2015) and RGDAL (Bivand et al. 2015). Raw data on land cover change were derived from land cover maps based on data from the National Oceanic and Atmospheric Administration's National Coastal Change Analysis Program (NOAA C-CAP) 1996 and 2011 (NOAA 2014), enhanced by Rubin and Justice (unpublished data). The 2011 map was also used as the base map for our simulations. Spatial patterns of land conservation were estimated from dates of land conservation in the NH GRANIT Conservation/Public Lands dataset, with additional dates of land conservation obtained from a query of a land transactions database maintained by the New Hampshire Department of Resources and Economic Development (NH DRED).

Table A2.1. Variables included in regression tree models

Variable	**Source**	**Notes**
Land cover	NOAA C-CAP 1996 and 2011[1] enhanced by NH GRANIT[2], 2014	Source categories aggregated to: forest, agriculture, development, wetland, water, and other
Distance from developed land	NOAA C-CAP 1996 and 2011[1]	
Distance from surface water	NOAA C-CAP 1996 and 2011[1]	
Conserved land	NH GRANIT: New Hampshire Conservation / Public Lands[3]	Dates of conservation supplemented with NH DRED database query
Distance from conserved	NH GRANIT: New Hampshire Conservation / Public Lands[3]	
Elevation	USGS National Elevation Dataset[4]	
Slope	USGS National Elevation Dataset[4]	
Soil drainage classification	NH GRANIT: Soil Survey Geographic (SSURGO) database for New Hampshire[5]	
Flood plain classification	Digital Flood Insurance Rate Maps[3]	
Farmland classification	NH GRANIT: Soil Survey Geographic (SSURGO) database for New Hampshire[3,5]	
Distance from major roads	NH GRANIT: NH Public Roads[3]	
Distance from population centers and municipalities of different size classes	NH GRANIT: New Hampshire Political Boundaries[3], U.S. Census Populations (1990, 2000, and 2010)[5], and U.S. Census Populated Places from USGS Geographic Names Information System (GNIS)[6]	Classes included: all NH population centers; all NH municipalities; all NH municipalities with population above 500; all NH municipalities with pop above 8000; Manchester and Nashua; Boston MA

[1]NOAA et al. (2014); [2]Rubin and Justice unpublished data; [4]USGS (2009); [5]NH OEP (2011); [6]NH OEP (2006)

To model the geographical distribution of land change and conservation within the state, RT models for geographic predictors of each change category were developed based on a randomly positioned uniform grid of sample points. In most cases the spacing of sample points was 1 km. Land categorized by NOAA C-CAP as wetland, surface water, or developed land, and conserved land were excluded from the development and conservation models.

For each change category, RTs were used to identify geographic zones corresponding to the terminal nodes of each tree. The resulting maps of probability zones were the basis for the land cover change simulations. For each land change category, we calculated area of change within each zone between 1996 to 2011, allocated among zones as 30 m grid cells based on the percent of total land change that had occurred in each zone in 1996 to 2011. In cases where regression trees included distance from development or distance from conserved land as driving variables, zones were re-calculated each decadal time step. When a zone did not contain sufficient undeveloped or un-conserved land area to accommodate a land change increment, the remaining increment was allocated among other zones. Specific details of this process varied by scenario.

Maps of population density and percent impervious surface were derived from the 30 m resolution land cover maps for each scenario, combined with base maps of current population density and assumptions about population growth that varied by scenario (Fig. A2.1). The base map for population density was a rasterization of 2010 U.S. Census block-level population densities. For each decadal time step, the resulting population density map was updated based on the scenario-specific assumptions about how population is spatially allocated.

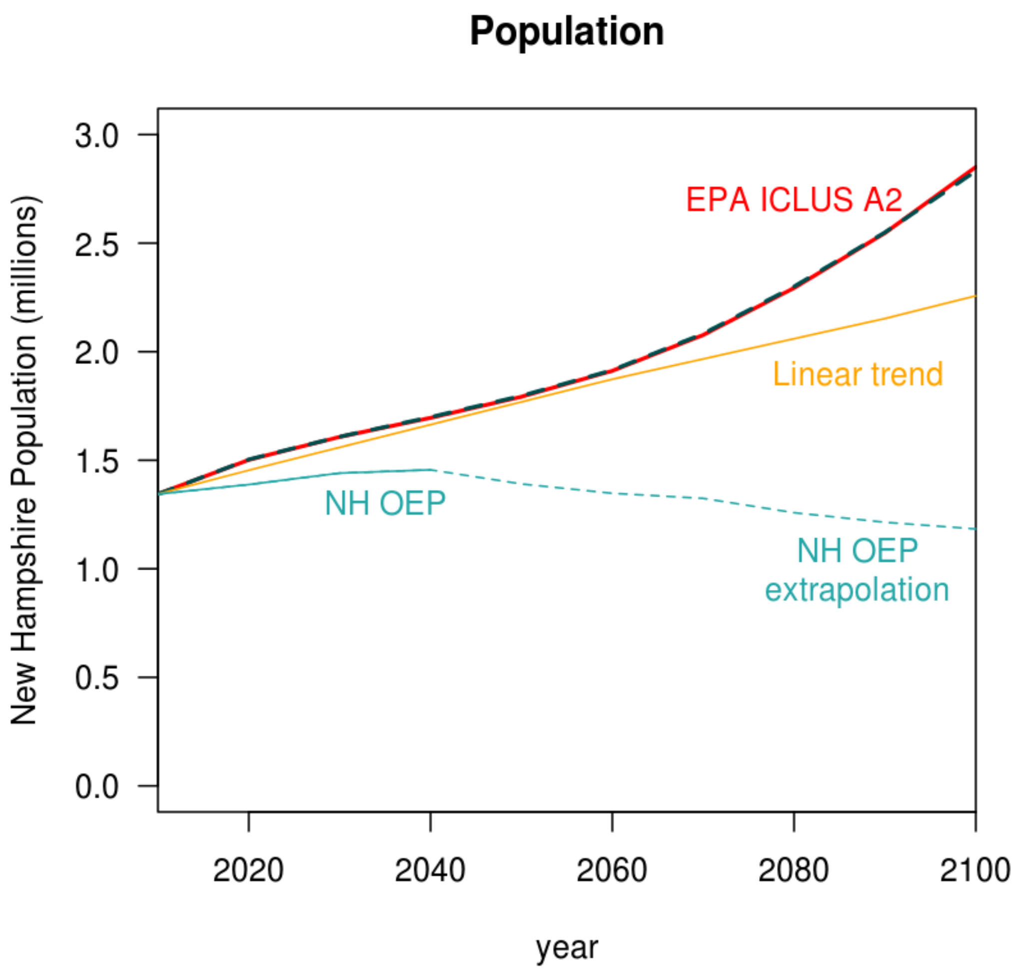

Fig. A2.1. The three New Hampshire population trajectories used in the scenarios: ICLUS A2, the EPA ICLUS population projection for the IPCC A2 scenario (EPA ICLUS), a linear extrapolation of 1990-2010 population trends (Linear trend), and NH Office of Energy and Planning (NH OEP) with projection out to 2100 (NH OEP extrapolation).

Impervious cover maps were generated by combining the National Land Cover Database (NLCD) impervious surface map for 2011 (Xian et al. 2011) with the simulated change in population density for each time step. A saturation curve was fit to the relationship between mean impervious cover and population density of U.S. Census tracts by non-linear least squares regression to produce a function relating percent impervious cover (I) to population density (P): $I = 100 * 0.00055 * P / (1 + 0.00055 * P)$. Details of how this function was used varied by scenario.

Scenarios

Linear Trends

Annual land cover change in each category is maintained at 1996-2011 rates through 2100, and conservation rates are maintained at 1996-2011 rates until 2060. Each decade, 102 km^2 of land is permanently converted from undeveloped to developed, 12 km^2 is converted to agricultural land, and 0.5 km^2 of agricultural land reverts to forest. Until 2060, 806 km^2 of undeveloped land is permanently conserved each decade. To reflect the common perception of key informant stakeholders that different parts of New Hampshire are subject to different drivers of land cover change (see Johnson 2012), the spatial distribution of land cover change and conservation were determined independently for each of four regions in the state: North (Coos and Carroll counties), Central (Grafton, Belknap, Merrimack, and Strafford counties), Southwest (Sullivan and Cheshire counties), and Southeast (Hillsborough and Rockingham counties).

We generated RTs for development and conservation within each region (see for example regional development RTs in Fig. A2.2). Because 1996-2011 development rates in the North and Southwest were very low, a 500 m grid, instead of a 1 km^2 sample grid, was used in those regions to increase the number of sample points that had new development during that interval. The resulting regional maps of probability zones were then combined into single maps (one for development and one for conservation) to determine the allocation of newly developed and newly conserved land across the state as 30 m grid cells in each decadal time step. Spatial projections for land cover change in the forest-to-agriculture and agriculture-to-forest categories were determined by a single statewide RT for each category.

To calculate population density maps, the population of New Hampshire was assumed to increase at a rate of 10,000 people per year, giving a total of 2.2 million people in the state by 2100, a linear extrapolation of 1990-2010 trends (Fig. A2.1). Because this new population was assumed to be uniformly distributed across newly developed land, each decade the population density increased by 96 / km^2 (=100,000 people / 104 km^2) for every newly developed pixel. In each time step, the impervious cover for newly developed pixels was calculated based on the new population density for that pixel. The population density and impervious cover for all other cells was assumed not to change.

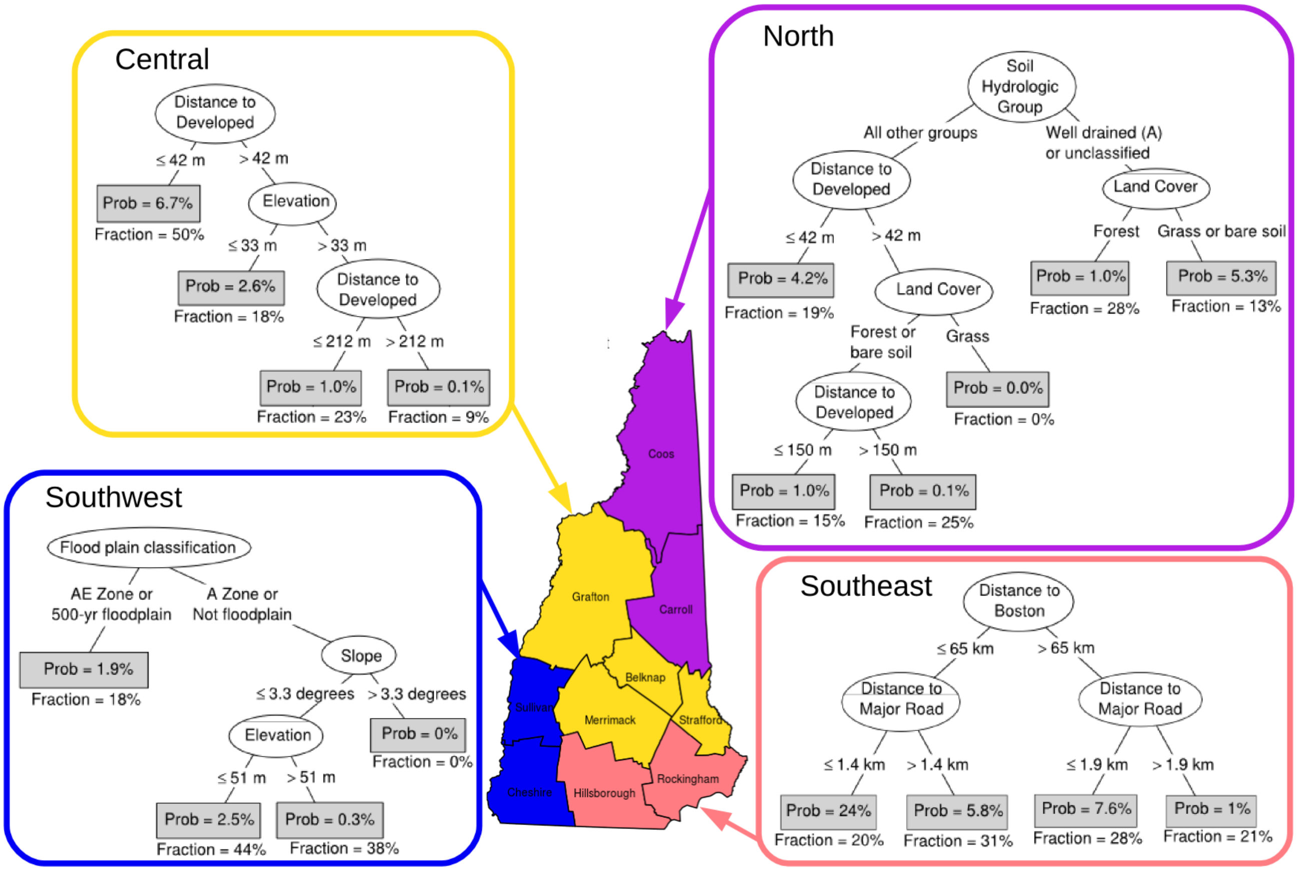

Fig. A2.2. Example regression trees (RTs) for development in regions of New Hampshire. RTs are shown used to generate zones of varied probability of development within the Central, North, Southwest, and Southeast regions of the state. Significant predictor variables are shown in the ovals, thresholds used to separate the zones are shown on the lines, probability of development is shown in the gray boxes, and the fraction of development occurring within each zone is shown below the boxes. These RTs were used for the Linear scenario. Similar trees were used to predict conservation, forest conversion to agriculture, and agriculture conversion to forest in each scenario.

Backyard Amenities

The area of newly developed land was determined separately for each municipality based on projected population growth, the typical lot sizes in each municipality, and the assumption (based on previous experience in southern New Hampshire; Michell et al. unpublished report) that residential zoning would shift toward cluster zoning as each community fills.

Municipal population growth projections were adapted from the EPA ICLUS scenario A2 for county-level population growth (U.S. EPA 2009, Bierwagen et al. 2010). Under this projection, the total NH population grows from the current 1.3 million (for 2014) to 1.8 million by 2050 and 2.8 million by 2100 (Fig. A2.1), with the vast majority of population growth in southeastern counties. We modified the ICLUS A2 population scenario by adjusting allocation among counties to allow suburban sprawl in high density counties to spill over into municipalities in neighboring counties and northward along major roads (I-89, I-93, and NH Route 16). This reflects previous findings suggesting that the areas of most rapid growth tend to be progressively further from urban centers as buildout occurs (e.g., Mockrin et al. 2012, Jeon et al. 2014, Thorn et al. 2016), as well as key informant perspectives on likely patterns of future development. Within most counties, we initially distributed population among municipalities in proportion to the current municipal population. We used special handling for Grafton county, a primarily rural county with two major population centers that had been identified by stakeholders as areas with high potential for growth. We therefore assumed that all growth in the county would initially be concentrated in those population centers (Hanover/Lebanon and Plymouth), with additional growth occurring as spillover population from other counties.

Within municipalities, the area of development required for the increase in population for each decadal time step was calculated assuming 2.5 people per housing unit and one housing unit per residential lot. Residential lot size for each municipality was initially set to the mean lot size based on 2014 zoning but was allowed to change dynamically in response to development pressure, based on analysis by Mitchell et al. (unpublished report). Specifically, when a municipality is 50% built out, it is assumed that mandatory cluster development zoning is adopted. Lot sizes are halved, and for every acre that is developed, an acre of land is set aside for conservation. When a municipality is 62.5% developed, more extreme cluster zoning was assumed, with lot sizes halved again and three acres set aside for conservation for every acre that is developed.

As municipalities run out of land that can be developed in the simulation, the excess population is distributed among nearby municipalities, based on a gravity model generated from a simple transportation cost-distance map. The cost of travel (e.g. in the form of commuting time) along the major roads was assumed to be half the cost of travel elsewhere on the map. The cost-distance map was produced from a raster map of major roads (see Table A2.1) using the R function COSTDISTANCE from the package GDISTANCE (van Etten 2015). Minor roads were not included as low-cost pathways because we assumed that new roads would be constructed to accommodate new development. Under the gravity model, the probability of spill-over population from a filled municipality going to each other municipality in the state scales with the inverse of the square of the cost-distance between the two (see Wang 2001). The excess population is then allocated by drawing from the resulting probability distribution for municipalities that are not yet filled.

Within municipalities, development and conservation are spatially allocated according to RTs generated for the entire state of New Hampshire. Because New Hampshire municipalities are typically only five to fifteen kilometers across, the driving variables that were most important at larger spatial scales were excluded from the RT analysis. Specifically, we excluded elevation and the distances from major roads, populated places, municipalities of different sizes, and surface water. Other land conversion (forest or other to agriculture and agriculture to forest) was allocated at the statewide level using the same regression trees as the *Linear* scenario.

Population density maps were generated from the population density base map by combining municipal population projections with development maps. In municipalities with a positive population increment, the population density increment for all newly developed land was defined as equal to the population increment for that municipality, divided by the developed land increment for the municipality that time step; in municipalities with a negative population increment, all land area within the municipality was assumed to decrease in population density by the same proportion as the decrease in municipal population as a fraction of previous population.

Impervious cover for newly developed pixels was then calculated from population density by applying the function for percent impervious cover for each newly developed cell. Impervious cover in other parts of the state was assumed not to change.

Community Amenities

In the *Community* family of scenarios, all land development is assumed to occur as redevelopment, so the simulated area of developed land does not change. Patterns of land cover change between forests and agriculture differed between the *Wildlands* and *Food* scenarios. For the *Wildlands* land cover change scenario, we assumed rates of conversion from forest or other to agriculture and agriculture to forest were the same as in the *Linear* scenario, and used the same regression trees to simulate land cover change. For the *Food* scenario, land was assumed to be converted to agriculture at a constant rate such that by the year 2060 there are a total of 3,640 km^2 (900,000 acres) of farmland and pasture in the state of New Hampshire, as described in the Omnivore's Delight scenario (Donahue et al. 2014). To accomplish this, 510 km^2 of forest is converted to farmland each decade. The spatial distribution was determined by the same RT as for the *Linear* scenario, but constrained to areas identified as prime farmland, prime farmland of state-wide importance, or prime farmland of local importance as identified by the Soil Survey Geographic (SSURGO) soils map (see Table A2.1). We assumed no additional change in agricultural land cover after 2060 and that no farmland reverted to forest.

In all scenarios, conservation was assumed to occur at a constant rate such that by the year 2060, all high priority conservation lands identified by the New Hampshire Wildlife Action Plan (WAP), The Nature Conservancy (TNC) New Hampshire portfolio plans and The Society for Protection of New Hampshire Forests (SPNHF) priority lands for conservation have been conserved, giving a total of 12,000 km^2 of conserved land in the state. For each decadal timestep, 1,203 km^2 of undeveloped land is conserved, using the same regression tree as for the Linear scenario, but constrained to the combination of habitat designated Tier 1 by NH WAP with the highest priority land targeted for conservation by the SPNHF and TNC conservation plans for 2014 and 2013 respectively (NH Fish and Game 2005, TNC 2013, SPNHF unpublished data).

Calculation of future population density depends on the population growth scenario (Fig. A2.1). In the *Large Community* scenario, the same municipal-level population growth pattern is assumed is assumed to be the same as for the *Backyard* scenario. For the *Small Community* scenario, we used county-level population projections developed by the NH Office of Energy and Planning (OEP) for 2010-2040 (NH OEP 2014), extrapolated out to 2100 (Bob Scardamalia, RLS Demographics, personal communication). Within counties, new population was allocated among municipalities based on existing population, as was the case for the *Large Community* scenario.

In both population scenarios, population growth within municipalities is accommodated by redevelopment of currently populated developed land. These areas were identified as 30 m cells of developed land with population density greater than 156 people/km^2 (the estimated population density with 4 acre lots) and less than 20,000 people/km^2 (the population density of the larger apartment blocks in downtown Manchester, NH), and for which the new population density would not exceed 30,000 people/km^2. If no land area met these requirements, the minimum population density was lowered first to include all developed cells with density greater than 0, and then, if necessary, to include all developed cells. In municipalities with positive population growth, the population density increment for previously developed land area is defined as the population increment for the municipality as a whole divided by the total area identified as available for growth, and other cells did not change in population density; for municipalities with negative population growth, the protocol for changing population density was the same as for the *Backyard* scenario.

Impervious cover for developed land was assumed to increase with increasing population density as larger residential structures are constructed, and to decrease with decreasing population density as unused buildings and pavement are cleared to make way for parks and gardens. To accomplish this, the impervious cover regression model was first applied to all cells with changing population density to give a preliminary map of new impervious cover. The resulting coverage was compared with the impervious cover for the previous time step, and the new map was used to replaced the previous map for all cells for which either the population density decreased or both population density and impervious cover increased.

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