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The consequences of four land-use scenarios for forest ecosystems and the services they provide

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Abstract. Anticipating landscape- to regional-scale impacts of land use on ecosystems and the services they provide is a central challenge for scientists, policymakers, and resource managers. Working with a panel of practitioners and regional experts, we developed and analyzed four plausible but divergent land-use scenarios that depict the future of Massachusetts from 2010 to 2060 to address two questions: (1) "How do the magnitude and spatial distribution of ecosystem service provisioning vary under the different land-use regimes?" and (2) "What are the synergies and trade-offs among direct human uses, ecosystem services, and habitat quality?" Each scenario specifies the detailed prescriptions for the major uses of the forests, including conversion to residential and commercial development, clearing new farmland, shifting silvicultural practices, and designating forests protected from development. We simulated the land-use scenarios and their interactions with anticipated climate change by coupling statistical models of land use to the LANDIS-II landscape model and then evaluated the outcomes in terms of the magnitude and spatial distribution of (1) direct human uses of the landscape (residential and commercial development, agricultural, timber harvest), (2) ecosystem services (carbon storage, flood regulation, nutrient retention), and (3) habitat quality (forest tree species composition, interior forest habitat). Across all scenarios, conflicts occurred between dispersed residential development and the supply of ecosystem services and habitat quality. In all but the scenario that envisioned a significant agricultural expansion, forest growth resulted in net increases in aboveground carbon storage, despite the concomitant forest clearing and harvesting. One scenario, called *Forests as Infrastructure*, showed the potential for synergies between increased forest harvest volume through the sustainable practices that encouraged the maintenance of economically and ecologically important tree species, and carbon storage. This scenario also showed trade-offs between development density and water quantity and quality at the watershed scale. The process of integrated scenario analysis led to important insights for land managers and policymakers in a populated forested region where there are tensions among development, forest harvesting, and land conservation. More broadly, the results emphasize the need to consider the consequences of contrasting land-use regimes that result from the interactions between human decisions and spatially heterogeneous landscape dynamics.

Key words: ecosystem services; land use; scenarios; socio-ecological futures.

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INTRODUCTION

Predicting regional-scale environmental impacts of land use is confronted by two fundamental challenges. First, the properties of future land-use regimes, that is, the rate, intensity, and spatial pattern of land use, are fraught with a high degree of irreducible uncertainty, which is characteristic of many coupled human and natural systems (Liu et al. 2007). Second, land-use regimes have complex and interactive effects on ecosystem structure and function, so understanding their environmental impacts requires integrative analyses of multiple processes and outcomes (Foley et al. 2005). Integrated scenario analyses offer a powerful approach for overcoming these challenges, advancing sustainability science, and informing land-use planning.

The development of alternative landscape scenarios offers a robust means for understanding the consequences of land-use regimes for a range of outcomes. In this context, scenarios are not intended to forecast the precise or even the probable condition of the future landscape (Thompson et al. 2012). Instead, scenarios describe plausible future trajectories in a way that explicitly incorporate relevant science, societal expectations, and internally consistent assumptions about major drivers, relationships, and constraints (Alcamo and Henrichs 2008). Alternative scenarios are typically developed, then simulated in sets, and are used to represent a range of potential futures, which venture beyond simple extrapolations of the current land-use regime. In this way, scenario studies help to stimulate thinking about the potential changes in systems characterized by high levels of irreducible uncertainty and low levels of controllability (Carpenter and Folke 2006).

Spatial simulations of land-use scenarios are also useful in assessing the potential changes in the amount and distribution of human land use, the supply of ecosystem services, and habitat for plants and animals. Such integrative analyses can reveal the potential conflicts or synergies between benefits to individuals and benefits to society, among different ecosystem services, and between ecosystem services and habitat for organisms (Nelson et al. 2009, Polasky et al. 2010). Land use often presents trade-offs between satisfying an immediate objective and generating unintended and often diffuse impacts on ecosystems. Land uses that are designed to maximize one benefit or service tend to negatively affect others (Costanza et al. 2007, Bennett et al. 2009). Furthermore, land uses that produce high benefits for individual landowners often degrade societal benefits derived from the land (Thompson et al. 2004, 2009, Nelson et al. 2009, Polasky et al. 2010). These relationships are often geographically constrained and the interactions between land use and ecosystem services, and among multiple ecosystem services, can be complex and variable over heterogeneous landscapes and through time (Blumstein and Thompson 2015). Mapping the supply of multiple services can identify the areas that support multiple services and where there are conflicts among competing benefits (Qiu and Turner 2013). Such an approach can be particularly valuable in regions with complex land-use and land tenure mosaics and where uncoordinated land-use decisions are aimed at diverse objectives.

We simulated the impacts of four land-use scenarios on forest ecosystems throughout the state of Massachusetts, in northeastern United States. The scenarios and simulations explicitly incorporate the anticipated impacts of climate change (in terms of the predicted changes in average temperature and precipitation) and their effects on land-use decisions, ecosystem processes, and services. The state is among the most forested and most densely populated in the nation and, as such, serves as an ideal model system for considering aggregate land-use and climate change impacts on forest landscapes. Massachusetts' forests provide important services at the local to global scales, including water filtration for more than 80% of the state's population who receive their drinking water from surface water, harvest of approximately 450,000 m^3/yr of timber, more than one million tons of carbon sequestered annually, and hydrological regulation that reduces flooding risks and supports summer base flows (Blumstein and Thompson 2015).

However, the extent to which the natural landscape will provide these benefits into the future depends in large part on the realized land-use regime. More than 200,000 different landowners privately own >80% of Massachusetts' forest. Since the 1970s, land-cover transitions from forest and agriculture to residential and commercial development have outpaced reforestation, which has culminated in a net loss of forest (Foster et al. 2010). Increasing parcelization is driving social and biophysical fragmentation that complicates the efforts to meet the long-term management goals, including timber harvest and biodiversity conservation (Kittredge et al. 2008). The decisions that landowners make in the future and the manner in which these various forest land uses play out will interact with other aspects of global change to determine the magnitude and geography of forest growth, carbon sequestration, water supply and control, and habitat quality. Examining these patterns and consequences and evaluating the relative importance and synergies among the various land uses and climate change are the central goals of this study.

Our overarching research question was "How are ecosystem structure, function, and services altered under plausible scenarios of land-use change?" More specifically, we asked: (1) "How do the magnitude and spatial distribution of ecosystem services vary under the different land-use regimes and climate change in 2060?" and (2) "What are the synergies and trade-offs among direct human uses, ecosystem services, and forest habitat?" To address these questions, we facilitated a small group of experts to develop a suite of statewide land-use scenarios, used spatial models to simulate how the forest landscape would change over 50 yr, and then evaluated the scenarios by quantifying their effects on three different types of environmental outcomes: (1) direct human uses, such as changes in the area of developed land and the amount and type of harvested forest products; (2) ecosystem services related to climate, flood regulation, and the provisioning of clean water; and (3) forest habitat it relates to the changes in forest structure, composition, and landscape configuration.

METHODS

Scenario development

We recruited a group of eight natural resource professionals in leadership positions in Massachusetts to assist with the development of land-use scenarios that are relevant to state and local decision making (Welp et al. 2006). This approach is distinct from broad participatory scenario development approaches, which is often aimed at the development of consensus-based normative scenarios (cf. Webler 1995, Schmitt Olabisi et al. 2010). Consistent with our aims, we sought senior experts in land-use planning, water policy, and forest policy and conservation, selected for their experience, access to data, and policy acumen. Please see *Acknowledgments* for a list of participants.

Over a series of meetings, the group developed four land-use scenarios that were designed to be plausible, but divergent in terms of the major drivers of land use. The *Recent Trends* scenario represents a linear continuation of the rate, pattern, and intensity of recent land use, whereas the remaining three were qualitative storylines that envisioned alternatives to the *Recent Trends*. After the qualitative scenarios were in place, the group and the researchers developed decision rules for the scenarios that served as input parameters for landscape simulations (sensu Mallampalli et al. 2016), including developing a suite of land-use prescriptions (i.e., types of forest conversion in terms of the size and intensity of events and type of harvests with regard to the species and age of trees harvested), the rate that each land-use prescription was applied per year, and the spatial distribution of land-use prescriptions within the state (Appendix S1). They made these determinations by using the empirical information on the type, intensity, and distribution of land use within the *Recent Trends* (Thompson et al. 2011) and arriving at agreement on how each scenario would depart from that scenario. The qualitative scenarios and the associated simulation parameters are given in the *Results* section.

Simulating scenarios

For each scenario, we simulated landscape change within the entire 20,300 km^2 of land area within the state of Massachusetts, United States (69.9–73.58° E, 41.3–42.98° N) at a 0.25 ha grain size. We modeled forest succession, natural disturbance (gap-scale wind), land use, and climate impacts at 5-yr time steps for 50 yr—ostensibly representing the years 2010—2060. While we tracked all land-cover classes throughout the state and the associated effects on various services, our focus was on the fate of the 12,800 km^2 classified as forest in the 2005 land-cover map produced by and obtained from the state's Office of Geographic and

Information (MassGIS; http://www.mass.gov/mgis/). As a result, we simulated the area moving from the forest class to other land-cover classes, such as residential or agriculture, but did not simulate the changes from non-forest classes in 2010 to other classes.

We simulated forest and land-use dynamics using LANDIS-II v 6.0 and its Biomass Succession 3.0 extension (Scheller and Mladenoff 2005, Thompson et al. 2011), a spatially interactive landscape modeling framework. LANDIS-II is designed for simulating the geographic distribution and aboveground biomass of individual tree species. It simulates forest dynamics over spatial scales ranging from 10^4 to 10^7 ha, including establishment, species competition and succession, decomposition, and biomass accumulation, while integrating natural disturbances such as wind and anthropogenic disturbances such as forest conversion and harvest. Within the model, tree growth and establishment are a function of soils and climate (Scheller and Mladenoff 2005). We modeled the 25 most abundant tree species in Massachusetts as determined by stem counts within forested plots in the U.S. Forest Service's Forest Inventory and Analysis (FIA) database (Woodall et al. 2010). Species attributes such as shade tolerance, seeding distance, and sprouting ability were determined from the literature (see Appendix S2). Details regarding the parameterization, calibration, validation, and sensitivity analysis of LANDIS-II for Massachusetts have been published previously in Thompson et al. (2011).

All four land-use scenarios included the same future climate conditions. We obtained the climate data from the Northeast Climate Impacts Assessment Group (NCAIG, available online: www.northeastclimateimpacts.org). The data are an average of three general circulation models (Pope et al. 2000, Washington et al. 2000, Delworth et al. 2006), all portraying the Intergovernmental Panel on Climate Change (IPCC) A1FI emissions scenario (Nakicenovic 2000). This climate scenario represents a "fossil fuel intensive" future where atmospheric carbon dioxide concentrations reach 640 ppm in 2060, generating high rates of warming compared with the other emission scenarios. In Massachusetts, the A1FI emissions scenario manifests as a 2–3°C increase in average annual temperature and a 4–6% increase in average annual precipitation by the year 2060.

We simulated timber harvests and forest conversion to developed or agricultural land using the Biomass Harvest Extension v.2.1 (Gustafson et al. 2000) and the Land Use+ v.1.0 extension (Thompson et al. 2016); both extensions track the forest biomass removed during land use and simulate the impacts on residual trees within a site. The scenarios dictate the types of land uses, the area of forest affected by each land use at each time step, their spatial distribution within the state, and their intensity (Table 1). The scenarios do not represent any explicit change in human population but, instead, represent the changes in the forest landscape that result from changing economic conditions and opportunities, using historical forest changes as a reference.

We did not attempt to predict the precise location of future forest conversion or harvesting; instead, we defined geographic probability zones based on social and biophysical parameters; the zones then dictated the total area affected by each of the land-use prescriptions (sensu Thompson et al. 2011). Within a probability zone, the spatial allocation of land-use prescriptions was random. The probability zones used in the *Recent Trends* scenario were developed based on regression tree analysis, which quantified the relationships between recent land-use change and a suite of potential predictors (e.g., distance from roads, population density, slope). For forest conversion to developed use, we analyzed all forests converted to developed uses in the period spanning 1999—2005 (following DeNormandie 2009), which are the dates of the most current and accurate land-cover maps available. For timber harvest, we used data describing the location and intensity of all harvests in the state during the period spanning 2000—2010 (Kittredge and Thompson 2016).

The group subjectively manipulated the empirically developed regression tree from the *Recent Trends* to produce maps for each of the land uses in each of the remaining scenarios. To do so, the group was guided through a process of adding new nodes to the tree, changing the suite of predictor variables or the values of nodes for existing predictor variables that, in turn, resulted in a map of the spatial configuration depicted in each of the storylines represented in the alternative scenarios (i.e., all but the *Recent Trends* scenario).

We then produced new probability zone maps based on their decision trees (i.e., modified regression trees) and again allowed them to make modifications (Appendix S1). We iterated through this sequence until the participants were satisfied that each map represented the distribution of land uses throughout the state that they envisioned for each of their scenarios. The maps were then used as inputs to the LANDIS-II simulations to dictate the probability of simulating land use in each zone.

The panel developed a suite of land-use prescriptions, which dictate the specifications for individual land-use events including conversion, harvest, and conservation in terms of their size, intensity, and, in the case of harvesting, the tree species removed. Each prescription was then set as a percentage of the total amount of that land use per time period. The expert panel developed four prescriptions for simulating forest conversion to development, five prescriptions for timber harvest, one prescription for forest conversion to agriculture, and two prescriptions for conservation (Table 1).

We simulated 50 yr of forest growth, succession, and land use at 5-yr time steps and replicated each scenario three times. The low number of replicates reflects a trade-off between computing time and capturing stochastic variation. Without large infrequent disturbances, the small-scale stochastic components operating within these models stabilize to their average when measured at watershed to landscape scales (Gustafson et al. 2010, Thompson et al. 2011). For this reason, we report the average values below with no estimate of variation.

Evaluating scenarios and simulations

We estimated the changes in impact metrics related to direct human uses, ecosystem services, and habitat quality (Table 2). Because land cover alone can be a poor proxy for ecosystem functions and services (Konarska et al. 2002, Seppelt et al. 2011), we coupled the estimates of land-cover change to ecosystem and hydrological models and to a range of publicly available land-use databases to better estimate the impact of land use on socio-ecological processes (sensu Qiu and Turner 2013, Blumstein and Thompson 2015).

Direct human uses.—We report the area converted from forest to developed and agricultural land within each of the scenarios. In addition, we summarized the removed wood biomass by land use (i.e., timber harvest or conversion to developed uses and agriculture) over time, assuming that wood removed during harvest and forest conversion is similarly used. The model describes forest harvesting in terms of the total removed biomass. Timber harvest is often considered a provisioning ecosystem service, but for the purposes of this study is classified as a direct human use because it generates a financial return to landowners. This distinction allows us to evaluate synergies and conflicts with ecosystem services that lack markets to generate a financial return.

Ecosystem services.—

1. Climate regulation—aboveground forest carbon. LANDIS-II simulates the growth and composition of tree species cohorts and tracks the resulting changes in aboveground live tree biomass. We assumed that half of that woody biomass was carbon and reported the changes associated with each scenario at the state scale. Thompson et al. (2011) and Appendix S2 describe the calibration, validation, and sensitivity analysis of this parameterization of LANDIS-II.

2. Flood regulation—impervious surfaces. We estimated the percentage of each land-cover class that is impervious to water within the 50-m land-cover map using a high-resolution (50-cm) impervious surface map, following the methods described in Blumstein and Thompson (2015) (Table 3, Appendix S3). We assumed that the relationship between land cover and percentage impervious is stationary over time and assigned the average percentage impervious to each land-cover class within the simulations. We tracked the area of impervious surfaces within each watershed and noted when a watershed exceeded 7% and 12% imperviousness, which are policy-relevant thresholds related to fish conservation and water quality, respectively (Bellucci 2007, Armstrong et al. 2011).

3. Flood regulation—average annual water runoff. Changes in surface water runoff associated with climate and land-cover change present adaptation challenges for communities and decision makers as they contend with increased peak flows and the associated flooding risk. The InVEST water yield model calculates a simple net hydrological balance—precipitation minus

Table 1. Specification for land-use prescriptions simulated for each of the scenarios.

Land-use category and land-use prescriptions by scenario	*Recent Trends*	*Opportunistic Growth*	*Forests as Infrastructure*	*Regional Reliance*
Forest conversion extent (ha/yr)	3000	4000–6000	2600–2800	1600–2200
Small development: Within a 1-ha area, remove 25% of all species/age cohorts and suppress all future regeneration	65%	50%	30%	60%
Medium development: Within a 1-ha area, remove 50% of all species/age cohorts and suppress all future regeneration	25%	20%	40%	35%
Large development: Within a 2-ha area, remove 50% of all species/age cohorts and suppress all future regeneration	9%	20%	25%	4%
Very large development: Within a 4-ha area, remove 50% of all species/age cohorts and suppress all future regeneration	1%	10%	5%	1%
Agriculture (ha)	0	0	0	800–4000
Agricultural development: Within a stand (3—20 ha), remove all species/age cohorts and suppress all future regeneration	0	0	0	100%
Timber harvest extent (ha/yr)	10,500	8000–13,000	13,500–18,000	14,500–24,400
Long-term revenue: Remove 100% of white pine older than 100 yr and 100% of red oak, red maple, hemlock, and sugar maple older than 80 yr. Leave 15% slash. Harvest size = 8–20 ha (% of annual extent)	66%	30%	30%	20%
Short-term revenue: Remove 100% of white pine older than 60 yr and 100% of red oak and sugar maple older than 80 yr. Leave 15% slash. Harvest size = 8–20 ha	34%	0	0	0
Short-term revenue with biomass: Remove 100% of white pine older than 60 yr and 100% of red oak and sugar maple older than 80 yr. Add biomass by removing 30% across all ages and size classes. Leave only 2% slash. Harvest size = 10–20 ha	0	40%	10%	50%
Biomass clear-cut: Remove 100% of all species and size classes. Leave only 2% slash. Harvest size = 10–16 ha	0	20%	0	20%
Improvement silviculture: Remove 80% of all trees older than 130 yr and 70% of all non-commercial species older than 40 yr. Harvest size = 10–20 ha	0	10%	60%	10%
Conservation extent (ha/yr)	4000	800–2000	4045–6070	1620–2225
Conversion and harvest prohibited	20%	20%	20%	20%
Conversion prohibited; harvest allowed	80%	80%	80%	80%

Note: Annual extent for each land-use category (i.e., forest conversion, timber harvest, agriculture, and land protection) is followed by the percentage allocation by land-use prescription.

evapotranspiration (ET)—to estimate the runoff on an annual time step at the watershed scale (Tallis et al. 2013). While InVEST does not provide production equations suitable for estimating the changes in runoff for discrete events (e.g., storm water), it does simulate the changes in average annual water runoff. The model requires several inputs that we obtained through a literature review and from public data repositories (Blumstein and Thompson 2015). We estimated temperature and precipitation at each time step by fitting regression models to the NCAIG temperature and precipitation maps (Appendix S4).

4. *Clean water provisioning—total nitrogen and total phosphorous runoff*. We assessed the land-cover impacts on water quality by estimating the changes in total nitrogen (TN) and total phosphorous (TP) export using the InVEST water purification model following the methods and using the calibration and validation described in Blumstein and Thompson (2015). We made small modifications to the model to incorporate the changes in water yield resulting from the predicted changes in climate estimated from the NCAIG climate change data (precipitation and actual evapotranspiration)

Table 2. Data requirements and outputs for the ecosystem services presented.

Metric	Process	Output	Data requirement
Direct human use			
Developed land	LANDIS-II land-use+ module simulates the conversion of forest to developed uses based on the specifications for annual amount, spatial allocation, and intensity dictated by the scenarios	50-m resolution LULC maps at 5-yr intervals	• LANDIS-II succession and disturbance parameters (Thompson et al. 2011) • Initial condition LULC and forest composition maps • Scenario land-use prescription allocation (Table 3) • Scenario prescription definition and distribution • Scenario land-use allocation maps
Agriculture land	LANDIS-II land-use+ module simulates the conversion of forest to agricultural uses based on the specifications for annual amount, spatial allocation, and intensity dictated by the scenarios	50-m resolution LULC maps at 5-yr intervals	Same as above
Harvested biomass	LANDIS-II land-use+ module simulates the removal of biomass based on the specifications for annual amount, spatial allocation, and harvest prescriptions dictated by the scenarios	Mg of harvested woody biomass at 5-yr intervals	Same as above
Ecosystem service			
Carbon (climate regulation)	LANDIS-II biomass succession module simulates the growth succession and disturbance of tree species-by-age cohorts and tracks the changes in their aboveground biomass	50-m resolution maps showing live aboveground biomass (Mg) at 5-yr intervals	Same as above
Impervious surfaces (flood regulation)	Developed relationship between land-cover classes and percentage imperviousness at initial condition and then applied those relationships to output LULC maps at each time step	50-m resolution maps of percent impervious cover at 5-yr intervals	• Output LULC maps for each five-year interval • Initial condition impervious map (50-cm Vexcel UltraCam acquired, April 2005)
Total nitrogen and phosphorus runoff (clean water provisioning)	Used a modified version of the InVEST nutrient export module, which calculates how much nutrient is lost and gained along a flow path to a stream and aggregates over the watershed while incorporating the effects of climate over time	Watershed maps showing nutrient export (kg/yr)	• Output LULC maps for each five-year interval • DEM (m) • Water yield output (mm, output from water yield) • Export coefficient ($g \cdot ha^{-1} \cdot yr^{-1}$) • Nutrient filtration efficiency (%) • Watershed boundary shapefiles
Average annual water runoff (flood regulation)	InVEST water yield module calculates the water yield per 50-m cell as the difference between rainfall and evapotranspiration by land-use class and then aggregates by watershed	Watershed maps showing the average annual water yield (m^3/yr)	• Output LULC maps for each 5-yr interval • Projected mean annual precipitation (mm) for 2010 to 2060 based on the A1FI scenario • Mean annual reference evapotranspiration (mm) • Plant available water content (PAWC, fraction, % value) • Evapotranspiration coefficient • Root depth (mm) • Zhang coefficient [0, 10] (zhang = 4) • Watershed boundary shapefiles

Table 2. Continued.

Metric	Process	Output	Data requirement
Habitat conservation			
Forest composition	Used Landis-II to simulate forest compositional changes over time in response to timber harvest, succession, and climate change	50-m resolution maps of aboveground biomass (Mg) by species at 5-yr intervals	Same as rows 1:3 above
Interior forest habitat quality	Used a modified version of the InVEST biodiversity module, which calculates the forest habitat quality per cell	50-m resolution maps of forest habitat quality index (unitless 0–100)	• Output LULC maps for each five-year interval • Threat impact distance (km) • Relative threat impact weight [0,1] • Threat raster maps • Habitat sensitivity to threats [0,1] • Accessibility to each LULC type [0,1] (protected = 1)

to affect nutrient runoff. We obtained loading and filtration parameters for each land-cover class through a review of the literature and then calibrated them using U.S. Geological Survey (USGS) estimates of land-cover-associated nutrient export, as interpreted through their SPARROW surface water quality model (Moore et al. 2004) (Table 3, Appendix S5).

5. Forest habitat quality—forest composition. We summarized the changes in simulated forest tree species composition within each scenario and reported the changes in their species abundance (i.e., live biomass by species) over time.

6. Forest habitat quality—interior habitat. We used a modified version of the InVEST habitat model, which is designed to map the extent and quality of a user-defined habitat type (Tallis et al. 2013). We focused on interior forest habitat, which is a valued conservation resource in the state and is particularly vulnerable to the changes in land use (Forman and Deblinger 2000). The InVEST approach quantifies the degradation of interior habitat in a grid cell as a function of the land cover of that cell, the land-cover classes in surrounding cells, and the sensitivity of the habitat to threats from surrounding land cover. We modified the InVEST habitat model in several ways that permit interior forest habitat to be temporarily degraded by timber harvest, thereby permitting the direct comparison of degradation values across time and across scenarios. The specifications of land-cover impacts on interior habitat are given in Appendix S6. In our approach, each pixel that was forested at the beginning of the simulation is assigned a degradation value at every time step: A value of

Table 3. Selected input parameters for land-cover classes used to estimate the changes in ecosystem services.

	Impervious surfaces	Habitat degradation	Average annual water yield	Total N runoff	Total P runoff
Name	Impervious surfaces (%)	Threat impact distance (km)	Plant evapotranspiration coefficient (etk × 1000)	Nitrogen loading ($g{\cdot}ha^{-1}{\cdot}yr^{-1}$)	Phosphorus loading ($g{\cdot}ha^{-1}{\cdot}yr^{-1}$)
Very large development	58.5	1.40	225	28,000	808
Large development	38.24	1.26	300	26,825	789
Medium development	24.07	0.96	350	26,800	785
Small development	16.26	0.79	400	25,450	779
Conifer	2.42	NA	988	504	474
Mixed	2.42	NA	988	413	402
Deciduous	2.42	NA	988	320	339
Agriculture	4.36	1.18	683	17,588	993

Note: Parameter values for all land-cover classes as well as information on data sources can be found in the supplementary material.

100 indicates that a forested cell is ideal interior habitat unaffected by any surrounding land use, while a value of zero indicates that the cell is no longer interior forest habitat. To summarize the changes at the scale of the entire state, we averaged habitat quality scores of all pixels (sensu Bhagabati et al. 2012).

RESULTS

Scenario development and simulation

Four scenarios were analyzed: the empirically based *Recent Trends* scenario and three alternative scenarios developed by the panel of experts (Fig. 1). See Table 1 for the details of land-use prescriptions.

Recent Trends—qualitative scenario.—This scenario represents a future in which the rate, geographic distribution, and intensity of land use emulate the period spanning 1999—2005. This period had a relatively low rate of residential and commercial development within the forested landscape; average forest loss to development was 3000 ha/yr. While this is a short reference period, the spatial configuration and drivers of development in the region are stable over many decades, even as the rate of development varies. The rate in the *Recent Trends* period compares with 6500 ha of forest loss per year during the period spanning 1980—1985 and 4500 ha/yr from 1985 to 1999 (DeNormandie 2009). There were negligible changes in agricultural lands during this time. Timber harvesting rates were moderate, with 10,500 ha harvested annually (less than 1% of the forest), mostly in the western part of the state (McDonald et al. 2006), have been relatively steady over the past 30 years, and have targeted high-value trees.

Recent Trends—simulation parameters.—Forest loss to commercial or residential development occurs at a rate of 3000 ha/yr, with most occurring as small (65%) and medium (25%) residential patches (Fig. 2, Table 1). Development is constrained to non-protected lands and is most prevalent where population density is highest (Appendix S1). For example, one-third of all forest loss to development occurs within the 7% of the state's forests where census block population density is >267 people/km. Timber harvest occurs at a rate of 10,500 ha/yr in harvest events ranging from 8 to 20 ha and focuses on the selective cutting of white pine, red oak, and sugar maple (Fig. 2, Table 1). Low road density is the best predictor of harvest occurrence, and overall, most harvest occurs in the western part of the state (Appendix S1). Conservation occurs at a rate of 4000 ha/yr, and the spatial allocation was random.

Opportunistic Growth—qualitative scenario.—This scenario depicts a future in which environmental protection and regulation is sharply reduced and the management and use of natural resources is determined by private interests with minimal government intervention. The objective of most natural resources policy in this scenario is to maximize economic returns to private landowners and to serve private sector interests, which may include selling-off or lifting of restrictions on public lands. The rate of forest conversion to developed uses throughout the simulation occurs at the highest levels experienced in recent decades, and the pattern of development is opportunistic rather than planned and is therefore more dispersed. Amenity development is on the rise and many rural areas are experiencing development for commuters and second homes. Timber harvest has a brief surge early in the scenario due to the introduction of biomass energy markets, but global competition and conflicts with new rural residential development eventually reduce the rate of harvest. Conservation is not an important land-use goal.

Opportunistic Growth—simulation parameters.—The rate of forest loss to development begins at 4000 ha/yr and increases to 6000 ha/yr over the first two decades (Fig. 2). Forest loss to development occurs in slightly larger parcel sizes than in *Recent Trends* (Table 1). Between 1% and 3% of development occurs on lands formally classed as protected conservation land. Development on non-protected land initially emulates the distribution of *Recent Trends*, but becomes progressively less concentrated around cities over time (Appendix S1). The rate of timber harvest increases from 11,000 to 13,000 ha/yr during the first 20 yr and then falls to 8000 ha/yr for the remaining three decades. Most harvesting is more intense than in *Recent Trends* due to the existence of biomass energy markets and the lack of forest practices oversight; this includes

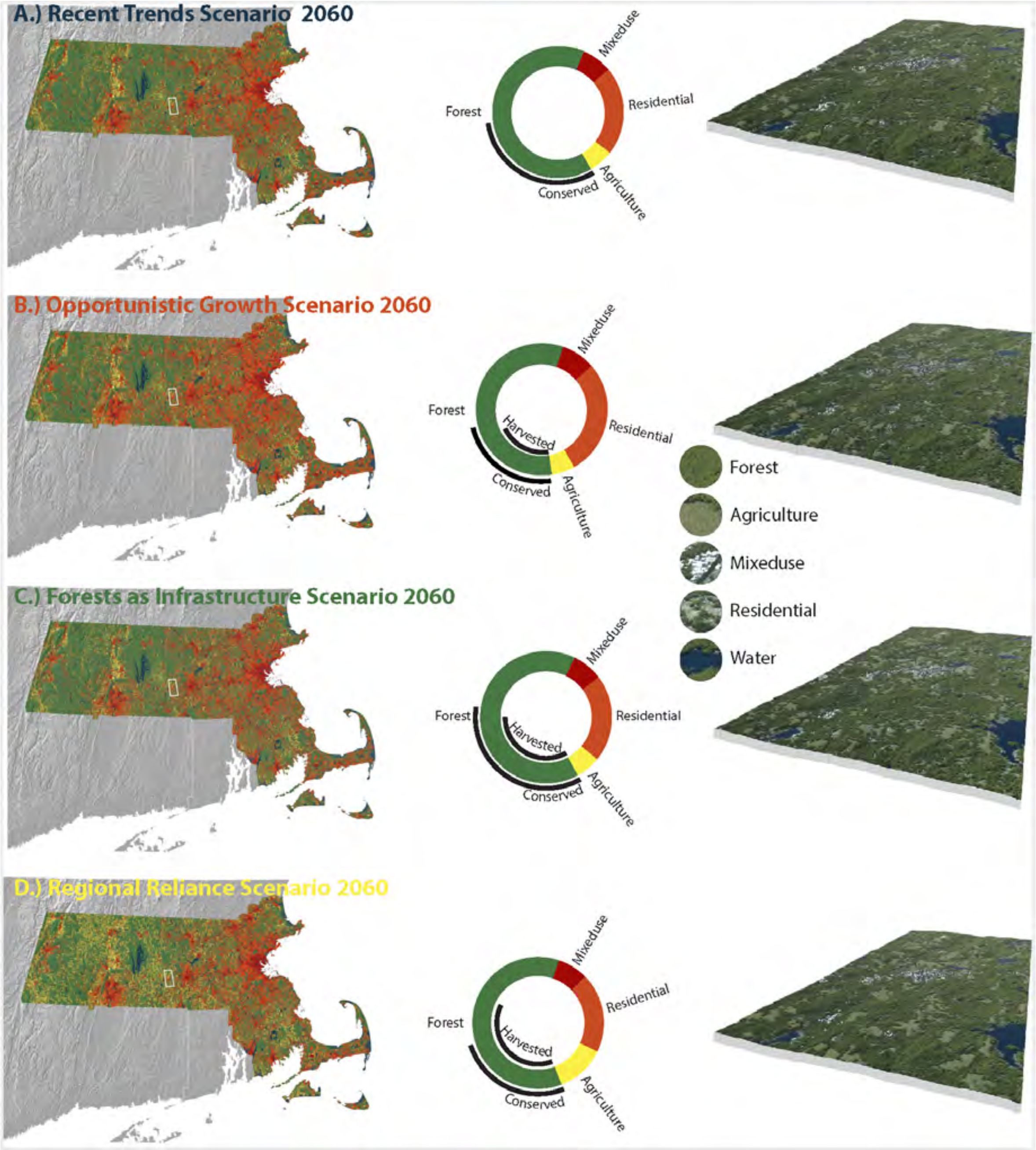

Fig. 1. Land-cover maps and aerial terrain visualizations showing one replicate simulation of the (A) *Recent Trends*, (B) *Opportunistic Growth*, (C) *Regional Reliance*, and (D) *Forests as Infrastructure* scenarios after 50 yr of simulated land use.

20% of all harvested area in clear-cuts. The spatial distribution of harvest is somewhat more dispersed than in *Recent Trends*, but generally follows the same pattern. New forest conservation occurs at a rate of 2000 ha/yr, declines to 800 ha/yr in the first decade where it remains for the rest of the simulation (Table 1).

Forests as Infrastructure—qualitative scenario.—This scenario represents a future in which active management of forests and watersheds is viewed

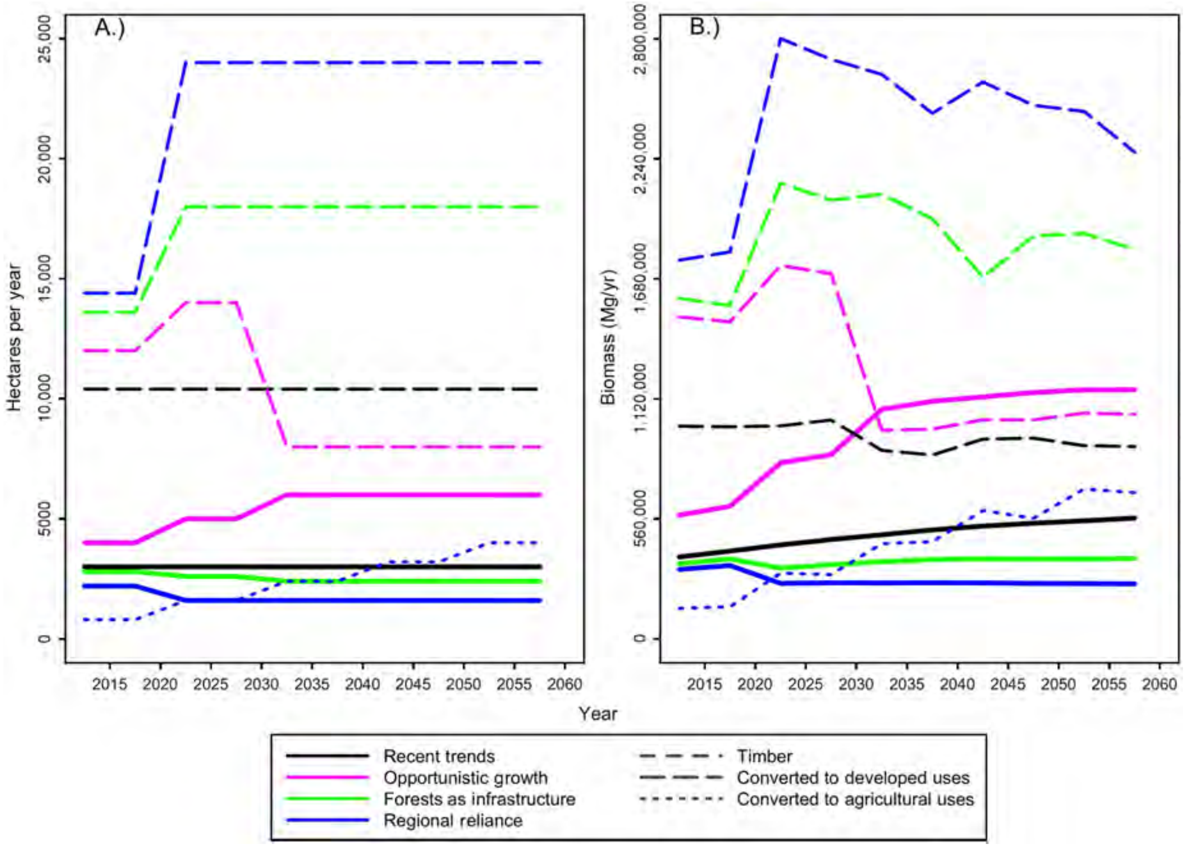

Fig. 2. (A) Annual area affected by each land use as prescribed by the four scenarios (RT, *Recent Trends*; OG, *Opportunistic Growth*; RR, *Regional Reliance*; and FAI, *Forests as Infrastructure*). (B) Forest biomass removed by land-use type as simulated within the LANDIS-II model. Note that only the *Regional Reliance* scenario includes agricultural conversion.

as vital to sustaining the state's infrastructure that directly supports people and provides amenities they rely on. Current policy priorities related to smart growth and land-use planning, forest practices, and climate action planning are significantly advanced, as are the goals set out within a regional conservation vision (Foster et al. 2005). Consequently, the natural infrastructure of the state is actively managed to maximize ecosystem services and the benefits they provide for high-quality and efficient provision of energy, water, transportation, housing, habitat, and green commons. Long-term silvicultural planning is widely adopted and designed to produce significant amounts of timber and energy while also promoting the desired tree species and structure. Economic development is similar to *Recent Trends* and forest losses to developed uses occur at moderate rates, but new development is planned around smart growth principles and is concentrated into larger units and is mostly around cities. The pace of forest conservation doubles from the historical average and preferentially targets high-priority areas.

Forests as Infrastructure—simulation parameters.—The rate of forest loss to development drops from 2800 to 2600 ha/yr through the first two decades and then remains at that level for the rest of the simulation (Fig. 2). Forest loss to development generally occurs in larger parcel sizes to simulate the clustered development (Table 1). Development is concentrated with 75% occurring within 20 km of city centers (Appendix S1). The rate of timber harvest increases from 14,100 to 18,200 ha/yr during the first decade and remains there for the rest of the simulation (Fig. 2). Sixty percentage of harvest is carried out in "improvement silviculture," which is a prescription developed by group to remove small trees and undesirable tree species while promoting large, oaks, white pine, and sugar maple. Uniquely, this prescription requires a return to the site after 20 yr to help maintain the stand characteristics. The spatial distribution of harvest is more dispersed than in *Recent Trends*, but generally follows the same pattern. New forest conservation builds from 4000 to 7500 ha/yr. Sixty-six percentage of new conservation occurs within priority habitat as defined by the state (Woolsey et al. 2010) and the Nature Conservancy (Anderson et al. 2012) (Table 1).

Regional Reliance—qualitative scenario.—This scenario represents a future in which a global energy crisis drives the dramatic increases in the cost of key commodities, namely oil and food, which is forcing a new paradigm of land use motivated by interest in greater reliance on locally sourced resources. Reliance on foreign oil is replaced to a great extent by harvesting of wood for fuel wood and biomass energy production within the state. Rising gas prices encourages development near cities to reduce the transportation costs associated with commuting by car. At the same time, droughts and heightened competition for land for biofuels in the Midwest have caused food prices to soar, driving a growing market for local foods and an agricultural renaissance in New England, which results in high rates of forest conversion to pasture and cropland, particularly on prime soils. The amount of new agriculture, while significant, still results in less total agricultural land than existed in 1950. In addition, timber harvests for fuel wood, municipal energy production, and timber production are at all-time highs. There is comparatively little forest lost for development and what does occur is close to cities.

Regional Reliance—simulation parameters.—The rate of forest loss to development declines from 2200 to 1600 ha/yr during the first 15 yr and then remains at that level for the rest of the simulation (Fig. 2). Most forest loss to development occurs in small residential parcels, and 70% of all development occurs <20 km from a city center (Appendix S1). The rate of timber harvest increases from 15,000 to 25,000 ha in the first 10 yr and then remains at that level throughout the remainder of the simulation. Harvesting is also more intense than in *Recent Trends* due to the demand for firewood and the thriving biomass energy markets (Table 1). The spatial distribution of harvest is dispersed throughout the state, which is necessary simply to find the forest area required to meet the demand. This is the only scenario where forest is converted to agriculture. The rate of agricultural expansion increases throughout the scenario, and by year 50, there is 120,000 ha of forest lost to agriculture in the state (Fig. 2). The distribution of new agriculture is prioritized toward land classified as prime agricultural soils (i.e., 65% of new agriculture is USDA-classified prime soils). The annual rate of forest conservation is 1600 ha/yr with a random spatial allocation of conservation patches.

Scenario evaluation

Direct human uses.—

1. Land-use change. At the start of the simulations, 64% of the land area in the state was forested (Fig. 1). Through the 50-year simulations, forest cover declined to 57% in the *Forests as Infrastructure* scenario, 56% in the *Recent Trends* scenario, 53% in the *Regional Reliance* scenario, and 50% in the *Opportunistic Growth* scenario. The area of forest converted to residential and mixed-use development ranged from 86,000 ha in *Forests as Infrastructure* to 270,000 ha in *Opportunistic Growth*. While only 86,000 ha was converted to development in the *Regional Reliance* scenario, another 120,000 ha was converted to agriculture, leading to a total of 206,000 ha.

2. Removed biomass. The amount of woody biomass removed from the forested landscape varied widely among scenarios, land uses, and through time (Fig. 2). As a result of comparatively low-intensity timber harvest prescriptions and only moderate levels of development, the *Recent Trends* scenario removed the least total forest biomass over the 50-year simulation (68.9 Tg), with 65% (44.5 Tg) explicitly removed for timber. The *Forests as Infrastructure* scenario removed 105.4 Tg of biomass with 83% (87.3 Tg) coming from timber harvest (the rest from development). The *Opportunistic Growth* scenario removed 110.9 Tg of biomass with 57% (62.6 Tg) coming from timber harvest. The *Regional Reliance* scenario removed, by far, the most biomass (154.5 Tg) with 77% (119 Tg) coming from timber harvest and (uniquely among the scenarios) and with 14% (21.7 Tg) coming from agricultural clearing. However, within the *Regional Reliance* and *Forests as Infrastructure* scenarios, high levels of annual harvest area and the terms of some silvicultural prescriptions that included repeat entries resulted in many individual sites experiencing multiple harvests during the 50-year simulations. This reduced the per area harvest volume over time within these scenarios (Fig. 2).

Ecosystem services.—

1. Climate regulation—aboveground forest carbon. Continued forest growth was a primary driver of regional aboveground live carbon dynamics, and in three of the four scenarios, the state's forests remain a net sink throughout the 50-yr simulation (Fig. 3). The *Recent Trends* scenario experienced the largest gains, increasing from 105 to 148 Tg C at the state scale. Carbon increased to 143 Tg C in the *Forests as Infrastructure* scenario and to 124 Tg C in the *Opportunistic Growth* scenario. *Regional Reliance* was the only scenario that experienced a net decrease in carbon, declining from 105 to 103 Tg. The amount of carbon sequestered varied geographically (Fig. 4). The largest absolute gains occurred in the west, but the largest percentage gains were seen in the east, due to the relatively lower starting biomass there.

2. Flood regulation—impervious surfaces. At the state scale, after 50 yr of simulated land use, there were 18,101 ha of new impervious surfaces in the *Regional Reliance* scenario, 20,199 ha in the *Forests as Infrastructure* scenario, 23,337 ha in the *Recent Trends* scenario, and 59,915 ha in the *Opportunistic Growth* scenario (Fig. 3). This represents an increase from 9.6% of the state at the beginning of the simulation to 10.5%, 10.6%, 10.7%, and 12.5%, respectively. Impervious surfaces within watersheds ranged from 3% to 24% at the beginning of the simulations and rose to 5% to 26% in *Opportunistic Growth*, 4% to 24.5% in *Recent Trends*, and 4% to 24% in both *Forests as Infrastructure* and *Regional Reliance* scenarios. The number of watersheds with 12% or more impervious surface rose from 8% at the beginning of the scenario to 14% in the *Opportunistic Growth*, 12% in *Recent Trends*, 11% in *Forests as Infrastructure*, and 10% in *Regional Reliance*. Interestingly, due to the more concentrated pattern of development within the *Forests as Infrastructure* scenario, two watersheds crossed the 12% impervious level before the *Recent Trends*, despite having less overall development. Across all scenarios, watersheds in the more urbanized eastern third of the state experienced higher percentages in impervious surfaces, but lower relative changes (Fig. 4).

3. Flood regulation—average annual water runoff. The combination of increased precipitation associated with climate change and decreased evapotranspiration (ET) due to land-use change led to increases in the average annual water yield (volume that runs off the land and reaches streams) in all scenarios. By the end of the simulation, at the state scale, *Opportunistic Growth* experienced the greatest increase in runoff (12%), followed by *Regional Reliance* and *Recent Trends* (both 9%), then *Forests as Infrastructure* (8%; Fig. 3). Watershed scale increases in runoff ranged from a low of 6.4% in the *Forests as Infrastructure* scenario to a high of 15% in the *Opportunistic Growth* scenario in rapidly developed watershed in the northeast (Fig. 4). In general, watersheds in the eastern third of the state, where forest conversion to development uses (and impervious surfaces) is more prevalent, tended to experience larger increases in water runoff.

4. Clean water provisioning—total nitrogen and total phosphorous runoff. TN production and export to rivers were highest in the *Opportunistic Growth* scenario. TN export increased 57% and TP export increased 12% over 50 yr in this scenario. *Regional Reliance* experienced the next highest increase in nutrient export, with a 35% rise in TN and an 11% rise in TP (Fig. 3). In the *Recent Trends* scenario, TN and TP increased by 28% and 5%, respectively. *Forests as Infrastructure* had a 22% and 4% increase in each nutrient. Because loading and filtration coefficients for TN and TP are strongly correlated, the spatial patterns of nutrients runoff within individual scenarios were similar (Fig. 4). Increases in N export rates among scenarios and watershed were, in general, correlated with the increases in forest conversion, and in particular, very large development, and agriculture. Increases in P export were similarly correlated with the increases in loading from very large development and agriculture and lost filtration capacity with lower forest cover.

5. Forest habitat quality—forest composition. The changes in abundance of individual tree species show the distinctive impacts of each scenario.

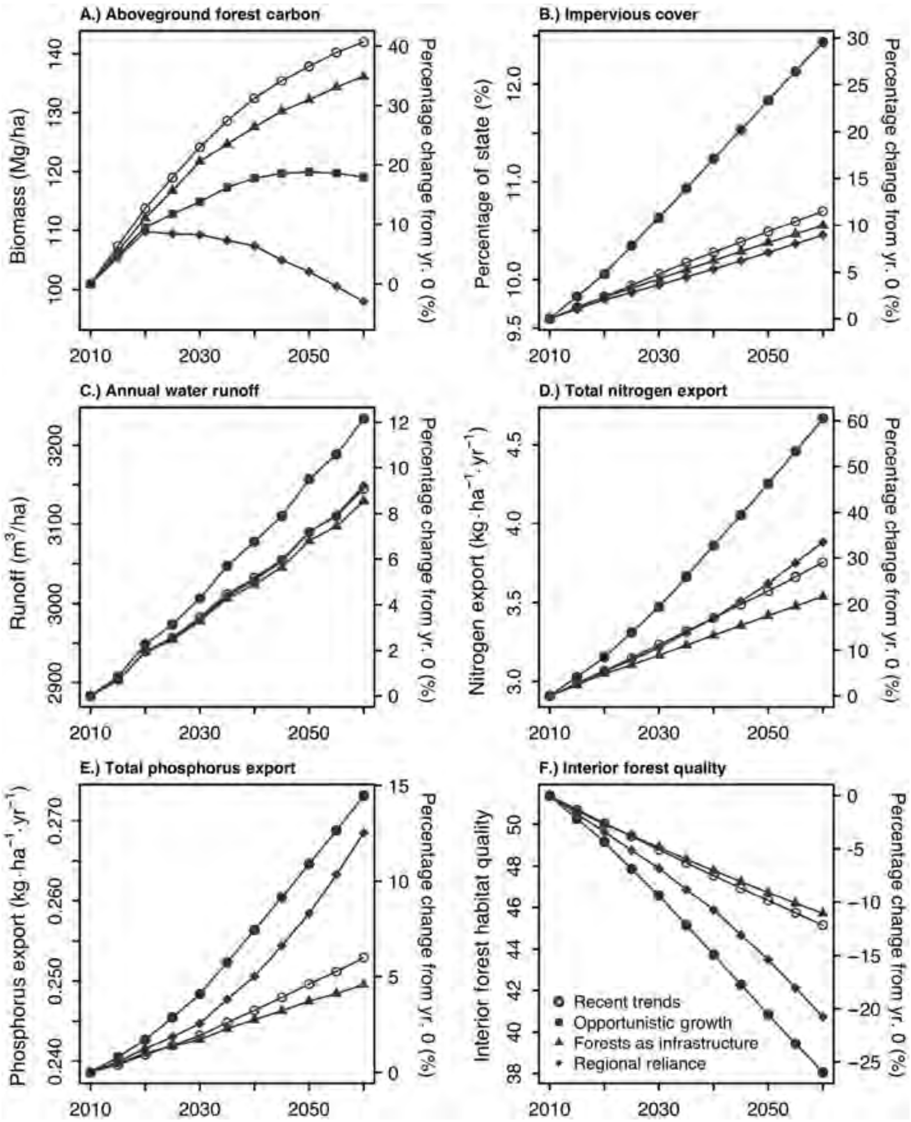

Fig. 3. Statewide changes in biophysical indicators of ecosystem services and forest habitat throughout the simulations of four land-use scenarios. Right-side y-axis shows the percentage change from time 0, whereas left-side y-axis shows the changes in units conventional to that metric. Note that the left-side y-axis for runoff, nitrogen export, and phosphorous export is given in units per unit-area averaged across the state. The x-axis in all graphs denotes the simulation year.

For example, in three of the four scenarios, red maple replaced white pine as the most abundant species in the state (Fig. 5). The exception was *Forests as Infrastructure* scenario, which included a substantial amount of "improvement silviculture" that harvested red maple and retained large old white pine. Selective harvests in the *Forests as Infrastructure* scenario also produced large increases in red oak, sugar maple, and white pine. Red maple and black birch increased most under the *Recent Trends* scenario. The *Opportunistic Growth* scenario resulted in lower levels of all species biomass than did *Recent Trends* scenario, but because land use was indiscriminant with regard to species, the general patterns largely mirrored *Recent Trends* scenario. Agricultural clearing within the *Regional Reliance* scenario reduced the abundance of

Fig. 4. Maps showing spatial variation in the percentage change from simulation time 0 to simulate time 50 for biophysical indicators of ecosystem services and forest habitat (RT, *Recent Trends*; OG, *Opportunistic Growth*; RR, *Regional Reliance*; FAI, *Forests as Infrastructure*). For water-related metric (B through E), change is shown at the watershed scale, whereas for forest carbon (A) and forest habitat (F), change is shown at the individual pixel scale (50 m^2).

Fig. 4. Continued.

several species, including white pine and hemlock. These differences notwithstanding, the overall composition was relatively stable from the beginning to the end of the simulations. Indeed, the ranked abundance of tree species within and across the scenarios varied little.

6. Forest habitat quality—interior habitat. Interior forest habitat quality decreased in all scenarios as forest conversion replaced and fragmented forests. The largest decrease occurred within the *Opportunistic Growth* scenario where the mean quality score decreased by 26%. However, the

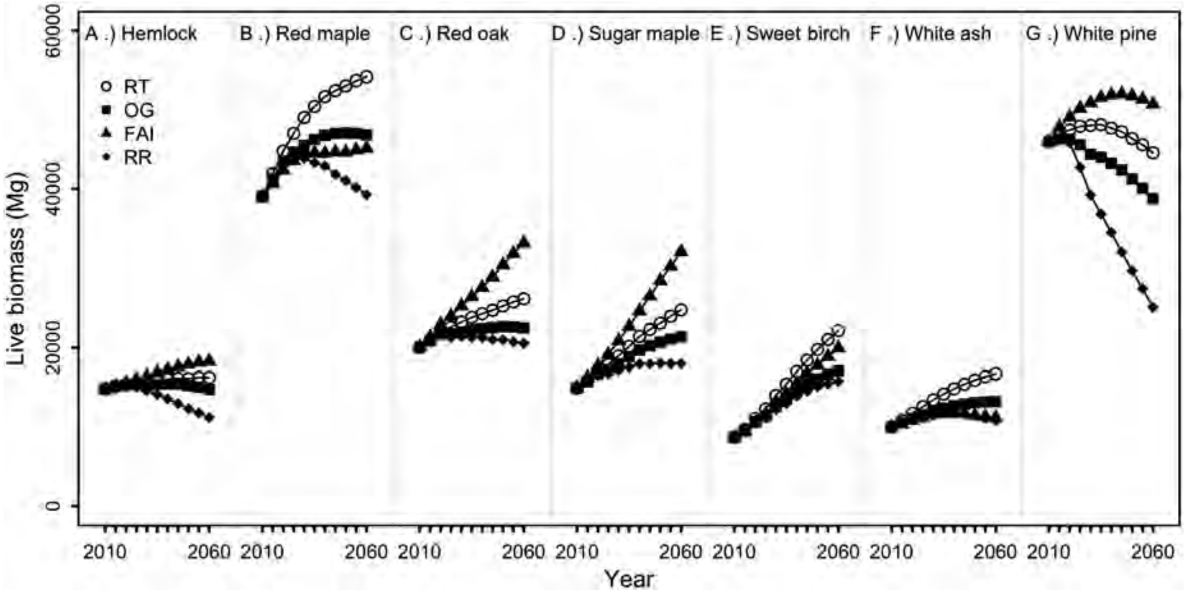

Fig. 5. Change in live aboveground biomass for the seven most abundant tree species in Massachusetts throughout the LANDIS-II simulations for four land-use scenarios (RT, *Recent Trends*; OG, *Opportunistic Growth*; RR, *Regional Reliance*; and FAI, *Forests as Infrastructure*).

mean quality score in *Regional Reliance* decreased by 20%; *Recent Trends* decreased by 12%; and *Forests as Infrastructure* decreased by 11% (Fig. 3). Changes in the habitat quality index measured at the state scale did not capture the within-state variability. At the beginning of the simulations, the western third of the state had the highest quality interior forest habitat. While an east-to-west gradient of increasing habitat quality persisted through all scenarios, the strength of the gradient was weakest in the *Regional Reliance* scenario, where agricultural land use fragmented forest habitat throughout the state (Fig. 4).

DISCUSSION

The simulations reveal a great deal about the ecological impacts of future land use and show the strong influence of the ecological inertia that exists on the landscape. For example, in three of the four scenarios, the state's forests remain a net sink for aboveground carbon throughout the 50-yr simulations, despite, in one scenario, a near doubling of the rate of forest loss to development. Only the *Regional Reliance* scenario, with its near tripling of the state's total agricultural area, resulted in a decrease in the total aboveground forest carbon; even there, the loss was less than 5%. Similarly, the land-use regimes depicted in the scenarios did not substantially disrupt the slow transition of forest composition toward more shade-tolerant species. Relative species abundance varied little despite the geographic patterns of forest loss and the strong tree species selectivity associated with the silvicultural prescriptions. Indeed, the ranked abundance of tree species within and across the scenarios varied little. In these and other ways, background forest dynamics superseded the changes imposed by the land-use scenarios, which only eroded the century-old process of forest recovery stemming from the colonial land-use era, which was much more extensive than anything envisioned by our experts. Such findings are a reminder of the important role of history in shaping future landscapes.

But this is not to say that the land-use scenarios did not produce in substantial and divergent ecological impacts. They did. For example, the *Opportunistic Growth* scenario, which envisioned a continuation of patterns of forest conversion observed in the 1980s and 1990s, resulted in greater than 10% increase in surface water runoff in 26 of 27 state's watersheds (Fig. 4). In contrast, in the *Forests as Infrastructure* scenario, where the development rates were slightly less than in *Recent Trends* and the patterns of development were clustered around cities, only one of the 27 watersheds experienced increases in runoff greater than 10%. Similarly, the differences in the spatial pattern of forest conversion between scenarios resulted in strong differences in the quality of forest habitat. There was a 2.5 times difference in the statewide mean interior habitat score between the *Opportunistic Growth* and *Forests as Infrastructure* scenarios (Fig. 3). Further, aggregating new development around cities within the *Forests as Infrastructure* scenario had a strong effect on the spatial pattern of interior forest habitat within the western third of the state: Forests near the cities in the west were highly degraded, while the rest of western Massachusetts was minimally changed. These results highlight the potential for land-use policies that influence the spatial patterns of development to affect a range of environmental outcomes.

Looking at landscape change through a diverse set of metrics also allowed us to assess the synergies and trade-offs associated with each of the scenarios (Fig. 6). Several studies have shown that land-use scenarios that provide greater economic returns to individual landowners typically incur trade-offs against societal benefits and ecosystem services (Polasky et al. 2008, Nelson et al. 2009). While we did not conduct an economic valuation, it is evident that in most cases, the Massachusetts scenarios followed this pattern: Increased

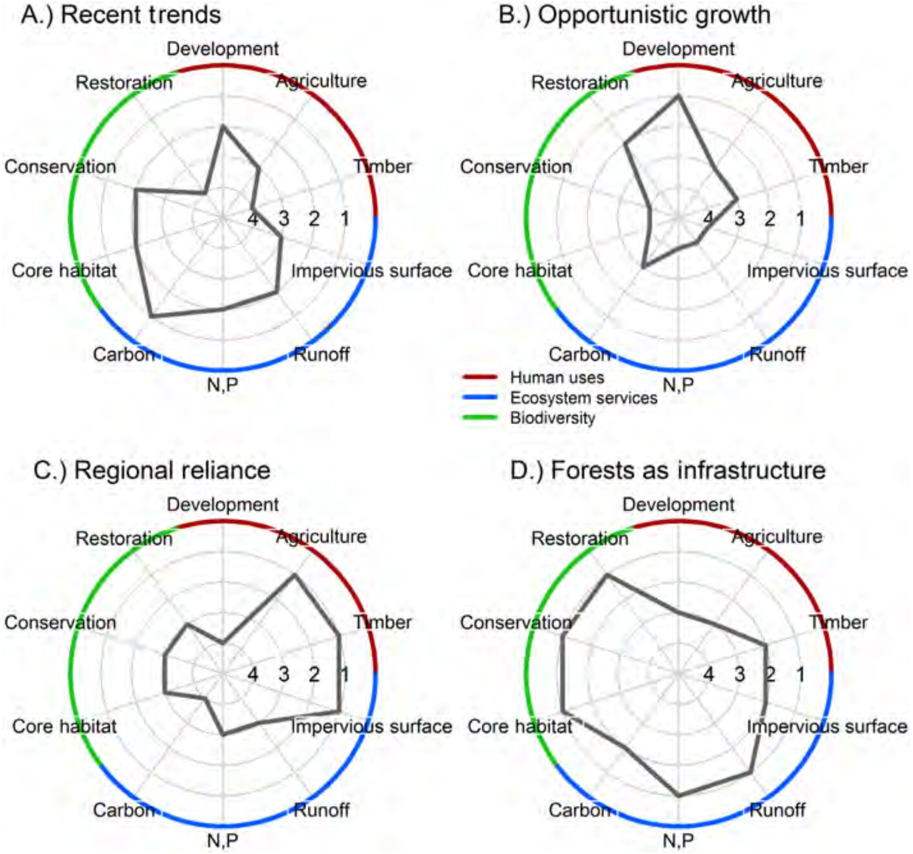

Fig. 6. Diagrams showing the performance of the four land-use scenarios in terms of their impacts on direct human uses, ecosystem services, and habitat conservation. Here, the rank of the metrics is scaled such that 1 = best and 4 = worst. For example, for nitrogen and phosphorous export (N, P), a rank of one means that scenario had the lowest levels of nutrient export. In contrast, for carbon, a rank of one means that scenario had the highest level of the stored forest carbon. Note that restoration refers to the amount of ecologically and economically desired tree species: white pine, sugar maple, and red oak.

levels of direct human uses typically resulted in decreased levels of ecosystem services and habitat quality. The *Opportunistic Growth* and *Regional Reliance* scenarios included high rates of forest conversion to developed uses and agricultural uses, respectively, which, among the land uses we considered, would have the highest economic returns to individual land owners (Polasky et al. 2010). Consistent with expectations, these scenarios also resulted in the greatest reduction in the ecosystem services that benefit society, including carbon storage, nutrient export, and flood regulation.

In some cases, however, timber harvest acted as an exception to the view that commodity production that benefits individuals comes with trade-off against societal benefits and ecosystem services. In fact, there were clear synergies between timber harvest and ecosystem services and habitat conservation within the *Forests as Infrastructure* scenario. This scenario demonstrated the capacity of the Massachusetts landscape to sustain the increased levels of harvest using the long-term silvicultural planning while also maintaining the forest as a strong sink for atmospheric carbon and increasing the abundance of ecologically and economically desirable trees. This is possible because most of the state's forests are mid-successional and within a self-thinning phase of stand development, and modern harvest regimes remove primarily dominant canopy trees. Indeed, the *Forests as Infrastructure* scenario harvested twice as much wood with just a 4% reduction in the amount of forest carbon stored within the state compared with *Recent Trends*. The scenario also resulted in 20% more (in terms of overall biomass) large (old) trees from desirable species, that is, white pine, sugar maple, and red oak. This finding suggests that in some cases, opportunities exist to modify extractive land uses in ways that provide benefits to the individual land owner while also increasing (or at least not significantly decreasing) ecosystem services that provide benefits to society. It is important to note, however, that we did not consider all potential ecosystem impacts of timber harvesting (e.g., changes in sedimentation rates, creation of other important habitat types) and so there may be unidentified trade-offs associated with the level and the type of land use associated with *Forests as Infrastructure*.

By developing alternative land-use scenarios, we were able to systematically explore an envelope of potential land-use consequences, despite the inherent uncertainty. The scenarios were crafted to be thematically divergent while remaining logical and plausible. The experts found this framework for landscape analysis to be powerful for contemplating an unknowable future without venturing so far beyond plausibility that the analyses lose credibility and utility. Indeed, even when the scenarios depicted their most significant shifts in the land-use regime, they remained within the bounds of recent historical precedent. For example, the high rates of forest conversion envisioned within the *Opportunistic Growth* scenario occurred in the late 1980s and early 1990. Similarly, the agricultural expansion portrayed in *Opportunistic Growth* scenario brought the landscape close to a level of agriculture in the 1950s. While purposely depicting alternative trajectories, the scenarios similarly incorporated some major elements of the modern land-use regime. For example, all four scenarios include a component of harvesting for biomass energy and also depict the continued forest loss and the associated reconfiguration of the quantity and spatial distribution of land use and ecosystem service provisioning.

The focus of this study was to describe the process of developing, simulating, and quantifying the consequences across the state; as such, we have relegated the detailed site-based analyses of changing patterns of co-occurrence and covariance of service provisioning to a subsequent study. Nonetheless, even using a broad-scale approach, we see clear synergies between water-related services and forest-related services and habitat, which is similar to other studies (e.g., Maes et al. 2012, Qiu and Turner 2013). This was true across scenarios; that is, scenarios that ranked higher in terms of forest carbon and interior habitat also ranked higher clean water provisioning and flood regulation (Fig. 6). It was also true spatially within each scenario; that is, areas of Massachusetts with more forest carbon and interior forest habitat had lower nutrient export to streams and rivers and more capacity to regulate flooding (Fig. 4). These trade-offs stem from the capacity of forests to filter nutrients and regulate flooding. Perhaps more interestingly, the scenarios did identify a geographically focused trade-off between the conservation of interior forest habitat and the protection of water-related service. In the *Forests as Infrastructure* scenario, new suburban development is concentrated near cities to minimize fragmentation and perforation of forest habitat. As a result, this land-use practice supported a similar level of direct human use of the land for development as in *Recent Trends* scenario while providing a higher degree of forest habitat protection. However, it caused some more urbanizing watersheds to cross the policy thresholds for impervious surfaces more quickly in *Forests as Infrastructure* scenario than in *Recent Trends* scenario. The potential synergies and trade-off between high-density zoning and ecosystem services have been reviewed by Pejchar et al. (2007) and point to the importance of integrating urban green space in areas of compact development.

Conclusions

Understanding and anticipating the aggregate effects of land use is a fundamental priority for ecosystem managers, land planners, and conservationists. Yet future land-use regimes are inherently uncertain. Analyzing a suite of plausible futures with regard to their potential impacts on a range of environmental outcomes is among the best ways to foster prescient thinking in the face of such uncertainty. Using an integrated scenario analysis, this study highlights broad implications and immediacy of a range of land-use decisions and resulting land-use regimes on a diverse set of environmental outcomes in Massachusetts. Specifically, the results show the trade-offs between land uses that promote benefits that accrue to individual landowners and those that maintain or enhance ecosystem services that serve a broader segment of society. Management, conservation, and policy decisions should consider the increasing value of the state's forests as a carbon sink, the potential for increased sustainable harvesting, the value of conservation and market mechanisms to sustain ecosystem services that serve broad segments or society, and the importance local green space and infrastructure to help mitigate the local impacts of dense development.

The panel of expert practitioners who developed the scenarios have assumed a high degree of ownership of the results and have helped advance the findings in the context of several critical state policies related to conservation funding, land-use zoning, and forest practices. The insights and impact of this collaborative scenarios research underscore that informed practitioners can be integral partners in complex landscape modeling, and this integrated approach to conducting science has exciting potential for advancing science, informing policy, and enhancing knowledge-and-action systems in complex coupled human–natural systems.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.1469/supinfo