Spatial Simulation of Codesigned Land Cover Change Scenarios in New England: Alternative Futures and Their Consequences for Conservation Priorities

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Abstract

Scientists are increasingly engaging with stakeholders to codesign scenarios of land use change necessitating methods to translate the resulting qualitative scenarios into quantitative simulations. We demonstrate a transparent method for translating participatory scenarios to simulations of land use and land cover (LULC) change using the New England Landscape Futures (NELF) project as a case study. The NELF project codesigned four divergent narrative scenarios that contrast with a Recent Trends scenario projecting a continuation of observed changes New England over the past 20 years. Here, we (1) describe the process and utility of translating qualitative scenarios into spatial simulations using a dynamic cellular land change model, (2) evaluate scenario LULC configuration relative to the Recent Trends scenario and to each other, (3) compare the fate of forests within stakeholder-defined areas of concern, and (4) describe how a user-inspired outreach tool was developed to make the simulations and analyses accessible to a diverse user group. The associated simulations are strongly divergent in terms of the amount of LULC change and the spatial pattern of change. Among the scenarios, there is a fivefold difference in the amount of high-density development and a twofold difference in the amount of protected land. Features of the simulations can clearly be linked back to the original storylines. Overall, the rate of LULC change has a greater influence on stakeholder areas of concern than the spatial configuration. The simulated scenarios have been integrated into an online mapping tool via a user-engagement process meeting the needs of a variety of stakeholders.

Plain Language Summary

To help prepare for an uncertain future, planners and scientists often engage with stakeholders to codesign alternative scenarios of land use change. Methods to translate the resulting qualitative scenarios into quantitative simulations that characterize the future landscape condition are needed to understand the consequences of the scenarios while maintaining the legitimacy of the process. We use the New England Landscape Futures (NELF) project as a case study to demonstrate a transparent and reproduceable method for translating participatory scenarios to simulations of land use and land cover (LULC) change. In addition, using the NELF simulations, we quantify the major drivers of land use change and show how the scenarios differentially alter potential land-use pathways and, in turn, affect conservation priorities. The NELF project codesigned four narrative scenarios that contrast with a Recent Trends scenario that projects a continuation of observed changes across the 18 × 10^6-ha region during the past 20 years. Here, we (1) describe the process and utility of translating qualitative scenarios into spatial simulations using a dynamic cellular land change model, (2) evaluate the outcomes of the scenarios in terms of the differences in the LULC configuration relative to the Recent Trends scenario and to each other, (3) compare the fate of forests within key areas of concern to the stakeholders, and (4) describe how a user-inspired outreach tool was developed to make the simulations and analyses accessible to diverse users. Each of the four alternative scenarios populates a quadrant of future conditions that crosses high to low resource natural planning and innovation with local to global socioeconomic connectedness. The associated simulations are strongly divergent in terms of the amount of LULC change and the spatial pattern of change. Features of the simulations can be linked back to the original storylines. Among the scenarios there is a fivefold difference in the amount of high-density development and a twofold difference in the amount of protected land. Overall, the rate of LULC change has a greater influence on forestlands of concern to the stakeholders.

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stakeholders than does the spatial configuration. The simulated scenarios have been integrated into an online mapping tool that was designed via a user-engagement process to meet the needs of diverse stakeholders who are interested in the future of the land and in using future scenarios to guide land use planning and conservation priorities.

1. Introduction

Scenario planning is a rigorous way of asking “what if?” and it can be a powerful tool for natural resource professionals preparing for the future of socioecological systems. In the context of land use or regional planning, scenario development uses a structured process to integrate diverse modes of knowledge to create a shared understanding of how the future may unfold (MA, 2005; Mahmoud et al., 2009; Wiebe et al., 2018). The resulting scenario narratives that emerge from participatory scenario planning describe alternative trajectories of landscape change that would logically emerge from different sets of assumptions (Thompson et al., 2012). Scenarios are not forecasts or predictions; instead, they are a way to explore multiple hypothetical futures in a way that recognizes the irreducible uncertainty and unpredictability of complex systems (Pedde et al., 2018).

Scientists are increasingly codesigning scenarios with stakeholders—that is, groups of people who are both affected by and/or can affect decisions or outcomes (McBride et al., 2017; Reed et al., 2013; Voinov & Bousquet, 2010). Codesigning scenarios increase the range of viewpoints and expertise included in the process and, in turn, attempt to increase the relevance, credibility, and salience of outcomes (sensu, Cash et al., 2003). Participatory land use scenario development is particularly useful in landscapes such as New England where landscape change is driven by the behaviors and decisions of hundreds of thousands of stakeholders that are not amenable to centralized planning or prediction. A land use scenario codesign process typically results in a set of contrasting storylines that describe the way the future might unfold, based on specific assumptions about dominant social and ecological forces of change within a landscape (McBride et al., 2017; Ramírez & Selin, 2014).

The utility of qualitative, codesigned scenarios can be enhanced by linking them to quantitative representations of future land use change, as generated by a spatially explicit simulation model. However, translating between narrative scenario descriptions and quantitative models presents challenges and trade-offs related to the treatment of uncertainty, the potential to accommodate stakeholders in the process, the resources required, and the compatibility with different types of simulation models (see reviews of these factors in Mallampalli et al., 2016; Pedde et al., 2018). These challenges notwithstanding, variations on the “Story and Simulation” approach (sensu Alcamo, 2008) to scenario planning are increasingly used in environmental planning and are the basis for many large-scale regional scenario assessments (Carpenter et al., 2015; Kline et al., 2017; MA, 2005; Rounsevell et al., 2006; Sohl et al., 2016; Thompson et al., 2014, 2016).

Cellular land change models (LCM) have features that make them well suited to the translation of qualitative scenarios to spatial simulations (Brown et al., 2013; Dorning et al., 2015; Thompson et al., 2017). Cellular LCMs are phenomenologically driven, as opposed to process driven, and are often used to project observed trends of land use and land cover (LULC) change forward in time. When used in this conventional way, by projecting observed trends of LULC change, they operate with the implicit assumption that the future will be a continuation of the past (e.g., Thompson et al., 2017). These models quantify the rate of LULC change and the relationships between the location of observed LULC change (i.e., a change detection) and a suite of spatial predictor variables—for example, patterns of existing development, proximity to city centers or roads, topography, and demographics. Simulating these patterns into the future constitutes a “recent trends” scenario, which can be used as a baseline, against which alternative scenarios can be evaluated. Then, by adjusting LULC change rates and/or redefining the strength or nature of the relationships between LULC changes and spatial predictor variables, modelers can systematically and transparently simulate alternative scenarios. Cellular LCMs can also incorporate feedbacks to LULC change and portray multiple interacting land uses. For example, on a simulated forested site, new land protection can prevent new residential development from occurring. New residential development in a simulation can also increase the probability that additional new development will occur in proximity to existing development. This dynamic modeling approach produces a realistic manifestation of LULC change by reproducing observed landscape patterns.
sequences of alternative land use pathways for conservation priorities. NELF is a multi-institutional, participatory scenario project with the overarching goal of building and evaluating scenarios that show how land use choices and climate change could shape the landscape over the next 50 years.

The six-state, 18 × 10^6 ha region has several characteristics that lend itself to participatory scenario planning (McBride et al., 2017). Seventy-five percent of New England forests are privately owned, including the nation’s largest contiguous block of private commercial forestland (>4 × 10^8 ha) plus hundreds of thousands of family forest owners with small to midsized parcels totaling >7 × 10^6 ha (Butler et al., 2016). It is among the most forested and most populated regions in the United States; average forest cover in the region exceeds 80% but ranges from 50% in Rhode Island to 90% in Maine (Figure 1). The future of these forests is in question. Since 1985, roughly 10,000 ha yr^{-1} of forest has been lost to commercial, residential, and energy development, marking the reversal of a 150-year period of forest expansion in the region (Olofsson et al., 2016). Working to slow the rate of forest loss are a range of robust conservation initiatives that have, to date, permanently protected 23% of the region from development; half of this conservation land has been protected since 1990 (Foster et al., 2017; Sims et al., 2019). Modern land protection in this region is primarily achieved by private land owners voluntarily placing conservation restrictions on their land. Likewise, development of forest or agricultural sites to residential or commercial uses is made primarily by individual private land owners. Thus, these individual choices are collectively determining the future of the shared landscape. There is no central decision-making authority for land use; instead, the condition of the future landscape will be the product of countless independent landowner decisions and a conglomerate of local, regional, and state policies.

McBride et al. (2017) describe the participatory process through which the NELF project codesigned four divergent narrative scenarios that contrast with a Recent Trends scenario. In brief, four scenarios were codesigned through a scenario development process that engaged >150 informed stakeholders and scientists from throughout the study region. Most of the stakeholders were professional resource managers, land use planners, or policy makers employed by public agencies or nonprofits. Participants were identified via a purposive snowball approach that drew on the knowledge and contacts of the researchers. The design process utilized the Intuitive Logics 2 × 2 matrix approach to scenario development popularized by Royal Dutch Shell/Global Business Network (Bradfield et al., 2005). In this approach alternative scenarios are developed around two critical uncertainties that help prompt the exploration of a large range of possible future end states (Cairns & Wright, 2017; Van der Heijden, 1998). The advantage of this approach lies in its clear, accessible, replicable, and easy to communicate structure, with the quadrants providing a useful scaffold around which to develop and locate scenarios in relation to each other, and helpful starting points for clearly fleshing out each scenario in the set (Bowman et al., 2013; Derbyshire & Wright, 2017; Ramirez & Wilkinson, 2014; Wright et al., 2013, 2020). However, the potential drawbacks to this approach include (1) it may restrict exploration of the future possibility space to only two uncertainty drivers if efforts are not made to deliberately explore other drivers within the resulting scenario set and (2) it may lead to somewhat formulaic views of the world and lose out on the more nuanced understanding and complexity contained in stakeholder insights if attention is not given to the use of axes that are based on highly uncertain, divergent drivers of change (Bryson et al., 2016; Lord et al., 2016; Parker et al., 2015; Wright et al., 2013). Our choice of this approach was driven by stakeholder interests in exploratory, yet “plausible” scenarios and a need for a scenario development process that was engaging and accessible (sensu Sheppard et al., 2011) and could be replicated in a 1-day workshop (refer to McBride et al., 2017, for more explicit discussion of the motivation for the use of the deductive intuitive logics 2 × 2 approach for our work, and some of the drawbacks involved). The 1-day workshop, repeated in six states, was formatted to meet stakeholder-defined time constraints as well as the organizational constraints inherent in a short-term grant-funded project that encompasses a large geographic area and that is led by an academic institution. This can be compared to, for example, long-term planning processes that occur within a single organization, ongoing small watershed
or landscape initiatives led by community groups, or a government-commissioned public process in which a strong authorizing environment for the work exists. These contexts are more conducive to highly complex and time-intensive inductive and abductive scenario approaches, which are thought to facilitate more creative or expansive scenarios. However, these more time-intensive inductive approaches can also limit participation to those with sufficient time to dedicate and may therefore be structurally less inclusive. The NELF project offers an example of a short-term, accessible, regional-scale participatory research project using a replicable protocol that balances theory and practical constraints to generate and analyze stakeholder-defined scenarios that represent views of the future that extend beyond immediate management and policy concerns.

Figure 1. The New England study area with numbered subregions primarily based on U.S. Census-Based Statistical Areas. Asterisk denotes non-CBSA subregions. The land cover map was produced by (1) Olofsson et al. (2016) applying the Continuous Change Detection and Classification (CCDC) algorithm to Landsat data for all of Massachusetts, New Hampshire, and Rhode Island, 93% of Vermont, 99% of Connecticut, and approximately 33% of Maine and (2) the 2011 National Land Cover Dataset (NLCD), also a Landsat product, for the remainder of New England. Conserved Forest was derived from the Harvard Forest's New England Protected Open Space data set.
The in-person stage of the scenario development process took the form of six structured 1-day scenario-development workshops and two interactive webinars that engaged stakeholders in the full scenario-development process from initial orientation and identification of driving forces through to fleshed out scenario narratives and initial quantitative descriptions of the scenarios. The scenario-development workshops used the same protocol in which stakeholders engaged in the following steps: (i) open-ended visioning about the future of the region, (ii) identification of driving forces using a “STEEP” framework (i.e., Social, Technological, Economic, Ecological, and Political trends), (iii) ranking and selection of two drivers with high perceived uncertainty and impact that are also viewed as divergent and independent, (iv) definition of the opposite poles of the two drivers and creation of the scenario matrix by crossing the resulting axes, (v) inhabiting and fleshing out of the scenario narratives to integrate remaining drivers from step two, (vi) listening to a presentation on recent trends, and (vii) translating the scenario storylines into initial quantitative land use change estimates. After the workshops, the research team convened two interactive webinars to iterate with stakeholders and reach agreement on the final quantification of the amount, intensity and location of LULC change in each of the scenarios to produce model inputs (Figure 2).

Consistent with the Intuitive Logics approach NELF project stakeholders envisioned opposing outcomes of two drivers of land use change that they identified as most impactful and uncertain: socioeconomic

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**Figure 2.** Steps employed in the NELF stakeholder scenario development protocol.
Table 1  
Scenario Narratives Representing Four Visions of New England in 2016

| Scenario                                | Narrative                                                                 |
|-----------------------------------------|---------------------------------------------------------------------------|
| **Connected Communities**               | This is the story of how a shift toward living “local” and valuing regional self-sufficiency and local resource use increases the urgency to protect local resources. The New England population has increased slowly over the past 50 years, and most communities are coping with climate change by anchoring in place rather than relocating, making local culture and the use and protection of local resources increasingly important to governments and communities. New England has been less affected by climate change than many other regions of the United States in this scenario. Concerns about global unrest and the environmental impacts of global trade have led New Englanders to strengthen their local ties and become more self-reliant. These factors combine with heightened community interest and public policies to strengthen local economies and fuel burgeoning markets for local food, local wood, and local recreation. |
| **Yankee Cosmopolitan**                 | This is the story of how we embrace change through experimentation and upfront investments. While environmental changes break records and urbanization continues to pressure natural systems, society responds with greater flexibility, ingenuity, and integration. In this scenario, New England has experienced substantial population growth spurred by climate and economic migrants who are seeking areas less vulnerable to heat waves, drought, and sea level rise. Most migrants are international but some have relocated from more climate-affected regions in the United States. At the same time, a strong track record in research and technology has made New England a world leader in biotech and engineering, creating a large demand for skilled labor. The region’s relative resilience to climate change and growing employment opportunities has made New England a major economic and population growth center of the United States. Abundant forests remain a central part of New England’s identity and support increases in tourism, particularly in Vermont, Maine, and New Hampshire. |
| **Growing Global**                      | This is the story of an influx of climate change migrants seeking refuge in New England and taking the region by surprise. New pressures on municipal services drive a trend toward privatization. Regional to national policies have promoted global trade but global agreements to address climate change have failed. In this scenario, by 2060, a steady stream of migrants has driven up New England’s population, with newcomers seeking to live in areas with few natural hazards, ample clean air and water, and low vulnerability to climate change. This influx of people has taken the region by surprise and local planning efforts have failed to keep pace with development. The region has experienced increasing privatization of municipal services as state and local governments struggle to keep up with the needs of the burgeoning population. Trade barriers were lifted in the 2020s to counter economic stagnation, and the volume of global trade has multiplied over the past 40 years as a result of increasing globalization. However, all attempts at global climate change negotiations and renewable energy commitments have failed in this globally divided world. |
| **Go It Alone**                         | This is the story of a region challenged by shrinking economic opportunities paired with increasing costs to meet basic needs, yet innovation is stagnant and new technologies are not rising to increase efficiency or create new opportunities. With local self-reliance and survival as the primary objectives, natural resource protections are rolled-back and communities turn heavily to extractive industries. In this scenario, population growth in the region has remained fairly low and stable over the past 50 years as the lack of economic opportunity, high energy costs, and tightened national borders have deterred immigration and the relocation of people from within the United States to New England. The concurrent shrinking of national budgets and lack of global economic connections have left little leeway to deal with challenges such as high unemployment, demographic change, and climate resilience. Within New England this has resulted in the rolling back of natural resource protection policies and the drying up of investments in new technologies and ecosystem protections in response to a lack of regulatory drivers. Over the last 50 years, the region has seen the significant degradation of ecosystem services as a result of poor planning, increased pollution, and heavy extractive uses of local resources using conventional technologies. |

Drivers: High natural resource planning and innovation/local socioeconomic connectedness  
Drivers: High natural resource planning and innovation/global socioeconomic connectedness  
Drivers: Low natural resource planning and innovation/local socioeconomic connectedness  
Drivers: Low natural resource planning and innovation/global socioeconomic connectedness

connectedness and natural resource planning and innovation. The process resulted in a matrix of four quadrants that encompassed four distinct alternative scenarios. Participants then added details about each scenario that incorporated other subsidiary drivers into the storyline in qualitative terms, which took the form of ~1,000-word narratives that are internally consistent and integrate the stakeholders perceptions of multiple integrating drivers (McBride et al., 2017); the Scenario Narratives are summarized in Table 1. Next, participants were presented with key features of the Recent Trends scenario and asked to describe how LULC would differ in each of the alternative scenarios using semiquantitative terms. We then adjusted model input parameters to reflect the characteristics of each of the four divergent scenarios. Finally, through a series of interactive webinars, we worked with participants to refine these parameters to ensure the scenarios captured their intent.
Here our objectives are to (1) assess the utility and challenges of translating qualitative scenarios into spatial simulations using a cellular LCM, (2) evaluate the outcomes of the scenarios in terms of the differences in the LULC configuration relative to the Recent Trends scenario and to each other, and (3) compare the fate of the landscape in terms of development and conservation within key Impact Areas, that is, areas that have been identified as being important for conservation, wetland, flood, drinking water, farmland, and or wildlife management (Figure 3).

2. Methods

2.1. Study Region

New England has a land area of 162,716 km² and includes the six most northeasterly states in the United States: Maine (80,068 km²), Vermont (23,923 km²), New Hampshire (23,247 km²), Massachusetts (20,269 km²), Connecticut (12,509 km²), and Rhode Island (2,700 km²) (Figure 1). In 2010, the nominal starting date for the scenarios, 80.1% of the region was forest cover, 7.3% was low-density development defined as development with <50% impervious cover, 1.3% was high-density development defined as development with >50% impervious cover, and 6.4% was agricultural cover. These estimates were calculated from two sources: (1) the 2010 land cover map produced by Olofsson et al. (Olofsson et al., 2016) applying the Continuous Change Detection and Classification (CCDC) algorithm to Landsat data for all of

Figure 3. The impact of the simulated land cover change scenarios was assessed relative to several Conservation Priority Areas. See Table 3 for data sources and definitions.
To account for regional variation in the patterns and drivers of land cover change, we delineated 32 subregions within New England (Figure 1) and independently fit the LCM to the rate and spatial allocation of change within each subregion. The subregions primarily follow U.S. Census Bureau-defined Core Base Statistical Areas (CBSAs), which represent both Census Metropolitan and Micropolitan statistical areas (www.census.gov; accessed 20 April 2019). CBSAs are delineated to include a core area containing a substantial population nucleus, together with adjacent towns and communities that are integrated with the core in terms of economic and social factors. New England includes 27 CBSAs; however, not all of New England is covered by a CBSA. Accordingly, we added five rural areas to fill the gaps, for a total of 32 unique subregions. Among subregions, the Boston-Cambridge-Newton subregion (hereafter “Boston”) is, by far, the most populous; it contains the city of Boston, which is the region’s largest city, and in 2010 accounted for 31% of the region’s total population.

2.2. The Simulation Framework

We used the Dynamica Environment for Geoprocessing Objects (Dinamica EGO v.2.4.1) to simulate 50 years (2010 to 2060) of LULC change for each scenario, using 10-year time steps. Dinamica EGO is a spatially explicit LCM capable of multiscale simulations that incorporate spatial feedbacks (Soares-Filho et al., 2002, 2009). The model has several attributes that make it well suited to simulating alternative LULC scenarios. Users prescribe the rate of each potential transition (Figure 4), the ratio of new vs. expansion patches, the mean and variance of new patch sizes, and patch shape complexity. The conditional probability of each transition is developed in relation to a suite of spatial predictor variables. When simulations are intended to project the pattern of LULC change observed in the past, Dinamica EGO employs a weights-of-evidence approach to set the transition probability for every pixel (Soares-Filho et al., 2009). This method is based on a modified form of Bayes theorem of conditional probability; it derives weights such that the effect of each spatial variable on a LULC transition is calculated independently. We used this approach to develop the spatial allocation of land use to simulate a Recent Trends scenario in New England (Thompson et al., 2017) then modified the conditional probabilities to simulate the alternative scenarios (see below).

2.3. Simulating Codesigned Scenarios

We simulated each of the five LULC change scenarios using Dinamica (Figure 5). The first scenario, the Recent Trends, projects the types, rates, and spatial allocation of LULC change and land protection observed during the period spanning 1990 to 2010. Thompson et al. (2017) described the approach for simulating the Recent Trends scenario; all LULC transitions in the alternative scenarios were simulated using the same approach. For every LULC transition type, the rate, and allocation observed within each subregion were applied to each time step in the simulation. For the Recent Trends scenario, the transition rate and spatial allocation of the transitions was based on the conversion rate, average patch sizes, ratios of new patch to patch expansion, and patch shape complexity found within the transitions observed in the 1990 to 2010 reference period. The spatial distribution of LULC change was based on the observed relationship to eight predictor variables (Table 2). When a subregion could not accommodate a new LULC transition, any remaining unfulfilled transitions were evenly distributed to neighboring subregions. This allowed high development growth subregions like Boston (#7) to spill over into neighboring subregions. The exception to this rule was the island subregions of Nantucket (#28) and Martha’s Vineyard (#3), which were not allowed to spill over since they had no neighboring subregions.
The four codesigned scenarios have many distinct characteristics of LULC change; they are Yankee Cosmopolitan, Connected Communities, Go it Alone, and Growing Global (Box 1). The spatial distribution of each LULC in each scenario varied across the landscape and among the scenarios (Figure 5 and Figure A1). We used the qualitative descriptions of LULC change provided by the stakeholders in the scenario narratives to develop and propose spatial allocation plans for the land use transitions in the codesigned scenarios. These spatial allocation plans were presented to the stakeholders in terms of modifications to the baseline weights calculated for the Recent Trends scenario. These modifications were then vetted with the stakeholders via webinars and online real-time polling to assess whether they accurately captured their intended deviation from the spatial patterns present in Recent Trends. For example, the Connected Communities scenario narrative stated that “New settlements tend to occur in planned urban centers”; in response, we suggested that the probability of development be increased as a function of proximity to urban centers and, in a webinar, the stakeholders voted on one of three such modifications that differed in terms of the magnitudes of the adjustment. Table 3 shows the final spatial allocation plans in conjunction with their corresponding quotes from the scenario narratives. The stakeholders assumed that shifts in the LULC change regime would take some time to deviate from the Recent Trends rate, so in the first 10-year time step, the rates of LULC change ramp up or down to half of their final target rate (Figure 6).
2.4. Scenario Impacts on Conservation Priorities

To explore the impacts of the scenarios, we estimated the impacts of simulated LULC change on forests within each scenario on the following seven key Impact Areas (Table 4). We selected these areas because they serve as reasonable proxies for a range of values and conditions that are important to stakeholders, such as unfragmented forests, wildlife habitat, and water related ecosystem services, (McBride et al., 2019), and have been mapped previously within New England.

Impact Areas were assessed based on the amount of land available for conversion to either development or conservation at the start of the simulations in 2010. Areas already developed or conserved in 2010 were considered unavailable and were thus not assessed. Additionally, areas within delineated Impact Areas that

Figure 5. LULC within New England for initial conditions at Year 2010 and five alternative scenarios at Year 2060.
were ineligible for a transition based on our model rules (e.g., nonforest covers such as agriculture and water) were not considered.

### 3. Results

#### 3.1. Recent Trends

The Recent Trends scenario assumes a continuation of the LULC changes observed between 1990 and 2010. The rate of LULC change is constant throughout the scenario: New development covers 97 km$^2$ per year; new agriculture covers 16 km$^2$ per year; and new land protection covers in 835 km$^2$ per year. At Year 2060 (after simulating 50 years of LULC change), developed land increased by 37% (from 14,098 to 19,265 km$^2$); there was little change (<5%) in agricultural land (10,409 to 10,908 km$^2$). The largest LULC change was to protected land, which increased by 123% (from 35,300 to 78,500 km$^2$).

Throughout the 50-year simulation, the rate of land protection in the Recent Trends scenario was more than 8 times greater than the rate of development. Because Impact Areas are not evenly distributed throughout New England, the spatial distribution of land protection in the Recent Trends scenario was most effective for securing protection in Impact Areas that are concentrated in the north, such as core forests, where 48% were protected and only 3% developed and TNC Priority Conservation Areas where 49% were protected and only 4% were developed. For Impact Areas that are concentrated in the south, such as with the important water-sheds for drinking water, only 28% were protected and 11% were developed. In addition, the impact of LULC change on other conservation priorities was driven by local patterns observed in the historical data. For example, wetlands have regulatory protection (included in our model) and thus have a low probability of development. Indeed, despite being common throughout the region, 45% of forested wetland areas were protected while just 0.7% were developed (note that nonforested wetlands were protected from any transition).

#### 3.2. Yankee Cosmopolitan

The Yankee Cosmopolitan scenario envisions a future New England that is a global hub of activity, with commensurate changes to land use. The population is growing much faster than Recent Trends, but, at the same time, natural resource planning and innovation are a priority. To accommodate population growth spurred by climate and economic migrants, development occurred at a rate 40% greater than Recent Trends (136 km$^2$ per year). Global food supply chains required minimal agriculture expansion, which was maintained at 16 km$^2$ per year (the same as Recent Trends). The rate of new land protection was reduced in the north and increased in the south, relative to Recent Trends. Overall, across the region, the rate of land protection in this scenario was 736 km$^2$ per year, 12% lower than Recent Trends.

Yankee Cosmopolitan includes several modifications to the spatial allocation of LULC change in Recent Trends, which were intended to minimize development within areas desirable for protection. However, the large (40%) increase in the rate of development often overwhelmed modifications to the spatial allocation rules. For example, the spatial allocation plan for Yankee Cosmopolitan included a reduced probability of

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**Table 2**

*Driver Variables Used to Parameterize Dinamica EGO*

| Variable                  | Units       | Minimum bin size | Source                                                                 |
|---------------------------|-------------|------------------|------------------------------------------------------------------------|
| Distance to development   | Meters      | 100 m            | Olofsson et al. (2016)                                                 |
| Distance to cities with   | Meters      | 10,000 m         | U.S. Department of the Census 1990, 2010                               |
| population >30,000        |             |                  | Note: 30,000 was based on previous research (Thorn et al., 2016) and represents a “typical” Micropolitan Statistical Area, which contain an urban cluster of 10,000 to 50,000 people. |
| Distance to roads/highways| Meters      | 100 m            | Olofsson et al. (2016)                                                 |
| Slope                     | Degrees     | 2°               | U.S. Department of the Census 1990, 2010                               |
| Land owner type           | Categorical | NA               | Sewall GIS Services (2015, http://www.sewall.com/services/geospatial/gis.php) |
| Wetlands                  | Categorical | NA               | U.S. Fish and Wildlife Service (2016), Federal Emergency Management Agency (2016), and U.S. Geological Service (2016) |
| Population density        | People per | 25 ppl/sq. km    | U.S. Department of the Census (1990, 2010)                             |
| Farm soil                 | Categorical | NA               | U.S. Department of Agriculture (2016)                                  |

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| Connected Communities                                                                 | Spatial Allocation Plan (modeling team) |
|--------------------------------------------------------------------------------------|----------------------------------------|
| 1. “From the early 2020s onward, local and regional governments have used tax incentives, public policies, and market subsidies to drive a shift toward sustainability and climate resilience.”   | 1. Probability of development is reduced by −40%:1 k, −30%:2 k, −20%:3 k, and −10%:4 k away from the coast. |
| 2. “This renewed focus on community planning and protection of natural resources has advanced “smart growth” measures that balance development needs with the need to protect natural infrastructure.” | 2. All FEMA +1 foot sea level rise, FWS wetlands, and NHD flood risk zones are ineligible for development. |
| 3. “New settlements tend to occur in planned urban centers ...”                      | 3. Probability of development is increased by 30% within 1 k of a city center with population over 10,000, 29% within 2 k, 28% within 3 k, ramping down to 1% within 30 k. |
| 4. “... resulting in higher-density development (in-fill), and as pockets of clustered growth at the urban fringe.” | 4. Mean patch size for new development has been doubled. Isometry modifier, which determines patch shape complexity, increased from 1.1 to 1.2. The ratio of new versus expansion patches has been increased by + 0.1 for all regions (a few regions max out at 100% by expansion). |
| 5. “Strong urban planning yields developments where more people can walk to work.”   | 5. Probability of development is increased close to town centers. +30%:1 k, +25%:2 k, +20%:3 k, +15%:4 k, +10%:5 k. |
| 6. “With the interest in localism there is a strong focus on the protection of wildlands for wildlife and ecosystem services.”   | 6. Probability of conservation types Private Reserves, Private Working Forests, and Small Private Multi-Use forests have probability increased by 10% in all high priority conservation areas (State Wildlife Action Plans). |
| 7. “State and local governments have invested greater public funding in land protection for forest health, flood control, and water quality.” | 7. Probability of conservation type Public Multi Use increase by 20% in all high priority conservation areas (State Wildlife Action Plans) and in the top 25% Forest to Faucets defined high importance watersheds, plus a further increase of 10% in FEMA and NHD flood zones. |
| 8. “Municipal governments are also protecting land for public parks near population centers.” | 8. Probability conservation type Public Park is increased by 30% within 1 k of city centers with populations over 10,000, 29% within 2 k, 28% within 3 k, ramping down to 1% within 30 k. |

| Yankee Cosmopolitan                                                                   | Spatial Allocation Plans |
|--------------------------------------------------------------------------------------|-------------------------|
| 1. “New England has experienced substantial population growth spurred by climate and economic migrants who are seeking areas less vulnerable to heat waves, drought, and sea level rise.” | 1. Probability of development is reduced by 20% within 500 m of the coast, -19% 1,000 m from the coast, -18% 1,500 m from the coast, down to -1% 20 k from the coast. All NOAH +1 foot costal flood zones have no chance of development. |
| 2. “Proactive city planning as well as public and private investment in infrastructure have helped to meet the needs of New England’s growing population through well-planned housing, transportation hubs, and municipal services near city centers.” | 2. Probability of development is increased by 30% within 1 k of city centers with populations over 10,000, 29% within 2 k, 28% within 3 k, ramping down to 1% within 30 k. Reduced probability of development on prime agricultural soils by 10%. All FEMA and NHD flood risk zones have probability of development reduced by 20%. |
| 3. “As the population influx continues through the 2030s and 2040s, the pace of development begins to exceed the planning and physical capacity of many cities and development patterns devolve into sprawl.” | 3. Mean patch size for new development has been doubled. Isometry modifier, which determines patch shape complexity, increased from 1.1 to 1.2. The ratio of new vs. expansion patches has been increased by +0.1 for all regions (a few regions max out at 100% by expansion). From 2030 onward, patterns follow recent trends. |
| 4. “Smart growth, high-density urban development, and carbon offset markets have facilitated a doubling in rates of land protection within high priority conservation areas throughout the 2020s and 2030s.” | 4. Probability of conservation has been increased by 20% on all high priority conservation areas (State Wildlife Action Plans). |
| 5. “New urban parks track with new development.”                                       | 5. Probability of new public park creation is increased by 30% within 1 k of city centers with populations over 10,000, 29% within 2 k, 28% within 3 k, ramping down to 1% within 30 k. |
new development within flood zones (Table 3); nonetheless, forest loss within flood zones by year 2060 was 86% higher than in Recent Trends. Reduced development probability in flood zones was only effective in rural subregions, where there was less development pressure. In urbanizing subregions, where development rates were highest, even low probability sites were eventually developed. Similarly, the spatial allocation plan for this scenario increased the probability of land protection within wildlife habitat areas; however, the increased rate of development had a greater influence. Overall, while there was a small increase in protected land within wildlife habitat areas, there was also a 49% increase in developed areas, as compared to Recent Trends. Other modifications to the spatial allocation were more effective. For example, this scenario envisioned more urban parks; thus, the spatial allocation plan increased the probability of new protected lands within 2 km of city centers, which resulted in a 75% increase in protected areas within 2 km of city centers, compared to the Recent Trends scenario. In addition, concentrating development around city centers resulted in a similar amount of core forest to the Recent Trends, despite accommodating 40% more development.

### 3.3. Connected Communities

The Connected Communities scenario envisions a future characterized by local socioeconomic connectedness and high natural resource planning and innovation. Population growth slowed and became more compact, and, as a result, the rate of new development was just 25% of the rate in the Recent Trends—24 km² per year. Local agriculture expanded to meet the need for local food and forests were converted to new agricultural land at a rate of 41 km² per year, more than 248% of the rate of forests to agriculture simulated in

| Table 3 Continued |
|-------------------|
| **Narrative Quotes (stakeholders)** | **Spatial Allocation Plan (modeling team)** |
| 6. “Land protection priorities focus on the maintenance of ecosystem services, particularly in southern New England where cities depend on watershed lands for low-cost, clean drinking water.” | 6. Probability of conservation has been increased by 20% in MA, CT, and RI in the top 25% Forest to Faucets defined high importance watersheds. |
| 7. “In northern New England a modest increase in agriculture occurs near existing farms and some small patch farming emerges near towns to feed local niche markets.” | 7. All nonprime agricultural soils are ineligible for new agriculture. Zero probability of new agriculture within Census Urban Areas, but increase by 30% within 1 k, 29% within 2 k, 28% within 3 k, down to 1% within 30 k of the urban area boundary. |
Recent Trends. This scenario also included a strong focus on land protection for wildlife and ecosystem services; the rate of new land protection was 1,045 km² per year.

Consistent with this scenario’s emphasis on natural resource conservation and planning, the spatial allocation of LULC change in the Connected Communities scenario included a lower probability of development

Table 4
Conservation Priority Area Data Sources and Definitions

| Conservation Priority Area | Data source and definition |
|---------------------------|---------------------------|
| Core Forests             | CCDC forest pixels that are >30 m from a nonforest land cover at the start of the simulation (i.e., in 2010). |
| Flood Zones              | Federal Emergency Management Agency FEMA Flood Zones with 1% annual probability of flooding (Zones A, AE, AH, AO, and VE) (Federal Emergency Management Agency, 2017). Note that not all subregions have FEMA-defined Flood zones. |
| Surface Drinking Water   | The 25% highest scoring watersheds as classified by the U.S. Forest Service Forest to Faucets report (Weidner & Todd, 2011). Watersheds were ranked based on the importance of their surface water quality in relation to the human demand on that water supply. |
| Wildlife Habitats         | Delineated using State Wildlife Action Plans (SWAP) (Maine Dept. of Inland Fisheries and Wildlife, 2015, Massachusetts Division of Fisheries and Wildlife, 2015, New Hampshire Fish and Game Department, 2012, Rhode Island Department of Environmental Management Division of Fish and Wildlife, 2015, State of Connecticut Department of Energy and Environmental Protection, 2015, and Vermont Fish & Wildlife Department, 2015). We accounted for state level variation in wildlife conservation priorities and for the variable proportion of land given priority status by focusing on the top tiers of each state’s Wildlife Habitat priorities as high-value wildlife conservation assets and then standardized the scores by scaling them relative to the mean score for all land in each state. Therefore, wildlife habitat values greater than 1.0 indicate areas with better than average wildlife value. |
| TNC Priority Conservation Areas | Delineated based on The Nature Conservancy’s Priority Conservation Areas. These areas aim to represent the full distribution and diversity of native species, natural communities, and ecosystems such that a conserving these areas will ensure the long-term survival of all native life and natural communities, not just threatened species and communities. |
| Wetlands                  | Defined as wetlands classified by the National Wetlands Inventory Wetlands (U.S. Fish and Wildlife Service, 2012). |
| Prime Farmlands           | Identified using the Farmland Class from the Gridded Soil Survey Geographic (gSSURGO) Database (SSURGO Soil Survey Staff 2011). We merged the Farmland Classes: farmland of statewide importance, all areas are prime farmland, farmland of unique importance, and farmland of local importance into one “Prime Farmlands” classification. |

Figure 6. Changes in LULC within New England over time for each LULC class and scenario. Note varying Y axes.
and increased probability of land protection within flood zones, wildlife habitat areas and important drinking water watersheds. These modifications, combined with a lower overall rate of new development, resulted in a 77% decrease in the amount of development in flood zones by 2060, an 80% decrease in the amount of development in wildlife habitat areas, and 71% increase in land protection in important watersheds for drinking water. Indeed, the Connected Communities scenario had the greatest increase in the amount of protected land within the Impact Areas across all the scenarios. The scenario narrative emphasized compact development and the simulation of the scenario had the greatest proportion of new development was within 10 km of cities among all scenario (48% of all new development was within 10 km of cities in Connected Communities where as only 35% was within 10 km of cities in the Recent Trends). As part of this scenario's emphasis on climate change adaptation, the proportion of development within 5 km of the coast (where sea level rise is a concern) was significantly less than Recent Trends.

### 3.4. Go It Alone

The Go It Alone scenario envisions a future with low natural resource planning and innovation and local socioeconomic connectedness. New England has shrinking economic opportunities and communities turn heavily to extractive industries. Rates of land development slowed to 75 km² per year, which was a 25% reduction from Recent Trends. Where development continued, it was characterized by unplanned residential housing that perforates the landscape. There was no new agriculture cover. Land protection tapered off dramatically early in the scenario, and by 2060 there was 80% less new protected land than in the Recent Trends scenario.

While the rates are much lower, the spatial allocation of LULC change in Go It Alone followed the patterns developed for the Recent Trends Scenario. Less new development resulted in proportionately less forest loss within Impact Areas, including 25% less priority wildlife habitat loss and 31% less development on flood plains. Relatedly, the large reduction in the rate of land protection resulted in Go It Alone having the lowest level of conservation within Impact Areas among the five scenarios.

### 3.5. Growing Global

The Growing Global scenario envisions and landscape undergoing massive changes. Migration into New England drives up the population. Local planning efforts have failed to keep pace with development. Economic and social connectivity is globalized, while natural resource planning and innovation is low. Compared to the Recent Trends scenario, Growing Global resulted in a 182% increase in the rate of new development, a 900% increase in the rate of new agriculture, and a reduction of 40% in the rate of new land protection.

In this scenario, the total amount of developed land in New England more than doubled (from 14,090 to 28,880 km²) by 2060. Boston grew to a sprawling mega city the size of modern day Tokyo, Japan (Figure A1). Rapid and largely unregulated development resulted in the greatest increase in development within Impact Areas among all scenarios. For example, the Growing Global scenario did not include any spatial modifier to decrease the probability of development in flood zones or other Impact Areas. As a result, by 2060, this scenario developed 275% more flood zones compared to the Recent Trends scenario. There were similarly high (+275%) increases in development within high priority wildlife habitats. More than twice as much land near the coast (<10 km) was developed, as compared to the Recent Trends.

### 4. Discussion

Our process for translating codesigned qualitative scenarios into quantitative simulations of LULC change yielded divergent representations of the future New England landscape. The simulations differ markedly in terms of the amount of LULC change and the spatial pattern of change (Figures 5, 6, and A1). Indeed, among scenarios there is a fivefold difference in the amount of high-density development and a twofold difference in the amount of protected land. While all the scenarios represent distinct storylines resulting in discrete manifestations of those stories, the Growing Global scenario stands out for having, by far, the greatest amount of change. By Year 2060, Growing Global envisions that urban expansion around Boston will sprawl to an area covering more than 10,000 km², larger in size than Tokyo, Japan. On one hand, this is such a drastic change that it may seem implausible to stakeholders and thereby undermine the utility of the scenario. On the other hand, the simulation is faithful to the stakeholders' storyline, which envisions New England as a
destination for millions of migrants fleeing the growing impacts of climate change elsewhere. Specifically, the stakeholders describe “sprawling cities with poor transportation infrastructure, inefficient energy use, and haphazard expansion of residential development.” The plausibility of this scenario is supported anecdotally by events such as Hurricane Maria, which, in 2017, displaced as many as 185,000 people from the island of Puerto Rico to the mainland United States (Alexander et al., 2019). Given that a single storm can cause such large changes to settlement patterns, it will be important to consider the consequences of scenarios, such as Growing Global which push our assumptions about how the past can or cannot shape the future.

Scenarios act as tools to allow stakeholders to engage with the implications of changes within the system they are a part of and through this reveal and challenge their implicit assumptions about the future (Wright et al., 2013). Particularly for complex systems where people are ill equipped to reason through the complexity of the interactions involved, simulations can play a valuable role in stimulating the learning and improved system understanding that ultimately drives successful scenario planning exercises (Derbyshire & Wright, 2017; Volkery et al., 2008). In this fashion, by revealing how a wide range of possible futures may unfold, the scenarios and their simulations developed here provide a tool to enhance understanding of the outcomes of the causal processes, connections and driving forces at play in New England. This in turn may help stimulate learning that overturns existing preconceptions and promotes new and shared mindsets for stakeholders in thinking about the range of possible futures (Wilkinson et al., 2013; Wright et al., 2013).

Despite the divergent simulation outcomes, it is worth noting that our scenario codesign process and the simulation framework relied heavily on information from the past to contextualize the future scenarios, which may perpetuate existing knowledge and assumptions. For example, the frequency of land use change and its spatial allocation on the landscape were all conveyed in terms of multipliers of the Recent Trends scenario. This could constrain the type of expansive thinking that scenario planning strives to engender. While the scenarios were divergent in the amount and distribution of LULC, none envisioned wholly new dynamics at play (e.g., new technologies, pandemics, or transformational events) and it is unclear whether the scenarios sufficiently broadened the perspectives of stakeholders regarding the future. Other recent examples of scenario planning in socioecological systems have also noted similar difficulties in generating highly divergent, novel scenarios, often finding relatively similar narratives were developed across scenario groups, for example, Totin et al. (2018), Falardeau et al. (2019), Vannier et al. (2019), and Raudsepp-Hearne et al. (2020).

Effectively stretching people’s thinking in this way is one of the aims of scenario methods, though one that is also recognized as being challenging to achieve in practice (Bonaccorsi et al., 2020; Bryson et al., 2016; Wack & P., 1985). Our scenario building approach aimed to facilitate this with the structuring the 2 × 2 matrix around extreme outcomes for each key driving force to help prompt consideration of more divergent futures outcomes. However, in other aspects the use of the 2 × 2 matrix may have constrained the realm of future possibilities, for example, by imposing two orthogonal driving forces as the structure around which shape a whole set of possibilities, possibly leading to the underestimating of the influence of other factors on future development (e.g Nilsson et al., 2019; van Vuuren et al., 2012; Wiebe et al., 2018). In addition, given that the more divergent scenarios are, the less plausible and thus less relevant to end-users they may be perceived to be, for the NE-LFP, we opted not to explicitly strive for extremely divergent scenarios that risked being deemed too uncomfortable, implausible, or pessimistic to be perceived as relevant by stakeholders (Ogilvy & Schwartz, 1998). Approaches that really push beyond current perceptions of the future may only be suitable when there is sufficient time for multiple interactions, deep reflection, and exploration (Vervoort et al., 2015), which, as noted above, did not align with the needs of the project or stakeholders. This remains a poorly understood area within the socioecological scenario literature and research that looks more closely into the factors that determine if, when, and why scenarios can generate transformational shifts in stakeholder thinking about the future is urgently needed (Burt et al., 2017; Nilsson et al., 2019; Totin et al., 2018).

In the context of a scenarios-to-simulation process (sensu Alcamo, 2008) and maintaining fidelity to stakeholders’ original vision, our simulations did effectively capture the land use dynamics and features described in the scenario storylines articulated by the stakeholders. Each specific modification to Recent Trends is annotated within the qualitative scenario descriptions so that our stakeholders can see how their vision for each scenario was incorporated into the simulation. By identifying specific quotes that referenced differences in land use patterns, then translating them into explicit rules for the spatial allocation of simulated LULC change (Table 3), we were able to capture the intentions of the stakeholders in ways that had
substantive and readily attributable impacts on the simulated landscape. For example, simulated development surrounding the area of Keene, New Hampshire (Subregion 24) in Go it Alone and Yankee Cosmopolitan both have the same rate of development but different spatial allocation of that development (Figure 7). The Yankee Cosmopolitan narrative described: “Proactive city planning as well as public and private investment in infrastructure have helped to meet the needs of New England's growing population through well‐planned housing, transportation hubs, and municipal services near city centers.” Thus, a spatial modifier was implemented in this scenario to concentrate development close to city centers while protecting farm soils and limiting development in flood zones (Table 3). Overall, this approach represents an effective and transparent method for bridging the gap between nontechnical stakeholders who developed the scenarios and the technical experts who simulated them (Mallampalli et al., 2016). We are hopeful that this clear translation of the scenarios to the simulations bolsters the legitimacy and salience of the participatory scenario process (sensu Cash et al., 2003) and results in greater use by the stakeholders and decision makers.

These simulations reveal much about the potential impacts of future LULC on conservation priorities. In general, the amount of projected LULC change affected the Impact Areas more than the differences in their spatial allocation. For example, the Yankee Cosmopolitan scenario has several spatial allocation rules designed to mitigate the impacts to conservation goals, including reduced probability of new development within flood zones and increased probability of land protection within wildlife habitat areas. In comparison, the Go It Alone scenario has no modifications to the spatial allocation rules. However, Yankee Cosmopolitan has 87% more development than Go it Alone. So despite substantial efforts to mitigate the impacts of development, the Yankee Cosmopolitan scenario resulted in more development in every category of Impact Area than Go it Alone. This pattern is consistent across all scenarios and Impact Areas, insomuch as the rank order of development within each impact area matched the rank order of the amount of development, despite strong differences in the spatial allocation patterns (Figure 8).

The simulated land cover scenarios were designed to meet multiple goals. One key goal was to create simulated land cover scenarios that catalyze new research which to understand and advance sustainable land use trajectories. In addition to the analyses presented here, our hope is that the scenarios will serve as a common platform that brings researchers together to examine the consequences of changing land use. To that end, all the spatial layers (i.e., GIS maps) from this project are available on Data Basin, an open-source spatial data repository (Plisinski & Thompson, 2017). Indeed, researchers from around the region have begun to use the simulation outputs within other landscape models to explore how these scenarios affect various ecosystem services and landscape outcomes, including stream flow and runoff, forest carbon sequestration, maple sugar production, and wildlife habitat.

4.1. The NELF Outreach Tool

In addition to making the data available to researchers, we used the scenarios and simulation products to develop an online interactive mapping tool to portray the interaction between land use choices and LULC...
Figure 8. Impact Areas. Inset bar charts represent the percent of each conservation priority area that was developed (top) and conserved (bottom) for each scenario at Year 2060.
outcomes in New England and support efforts by community groups and conservation groups to explore how they might adapt their LULC plans and conservation priorities to ensure that they are robust under an uncertain future. The tool was designed via a user-engagement process to meet the needs of diverse stakeholders, including many of the stakeholders who codesigned the scenarios.

The NELF Explorer (www.newenglandlandscapes.org) was built by FernLeaf Interactive and the National Environmental Modeling and Analysis Center (NEMAC) at the University of North Carolina, Asheville. The NELF Explorer was built using the simulation outputs in consultation with user perspectives, via a project launch visioning session plus three cycles of prototyping and user review. Users can use the NELF Explorer to navigate among five scenarios (Recent Trends, Go it Alone, Connected Communities, Yankee Cosmopolitan, and Growing Global) and visualize how each scenario influences LULC and conservation priorities at six time points (2010, 2020, 2030, 2040, 2050, 2060), across all six New England states, at multiple scales including state, county, town, and watershed. The NELF Explorer displays maps with LULC color coded (High-Density Development, Low-Density Development, Unprotected Forest, Conserved Forest, Agriculture, and Water). Graphs show the number of acres in each type of LULC for each scenario at the six time points. Also, the outcomes of scenario comparisons in 2060 for Impact Areas of Flood Zones, Surface Drinking Water, Wildlife Habitats, Priority Conservation Areas, Wetlands, Prime Farmland, and Core Forests are described within the tool. The tool is static; the underlying data and calculations were completed in advance via the simulation process. Therefore, the NELF Explorer is a conduit for accessing pre-computed data and visualizations.

The NELF Explorer was launched in March 2019. We are currently tracking use of the tool and collaborating with NELF Explorer users to document use cases. Potential uses of the NELF Explorer include understanding the future of the land through local scenario planning, conservation and development planning, and community engagement/education.

5. Conclusions

Through a deliberate process of stakeholder engagement and codesign, the NELF project developed a set of qualitative land use scenarios that describe four exploratory future landscape scenarios. Here, we have described the rigorous and transparent process that we used to translate those scenarios into spatially explicit LULC simulations, and we assessed the potential consequences of those simulations on several conservation priorities. The research contributes to a growing literature on the development of land use scenarios and simulations and their capacity to explore possible futures outside of previous assumptions, deepen system understanding, and aid long-term planning (Alcamo & Henrichs, 2008; Carpenter et al., 2006; Patel et al., 2007; Qiu et al., 2018; Thompson et al., 2012, 2016). The simulation outputs and a webtool designed for exploring the future landscapes are being used by a range of different researchers and nontechnical stakeholders to assess vulnerabilities and guide planning. The wide range of applications and high level of uptake suggest that this accessible and replicable participatory approach to landscape research that combines story and simulation—while resource intensive for researchers—can live up to its promises of increased relevance, credibility, and salience.

Appendix A

Because the higher quality Continuous Change Detection and Classification (CCDC) data were unavailable for entirety of the New England study area, we chose to fill in the remaining areas with data from the National Land Cover Dataset (NLCD) product suite (Homer et al., 2012). The CCDC and NLCD maps were reclassified to a common legend consisting of High-Density Development, Low-Density Development, Forest, Agriculture, Water, and a composite “Other” class (Table A1). The CCDC data cover all of Massachusetts, New Hampshire, and Rhode Island, 93% of Vermont, 99% of Connecticut, and approximately 33% of Maine.

The NELF scenarios contain two main types of LULC transitions, (1) those that constitute a change in a natural land cover to an anthropogenic land cover such as Forest to Development or Forest to Agriculture and (2) those that constitute a change in land use designation, such as Forest to Conserved Forest. Figure A1 illustrates simulated anthropogenic LULC transition while Figure 5 shows all LULC transition.
Table A1
Reclassification Scheme for CCDC and NLCD Data

| This study                        | CCDC class                  | CCDC class description                                    | NLCD 2001/2011 class               | NLCD 2001/2011 class description                                      |
|----------------------------------|-----------------------------|------------------------------------------------------------|------------------------------------|---------------------------------------------------------------------|
| High density, developed          | Commercial/industrial       | Area of urban development; impervious surface area target 80–100% | Developed, high intensity         | Highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover. |
|                                  | High density, residential   | Area of residential urban development with some vegetation; impervious surface area target 50–80% | Developed, medium intensity       | Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units. |
| Low density, developed           | Low density, residential    | Area of residential urban development with significant vegetation; impervious surface area target 0–50% | Developed, Low Intensity          | Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units. |
|                                  |                             |                                                             | Developed, Open Space             | Areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or esthetic purposes. |
| Agriculture                      | Agriculture                 | Nonwoody cultivated plants; includes cereal and broadleaf crops | Pasture/hay                       | Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation. |
|                                  |                             |                                                             | Cultivated crops                  | Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled. |
| Forest                           | Mixed forest                | Forested land with at least 40% tree canopy cover comprising no more than 80% of either evergreen needleleaf or deciduous broadleaf cover | Mixed forest                      | Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover. |
|                                  | Deciduous broadleaf forest  | Forested land with at least 40% tree canopy cover comprising more than 80% deciduous broadleaf cover | Deciduous forest                  | Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change. |
|                                  | Evergreen needleleaf forest | Forested land with at least 40% tree canopy cover comprising more than 80% evergreen needleleaf cover | Evergreen forest                  | Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage. |
| Woody wetland                    |                              | Additional class of wetland that tries to separate wetlands with considerable biomass from mainly herbaceous wetlands | Woody wetlands                    | Areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water. |
|                                  |                              |                                                             | Shrub/scrub                       | Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions. |
| Other                            | Wetland                     | Vegetated land (woody and nonwoody) with inundation from high water table; includes swamps, salt and freshwater marshes and tidal rivers/mudflats | Emergent herbaceous wetlands       | Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water. |
Table A1
Continued

| This study | CCDC class          | CCDC class description                                      | NLCD 2001/2011 class | NLCD 2001/2011 class description                                                                 |
|------------|---------------------|----------------------------------------------------------------|----------------------|------------------------------------------------------------------------------------------------|
| Herbaceous/grassland | Nonwoody naturally occurring or slightly managed plants; includes pastures | Barren land (Rock/sand/clay) | Areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover. |
| Bare       | Nonvegetated land comprised of above 60% rock, sand, or soil    | Open water           | Areas of open water, generally with less than 25% cover of vegetation or soil.               |
| Water      | Water               | Lakes, ponds, rivers, and ocean                               |                      |                                                                                                  |

Figure A1. Simulated anthropogenic LULC transitions (forest to development) and (forest to agriculture) 2010–2060.
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Data Availability Statement

All relevant data are publicly available on the Databasin repository “New England Landscape Futures” accessible at the website (https://databasin.org/groups/26ceb6c7ece6b0d9872e118bae80d41).

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