

Simulation of forest change in the New Jersey Pine Barrens under current and pre-colonial conditions

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Abstract

Changes in land use patterns in and around forests, including rural development and road building, have occurred throughout the United States and are accelerating in many areas. As a result, there have been significant departures from ‘natural’ or pre-settlement disturbance regimes. Altered disturbance regimes can shift composition and dominance in tree species communities, potentially affecting ecosystem functioning. We examined the potential consequences of various forest management practices and forest fragmentation on tree community composition. Both forest management and fragmentation are changing as land use changes within the New Jersey Pine Barrens (NJPB). The NJPB has and is continuing to experience rapid rural development and urbanization that are altering the types, frequency, and intensity of forest management, and are increasing forest fragmentation. In the NJPB, the size and frequency of wildfires have declined and the use of prescribed fires is limited to a small portion of the landscape. In addition, the expansion of roads and decline in total forested area – two common measures of fragmentation – may impede the ability of tree species to colonize available habitat. To assess the consequences of fire management and fragmentation on fire regimes and forest communities, we simulated forest landscape change using LANDIS-II, a stochastic, spatially dynamic forest succession model that simulates the growth of tree species cohorts (defined by species and age), dispersal and colonization, and mortality. Simulated fires are sensitive to fuel loads and fuel load continuity. We constructed scenarios to mimic the pre-colonial contiguous landscape with an estimated pre-colonial fire regime; scenarios of the current day landscape with current and potential fire management; and scenarios designed to highlight the effects of fragmentation. Our simulations indicate that relative to the pre-colonial landscape and fire regime, the landscape is changing from a pine-dominated to an oak-dominated state. However, within areas where prescribed burning remains a viable management option, a doubling of the mean annual area that is managed with prescribed burns may substantially push the system back towards pre-colonial conditions, although oaks will continue to retain a higher than pre-colonial dominance. Our results also indicate that aside from a reduction in the potential fire sizes, fragmentation does not appear to substantially alter forest successional dynamics. In summary, our simulations estimate the departure from pre-colonial conditions and indicate the potential for a limited restoration of these conditions.

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1. Introduction

The Pine Barrens of southeastern New Jersey (NJPB) have a long history of human use and habitation (Luque et al., 1994). However, details of the pre-colonial vegetation and fire history of the NJPB are not well known, due in part to uncertainty about

the extent to which Native Americans influenced fire regimes (Russell, 1983). Pre-colonial land surveys have been successfully used in other areas of New England (e.g., Cogbill et al., 2002) and the Mid-Atlantic US (e.g., Russell, 1981), but no investigation of the extant land survey records for southern New Jersey has been conducted to date. Likewise, available palynological data (Watts, 1979), which are often used to determine vegetation and disturbance history, are not spatially extensive within the NJPB due to a lack of suitable sites.

As compared to the current vegetation of the NJPB, pre-colonial vegetation in other Atlantic Coastal Plain Pine Barrens

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systems (e.g., Long Island, New York and Cape Cod, MA) had a greater dominance of oaks (*Quercus* spp.) than pines (*Pinus* spp.) (Kurczewski and Boyle, 2000; Cogbill et al., 2002). These studies suggest that the fire rotation periods in these Pine Barrens systems may have been longer than is often assumed. Likewise, the NJPB may have also experienced less frequent burning during the pre-colonial period as compared to the post-colonial period.

After European settlement, upland forests in the NJPB were variously logged for fuel wood for iron and glass production, timber for the coastal shipyard industry, and charcoal production. Along with intensive human use, the NJPB experienced large wildfires throughout the nineteenth century due to large volumes of slash following logging and an increase in human caused ignitions due to increased population density and ignitions from the primary industries in the region (charcoal and iron production; Wacker, 1979). During the twentieth century, intense extractive activities declined although significant rural development, primarily for housing, occurred around the periphery of the NJPB. Many forest stands regenerated naturally, especially within the areas that would become the larger state forests (now Brendan Byrne, Wharton, and Bass River State forests), wildlife management areas (Greenwood, Stafford Forge) and military bases (Fort Dix, Warren Grove). The New Jersey Forest Fire Service was founded in 1906, and prescribed fire treatments were initiated in the 1930s. The Pinelands National Reserve effectively preserved ~445,000 ha of forest in 1979. Nevertheless, development continues on the remaining unprotected forested area (Lathrop and Kaplan, 2004) as well as in agricultural areas. Such development generally occurs in the form of numerous small parcels that are converted to housing or commercial uses.

Land use change has significantly altered the disturbance regime relative to pre-colonial conditions. Roads have reduced fuel continuity (Heyerdahl et al., 2001) and increased the effectiveness of fire suppression, generally causing a reduction in fire size and a lengthening of the fire rotation period. The expansion of housing at the margins and along major transportation corridors in the NJPB changes the socio-economic context of forested landscapes (Ward et al., 2005; Clendenning et al., 2005). Frequently, new residents oppose active forest management (e.g., prescribed fire) and therefore limit management options (Clendenning et al., 2005).

Agriculture, development, and road networks have also fragmented much of the NJPB (Fig. 1) (Luque et al., 1994). The effects of fragmentation on forest structure and function in other systems include the loss of habitat, the loss of core forested area, changes in edge density, increased erosion, and increased vehicular traffic and human presence (Reed et al., 1996; Forman and Alexander, 1998; Jules, 1998). Fragmentation may also reduce the ability of tree species to colonize available habitat, potentially reducing tree species richness and ecosystem functioning (Hooper and Vitousek, 1997; Chapin et al., 1998; Naeem et al., 1999).

Our objectives were to examine the consequences of altered fire regimes, fire management, and fragmentation on the current

and future state of the NJPB, as compared to estimated pre-colonial conditions. We used a simulation modeling approach using LANDIS-II to meet our objectives. This forest landscape simulation model enabled us to estimate pre-colonial conditions, directly test the effects of fragmentation on forest composition, and estimate future conditions under current and hypothetical fire management scenarios. Because little data are available about the pre-colonial vegetation and disturbance regimes in the NJPB, we simulated two potential pre-colonial reference conditions based on the range of available data in the literature with respect to the pre-colonial condition in the NJPB.

2. Methods

2.1. Study area

The NJPB encompass pine, oak and wetland forests, covering much of southern New Jersey. The climate is cool temperate, with mean monthly temperatures of 0.3 and 23.8 °C in January and June, respectively (1930–2004; NJ State Climatologist). Mean annual precipitation is 1123 mm (S.D. 82 mm). The terrain consists of plains, low-angle slopes and wetlands, with a maximum elevation of 62.5 m. Soils are derived from the Cohansey and Kirkwood Formations (Lake-wood and Sassafras soil series), and are coarse-textured, sandy, acidic, and have extremely low cation exchange capacity and nutrient status (Rhodehamel, 1979; Tedrow, 1986). Despite the widespread occurrence of sandy, well-drained, nutrient-poor soils, upland forests are moderately productive and fuels can accumulate rapidly (Pan et al., 2006).

Upland forests comprise 62% of forested lands of the NJPB and are dominated by pitch pine (*Pinus rigida*) and numerous oaks (*Quercus* spp.) (Lathrop and Kaplan, 2004). The uplands are often divided into three major communities: oak dominated forests with scattered pines (Oak/Pine), pine dominated forests with oaks in the overstory (Pine/Oak), and Pitch Pine dominated forests with scrub oaks and shrubs in the understory (Pine/Scrub Oak) (McCormick and Jones, 1973; Lathrop and Kaplan, 2004). In the more mesic western area co-dominates include Virginia pine (*P. virginiana*) and black cherry (*Prunus serotina*). All upland forests have moderate to dense shrub cover in the understory, primarily *Vaccinium* spp., *Galussacia* spp., *Kalmia* spp. and *Quercus* spp., and sedges, mosses and lichens are also present. Many of the dominant species are highly adapted to fire and readily resprout (Boerner, 1981). Upland forests are of major concern to fire managers, because dense residential developments and key transportation corridors occur adjacent to these flammable forests. Interlaced through the area are numerous rivers and streams; associated lowland forests are dominated by Atlantic white cedar (*Chamaecyparis thyoides*), red maple (*Acer rubrum*), swamp tupelo (*Nyssa sylvatica*), pitch pine, shortleaf pine (*P. echinata*), and mesic adapted oaks (*Q. alba*, *Q. velutina*). After excluding urbanized and other non-forested areas, the combined area simulated covers approximately 650,000 ha (Fig. 1).



Fig. 1. New Jersey Pine Barrens study area.

2.2. Simulation model

We simulated change within the NJPB with the forest landscape model LANDIS-II (Scheller et al., 2007). LANDIS-II simulates both succession (Scheller and Mladenoff, 2004) and disturbance in a spatially dynamic framework that emphasizes spatial interactions among individual sites (cells) and among processes (e.g., fire, succession, and dispersal). LANDIS-II is derived from LANDIS (Mladenoff et al., 1996; Mladenoff, 2004). LANDIS-II simulates the geographic distribution and the aboveground biomass of individual tree species. The successional and disturbance dynamics of tree species is dependent upon their unique life history attributes (Roberts, 1996), their growth rates, and their ability to establish or resprout at a given location. Growth rates and species establishment are assumed to be a function of soils and climate. LANDIS-II does not represent individual trees, rather trees are represented as species and age defined cohorts. Any simulated site on the landscape can have zero or many cohorts, each behaving individually (Scheller et al., 2007). We used LANDIS-II v5.1 with the Biomass Succession (v1.0) and

Base Fire (v1.2) extensions (<http://www.landis-ii.org>). Our study area was simulated at a resolution of 100×100 m.

2.3. Model inputs

The STATSGO soils database was used to classify the NJPB into distinct ecoregions (STATSGO, 1994). Our study area was delimited from STATSGO management units, keeping those units within the NJPB that remain significantly forested. However, STATSGO has poor resolution for forested wetlands. A 2001 land cover classification (LULC-2001) was used to further delineate forested wetlands (Lathrop and Kaplan, 2004). The LULC-2001 data also indicated non-forested cover classes (urban, agriculture, etc.); these cells were treated as non-active areas. For the pre-colonial scenarios, non-forested classes identified from LULC-2001 were treated as either an upland ecoregion or forested wetland, as estimated from a nearest neighbor analysis.

The initial community composition of the landscape was generated from 1999 Forest Inventory and Analysis (FIA) plot data (Hansen et al., 1992) and Land Use Land Cover class from

2001 (LULC-2001; Lathrop and Kaplan, 2004). A species list with cohort ages was generated from each FIA sub-plot within the study area. Ages were estimated from a regression of maximum diameter and breast height against plot ages. From this analysis of FIA data, we derived 237 unique current “communities” containing from 1–7 species and one to many initial cohorts (lumped into 10 year bins) for each species. Each species and ages list derived from an FIA sub-plot was assigned to a LULC-2001 forest type, dependent upon species composition and relative dominance.

Next, each forested cell within the study area was randomly assigned a community (derived from the 237 FIA sub-plots), contingent upon the LULC-2001 forest type of that cell and contingent upon whether the cell occurred in an upland or lowland area. For the pre-colonial scenarios, urban and agricultural areas were assigned a current community estimated from a nearest neighbor analysis.

Species life history parameters (Table 1) were estimated from expert knowledge of the Pine Barrens vegetation. Also for each species, and within each ecoregion, the probability of a cohort becoming established (the probability of establishment, P_{EST}) must be calculated (Scheller and Mladenoff, 2005). P_{EST} is dependent upon ecoregion-scale soil properties and climate. Soils data (soil carbon, field capacity, and wilting point) were derived from STATSGO for each ecoregion (Davidson and Lefebvre, 1993; Davidson, 1995). Average temperature and precipitation per ecoregion were derived from PRISM data (<http://www.ocs.orst.edu/prism/>) (Daly et al., 2002). Average growing season was calculated by averaging data from NRCS for the seven counties in the study area (<http://www.wcc.nrcs.usda.gov/>). A forest gap model (0.1 ha plot), LINKAGES, was used to estimate P_{EST} (Scheller et al., 2005). LINKAGES was run for each species within each STATSGO management unit. The P_{EST} for each species was then mapped and the mean P_{EST} was computed for each of our ecoregions. A minimum value of 0.05 was assigned to P_{EST} for each species present in the FIA data when LINKAGES estimated P_{EST} to

be less than 0.05. LINKAGES performed poorly for estimating P_{EST} within forested wetlands (many abundant lowland species had a P_{EST} of 0.0). Therefore, P_{EST} was estimated as the percentage of cells in forested wetlands that contained each species, based on the current communities map.

The PnET-II ecosystem process model was used to estimate maximum annual aboveground net primary productivity (ANPP) for each species within each ecoregion (Aber and Federer, 1992; Scheller and Mladenoff, 2004). Weather data for PnET-II were estimated for each ecoregion from PRISM data (<http://www.ocs.orst.edu/prism/>) (Daly et al., 2002). Species parameters were derived from available literature data (Aber and Federer, 1992). Soil water holding capacity for each ecoregion was derived from STATSGO (Pan et al., 2006). Annual ANPP was calculated as the sum of foliar NPP and wood NPP estimated from PnET-II.

2.4. Vegetation classification

A LANDIS-II model extension was written to assign each forested cell to one of 11 vegetation classes. The classification system was developed for the Eastern LANDFIRE Prototype in conjunction with NatureServe (www.natureserve.org) to classify vegetation to the Ecological Systems Classification (Comer et al., 2003) based on the relative abundance of indicator species at field reference plots (e.g., forest inventory plots). Ecological systems are assemblages of biological communities that are found in similar environmental conditions with similar disturbance regimes. They are meant to represent a level of vegetation classification that is readily identifiable in the field and from remote sensing platforms for mapping purposes (Comer et al., 2003). The original key was developed to classify plot-level data using relative basal area to indicate the relative abundance of indicator species. Thresholds of relative basal area were selected based on expert opinion and a heuristic approach for classifying thousands of plots, examining the resultant classification, and then making adjustments to

Table 1
Species names and life history attributes

| Species | Longevity (years) | Minimum seeding age (years) | Shade tolerance | Fire tolerance | Effective seeding distance (m) | Maximum seeding distance (m) | Probability of resprout | Minimum resprout age (years) | Maximum resprout age (years) | Post-fire regeneration |
|-------------------------------|-------------------|-----------------------------|-----------------|----------------|--------------------------------|------------------------------|-------------------------|------------------------------|------------------------------|------------------------|
| <i>Acer rubrum</i> | 150 | 10 | 4 | 1 | 100 | 1000 | 0.5 | 10 | 140 | None |
| <i>Chamaecyparis thyoides</i> | 400 | 12 | 3 | 3 | 183 | 1000 | 0.5 | 5 | 100 | Resprout |
| <i>Nyssa sylvatica</i> | 200 | 15 | 4 | 2 | 30 | 1000 | 0.75 | 0 | 100 | None |
| <i>Pinus echinata</i> | 200 | 20 | 1 | 3 | 60 | 500 | 0.75 | 5 | 25 | Resprout |
| <i>Pinus rigida</i> | 200 | 5 | 1 | 3 | 60 | 250 | 0.75 | 5 | 60 | Resprout |
| <i>Pinus virginiana</i> | 120 | 5 | 1 | 2 | 30 | 1000 | 0 | 0 | 0 | None |
| <i>Prunus serotina</i> | 180 | 30 | 3 | 1 | 30 | 3000 | 0.5 | 10 | 150 | None |
| <i>Quercus alba</i> | 300 | 40 | 3 | 3 | 30 | 3000 | 0.5 | 5 | 40 | Resprout |
| <i>Quercus coccinea</i> | 120 | 20 | 2 | 1 | 30 | 500 | 0.5 | 5 | 75 | Resprout |
| <i>Quercus falcata</i> | 150 | 25 | 3 | 2 | 30 | 500 | 0.75 | 5 | 25 | Resprout |
| <i>Quercus prinus</i> | 200 | 20 | 3 | 3 | 30 | 500 | 0.75 | 5 | 60 | Resprout |
| <i>Quercus velutina</i> | 250 | 20 | 3 | 2 | 30 | 3000 | 0.4 | 5 | 25 | Resprout |

Shade tolerance is an ordinal scale whereby 1 is least shade tolerant, 5 is most tolerant. Fire tolerance is an ordinal scale whereby 1 is least fire tolerant, 5 is most tolerant.

Table 2
Vegetation classification for simulation model output

| Order | Forested wetland | Ecological Systems Classification | Abbreviated label | Indicator species | Relative biomass | Secondary species | Relative biomass |
|-------|------------------|---|--------------------|---|------------------|---------------------|------------------|
| 1 | No | Atlantic Coastal Plain Northern Basin Peat Swamp | Wet Conifer | <i>Chamaecyparis thyoides</i> | >10% | | |
| 2 | No | Atlantic Coastal Plain Northern Basin Swamp and Wet Hardwood forest | Wet Hardwood | <i>Nyssa sylvatica</i> | >10% | | |
| 3 | Yes | Atlantic Coastal Plain Northern Basin Swamp and Wet Hardwood forest | Wet Hardwood | <i>Acer rubrum</i> | >15% | | |
| 4 | No | Atlantic Coastal Plain Northern Upland Pitch Pine Barrens | Upland Pitch Pine | <i>Pinus rigida</i> | >10% | <i>Quercus</i> spp. | >10% |
| 5 | Yes | Atlantic Coastal Plain Northern Pitch Pine Lowland | Lowland Pitch Pine | <i>Pinus rigida</i> | >10% | | |
| 6 | No | Atlantic Coastal Plain Northern Maritime forest | Maritime forest | <i>Prunus serotina</i> | >10% | | |
| 7 | No | Atlantic Coastal Plain Northern Upland Pitch Pine Barrens | Upland Pitch Pine | <i>Pinus rigida</i> | >60% | | |
| 8 | No | Atlantic Coastal Plain Northern Dry Hardwood forest | Dry Hardwood | <i>Pinus echinata</i> | >2% | | |
| 9 | No | Atlantic Coastal Plain Northern Dry Hardwood forest | Dry Hardwood | <i>Quercus falcata</i> | >5% | | |
| 10 | No | Atlantic Coastal Plain Northern Dry Hardwood forest | Dry Hardwood | <i>Quercus alba</i> , <i>Quercus velutina</i> , <i>Quercus coccinea</i> | >10% | | |
| 11 | – | Regenerating | Regeneration | No biomass due to recent fire | | | |

Ecological Systems Classifications were assigned based on order with the first having precedence and so on.

the relative basal area threshold values where needed until, at the landscape level, the classification matched known spatial patterns of vegetation. For classifying LANDIS-II output, we removed indicator species and thresholds from the original key that were not included in the simulations, substituted relative aboveground biomass for relative basal area, and classified each forested cell at 10 year time steps, based on the resultant key (Table 2). Results were summarized by the Ecological System Classification.

2.5. Experimental design/fire parameterization

Seven scenarios were developed to explore the implications of forest and fire management, fire suppression, and fragmentation using LANDIS-II in the NJPB (Table 3):

2.5.1. Scenario A1: Pre-colonial landscape, pre-colonial fire regime

The goal of scenario A1 was to estimate pre-colonial vegetation assuming that anthropogenic fire ignitions significantly affected the pre-colonial disturbance regime. Pre-colonial fire sizes were based on the estimated pre-colonial disturbance fire regime from LANDFIRE Rapid Assessment reference condition models (www.landfire.gov), which assumed Native American influence on the fire regime of the NJPB. Reference condition models were developed at regional LANDFIRE workshops by experts in fire ecology and vegetation dynamics. Fire ignition frequency was determined by model calibration to the expected fire rotation periods as determined by the Rapid Assessment reference conditions (Table 3). The pre-colonial species composition was estimated

Table 3
Parameters for six model scenarios used to simulate landscape change in the New Jersey Pine Barrens

| Scenario name | Successional time step | Fire time step | Number of simulation years | Unmanaged upland fire rotation period (years) | Unmanaged lowland fire rotation period (years) | Managed upland fire rotation period (years) | Managed lowland fire rotation period (years) | Fragmented |
|---|------------------------|----------------|----------------------------|---|--|---|--|------------|
| (A) Pre-colonial landscape, pre-colonial fire rotation period | 10 | 1 | 500 | 32 | 158 | – | – | No |
| (B) Current landscape, current fire regime | 5 | 1 | 50 | 186 | 188 | 44 | 187 | Yes |
| (C) Current landscape, double prescribed fire within controlled locations | 5 | 1 | 50 | 186 | 187 | 27 | 186 | Yes |
| (D) Current landscape, increased prescribed fire, random locations | 5 | 1 | 50 | 94 | 94 | 26 | 26 | Yes |
| (E) Current landscape, pre-colonial fire rotation period | 10 | 1 | 500 | 32 | 159 | – | – | Yes |
| (F) Current landscape, pre-colonial ignition frequency and fire sizes | 10 | 1 | 500 | 38 | 233 | – | – | Yes |

after simulating landscape change (assuming current climate conditions) until the landscape reached approximate equilibrium (500 years).

2.5.2. Scenario A2: Pre-colonial landscape, alternate pre-colonial fire regime

The goal of scenario A2 was to estimate pre-colonial vegetation assuming fewer anthropogenic ignitions due to Native Americans. Given an infrequent fire return interval, fuel buildup would have likely increased fire severity. Therefore, scenario A2 was given a fire rotation period of ~ 70 years for upland areas, based on the frequency of stand replacing fires in the LANDFIRE Rapid Assessment reference condition models. Again, we simulated landscape change for 500 years to reach our estimate.

2.5.3. Scenario B: Current landscape, current fire management

Scenario B simulated current day fire management using the current landscape composition. Current day fire management practices generally limit prescribed fires to large, contiguous areas (i.e., Wharton State Forest, Greenwood Wildlife Management Area, Fort Dix Army Base) within the National Pinelands Reserve (Fig. 2). We calculated present day fire rotation periods separately for managed and unmanaged lands. Databases of wildfire (1986–1995) and prescribed fire (1990–2006; for managed areas only) occurrences and fire sizes were provided by the New Jersey Forest Fire Service (NJFFS). The annual percentage of total vegetated area burned was used to determine the fire rotation period for managed and unmanaged areas. Prescribed fire data were available for only a portion of

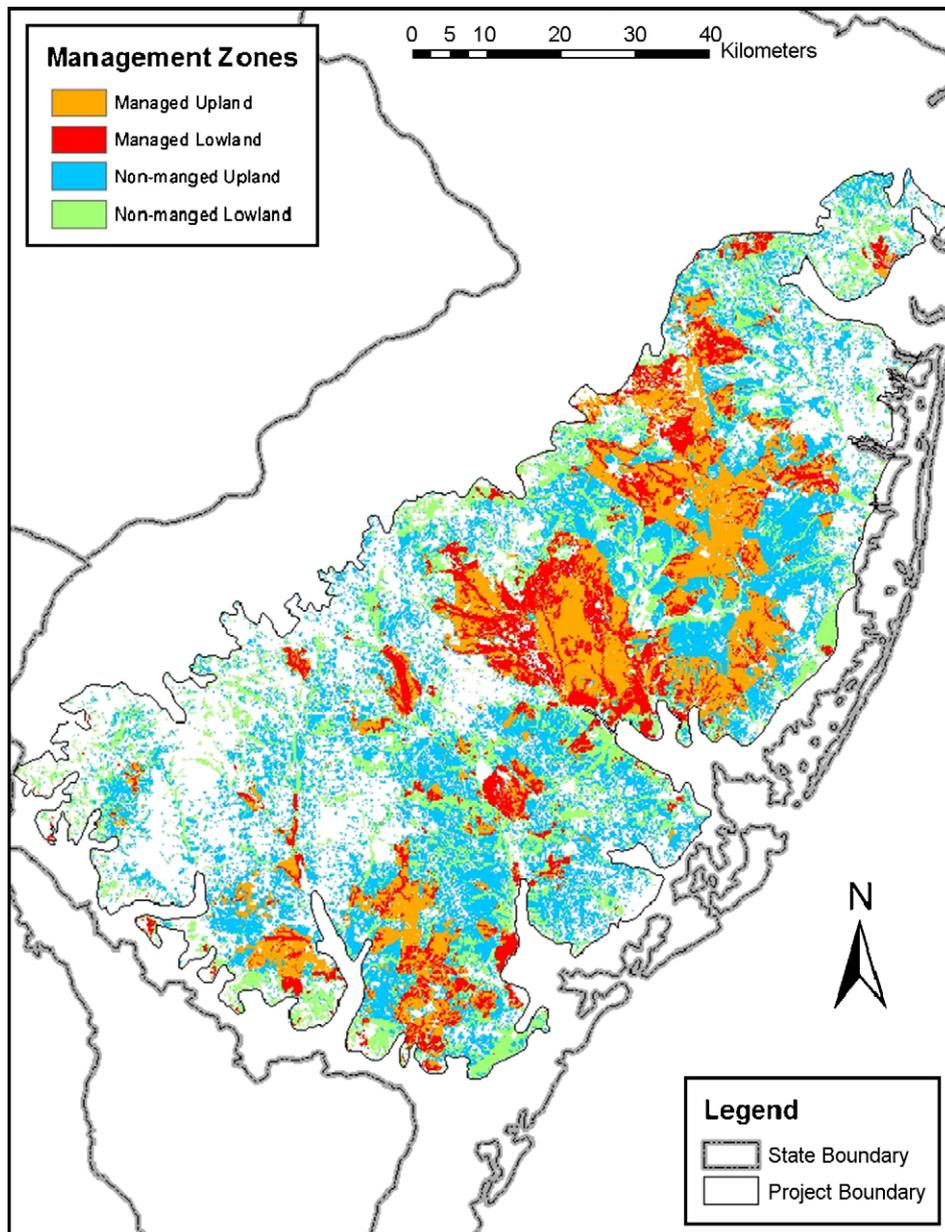


Fig. 2. Fire management zones used for NJPB model simulations.

the managed areas and we assumed that the area burned annually in this management regime characterized the remainder of these management areas. This may underestimate the fire rotation period in some management areas, as the prescribed fire regime in the areas for which data were provided is generally more frequent. Also, although prescribed fire may be used in unmanaged areas, little data were collected by the NJFFS in unmanaged lands. It is, however, unlikely that the intensity of managed fire use in the unmanaged lands is sufficient to significantly alter the fire rotation period used in our simulations.

2.5.4. Scenario C: Current landscape, increased prescribed fire, controlled locations

The goal for scenario C was to estimate near-term landscape change assuming an approximate doubling in the area burned in areas where fire management is currently used to reduce fuel loading. The doubling of burns occurred only in designated management areas (Fig. 2), while the area burned in unmanaged areas remained the same as in scenario B.

2.5.5. Scenario D: Current landscape, increased prescribed fire at random locations

The goal for scenario D was to estimate near-term landscape change assuming a doubling in area burned. The increased area was distributed throughout the NJPB, including both managed and unmanaged areas (Fig. 2) to simulate the effects of increasing fire management activities in both areas. This scenario represents a significant departure from the current management regime which is restricted primarily to state and federal lands. However, municipalities and private land owners may show an increased interest in fire management in the future given the high risk of fire in wildland–urban interface areas in the NJPB.

2.5.6. Scenario E: Current landscape, pre-colonial fire rotation period

The goal for scenario E was to estimate what effect fragmentation alone would have on vegetation dynamics. The current fragmented landscape was used as our initial condition. While maintaining current fragmentation, we calibrated the model such that fire rotation periods (years) approximated pre-colonial (scenario A1) fire rotation periods.

2.5.7. Scenario F: Current landscape, pre-colonial fire frequencies and potential fire sizes

The goal for scenario F was to estimate what effect fragmentation would have on vegetation dynamics, including any lengthening of the fire rotation period caused by fragmentation. We overlaid pre-colonial fire ignition frequencies and potential fire sizes onto the current fragmented landscape (using identical fire parameters from scenario A1). The resulting fire rotation period therefore was reduced by the lack of fuel continuity, i.e., fires reached their potential size less frequently than during the pre-colonial era.

3. Results

3.1. Estimates of Ecological Systems Classifications

The two pre-colonial scenarios (A1 and A2) show little difference in the percent of the overall landscape dominated by each Ecological Systems Classification. Scenario A2 resulted in a slight decrease in the amount of Upland Pitch Pine forest and Regeneration classes, and a slight increase in the amount of Maritime forest and Dry Hardwood forest (Fig. 3). Our simulations estimate that the pre-colonial NJPB was dominated by between 58% (scenario A1) and 53% (scenario A2) Upland Pitch Pine forest, as compared to 48% today (Fig. 3). Simulation results also indicate a lower amount of current day upland forested area dominated by the Wet Conifer and Lowland Pitch Pine classes relative to pre-colonial scenarios (Fig. 3). Similarly, our results indicate that current day forests contained more Wet Hardwood and Dry Hardwood relative to our pre-colonial scenarios.

Departure of the current and future landscapes differ, in some cases, depending on the pre-colonial scenario (A1 or A2) used as the reference condition. Typically, the degree of departure is different between the unmanaged and managed lands, given the differences in pre-colonial and current day fire regimes. For instance, in unmanaged uplands, using the anthropogenically influenced pre-colonial scenario (A1) as a reference condition suggests that the Upland Pitch Pine Barrens in the unmanaged lands show departure (lower in the current day; Fig. 4), while in the managed uplands, Pitch Pine forests have not departed from the pre-colonial condition (Fig. 5). The opposite is true when using the second pre-colonial condition (A2) with a less intense fire regime (Figs. 4 and 5). Typically, the differences in departure between pre-colonial scenarios (A1 and A2) and current day are apparent only in the upland

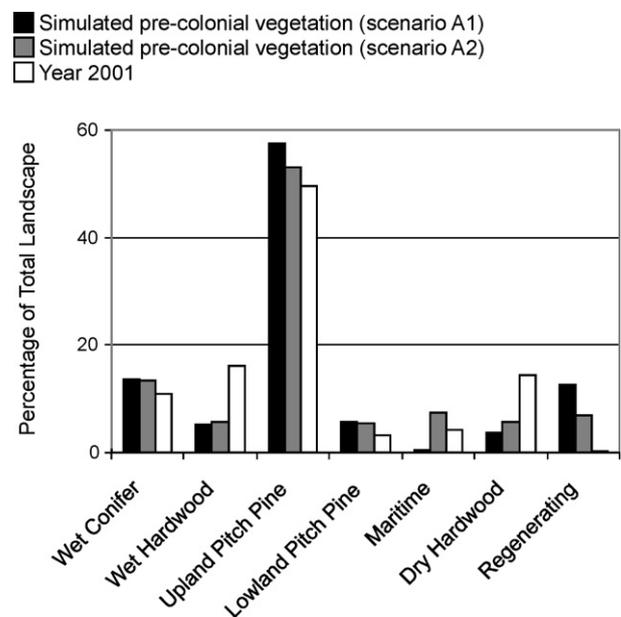


Fig. 3. Current day classified forest vegetation and estimates of pre-colonial vegetation (scenario A) from a forest landscape simulation model.

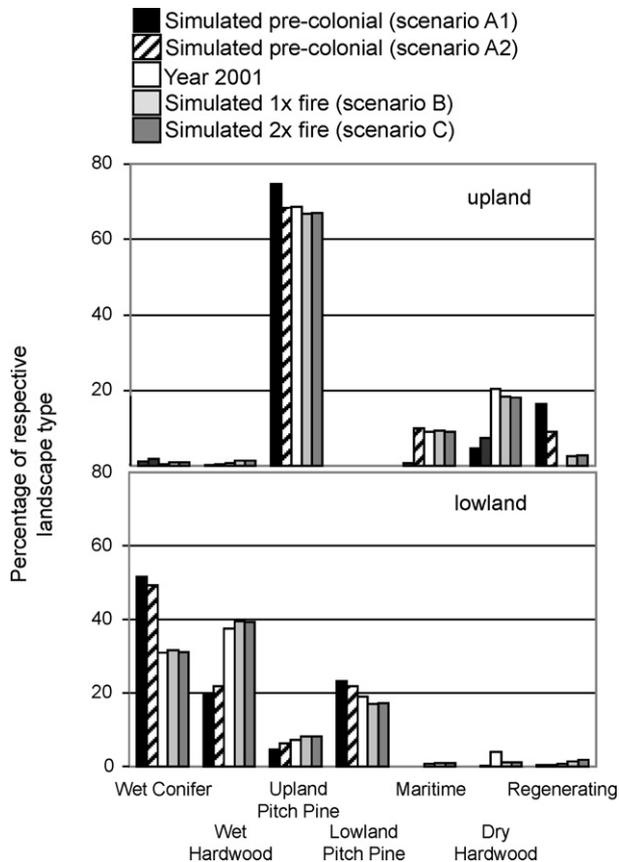


Fig. 4. Simulated unmanaged upland (upper panel) and lowland (lower panel) forests within the New Jersey Pine Barrens (50 year simulations). Estimated pre-colonial and year 2001 vegetation classes are provided as reference. Classes are defined in Table 3.

systems. Unmanaged lowlands systems are typically quite departed from the reference condition regardless of the reference condition used while managed lowlands tend to show somewhat less departure with respect to the reference condition (Figs. 4 and 5).

Our simulations estimate only minor changes in the ecological systems classification of the unmanaged NJPB forests (upland and lowland) after 50 years under the two management scenarios (B and C) (Fig. 4). Within the unmanaged areas, future management scenarios indicate that continuation of current day fire regime (B) or a doubling of fire regime (C) would have little effect on the proportion of vegetation classes across the landscape (Fig. 4). The results indicate that without substantially more harvesting, prescribed fire, or wildfire, we should not expect any significant alteration in the unmanaged landscape within the next 50 years (Fig. 4).

The managed forests, like the unmanaged forests, show little difference between current day and future management scenarios with the exception of slight shifts in the amount of Pitch Pine Barrens, Maritime forest, and Dry Hardwood forests (increase, decrease, and decrease, respectively) under the continuation of current day management (B) and increased fire frequency scenario (C). The differences between current day and the two future management scenarios, is relatively small

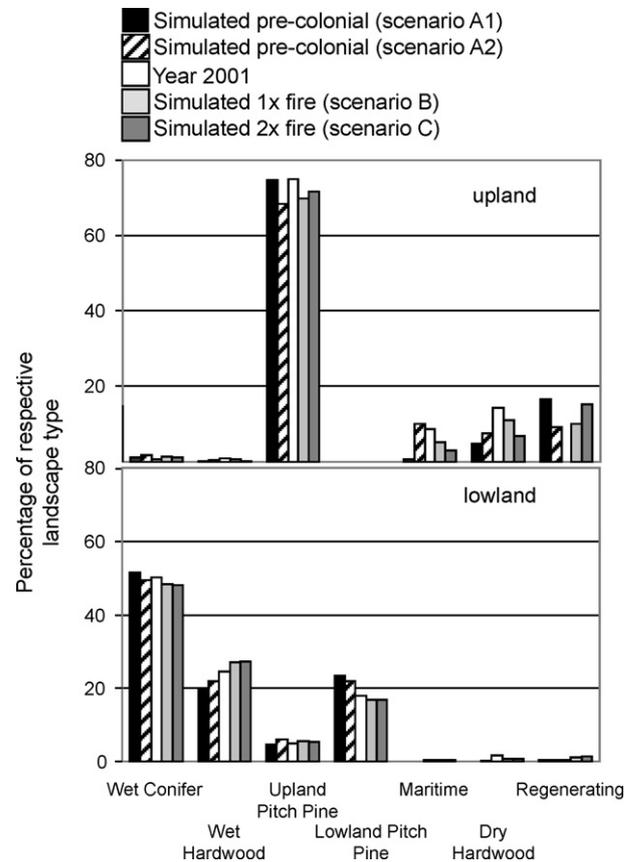


Fig. 5. Simulated managed upland (upper panel) and lowland (lower panel) forests within the New Jersey Pine Barrens (50 year simulations). Estimated pre-colonial (scenario A) and year 2001 vegetation classes are provided as a reference. Classes are defined in Table 3.

compared with differences, in some cases, between pre-colonial and current day condition.

3.2. Transitions in oak dominance within the Atlantic Coastal Plain Northern Upland Pitch Pine Barrens

The Upland Pitch Pine Barrens vegetation class includes a mix of Pitch Pine and a variety of oak species. The ecology of this system suggests that under increased frequency of fire, a shift from dominance of oaks to pine might occur. For every scenario, we compared the abundance of oak species (measured as a percentage of aboveground biomass occupied by the sum of all oak species) for all Upland Pitch Pine forests (Fig. 6). The pre-colonial scenarios indicate that oak species were limited to <60% biomass within Upland Pitch Pine forests and were generally a minor component. Scenario A1 shows oaks as a minor component with >90% of the landscape having <10% oak by biomass (Fig. 6). Scenario A2 shows a more uniform distribution of oak biomass than A1, though oak biomass is never greater than 60% of total biomass. Current day forests have a much greater abundance of oaks, comprising up to 90% which is greater than the dominance of oaks in both of the pre-colonial scenarios. The trend towards greater oak abundance may continue under current day management and with a doubling of fires within current fire management zones. Only a

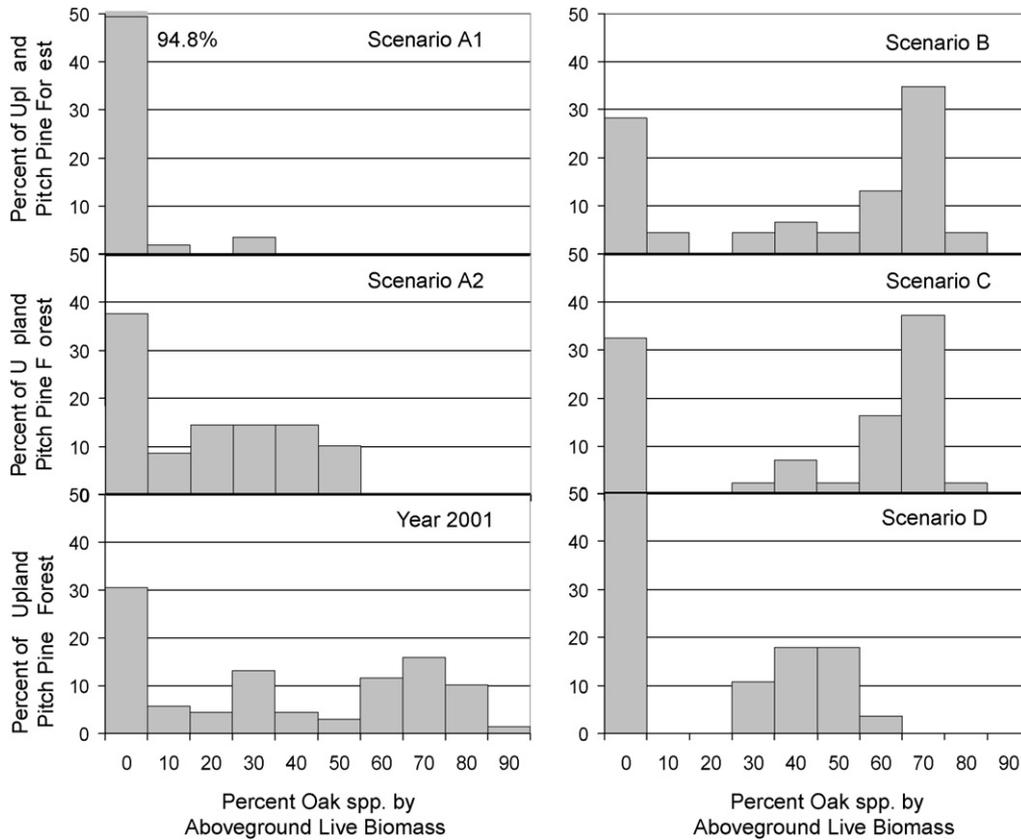


Fig. 6. Percent Atlantic Coastal Plain Northern Upland Pitch Pine Barrens (upland pitch pine forest) for six scenarios.

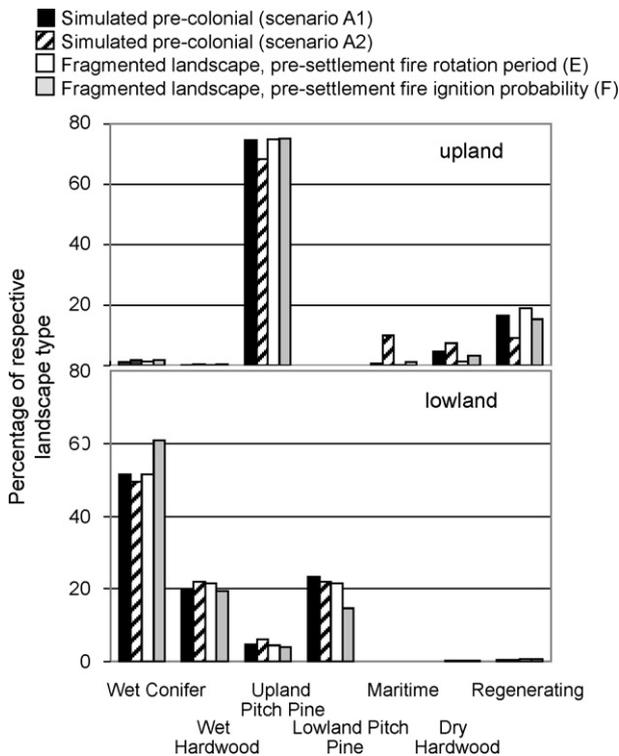


Fig. 7. Simulated pre-colonial forests within the New Jersey Pine Barrens (NJPB), fragmented NJPB forests with pre-colonial fire rotation period, fragmented NJPB forests with pre-colonial fire ignition probability and potential fire size. Upland forests are represented in the upper panel, lowland in the lower panel. Data represent composition at equilibrium (year 500).

doubling of fires across all of the NJPB (scenario D) would reduce the prevalence of oaks such that the oak component will be more similar to pre-colonial conditions (Fig. 6).

3.3. Estimates of the effect of fragmentation

Simulations of the effects of fragmentation on lowland forests show a negligible effect beyond what would be expected from a lengthening of the fire rotation period from 32 to 38 years (scenario F, Table 3) and a subsequent increase in Wet Conifer forests and reduction in Lowland Pitch Pine forests (Fig. 7). Within upland forests, all forest types fell within or near to the estimated range of variation. In general, shifts in landscape dominance were typically less than 5%, indicating that while fragmentation reduces fire burned area, it would have little effect on the ability of species to colonize available habitat.

4. Discussion

Our simulations indicate that the New Jersey Pine Barrens may have, to a degree, departed from the pre-colonial composition. Departure is most prevalent in unmanaged lowland systems and, to a lesser degree, in unmanaged upland systems. The degree of departure depends, in most cases, on the pre-colonial reference condition used to compare with current conditions, which suggests that further investigation to clarify the pre-colonial condition of the New Jersey Pine Barrens is

warranted. The uncertainty in our estimates of pre-colonial conditions is further magnified by our use of current climate in the pre-colonial scenarios. The use of departure indices (e.g., fire regime condition class; www.frcc.gov) in management decisions should take into account uncertainties in the reference condition used to calculate departure.

The amount of data available to parameterize fire regimes was fairly limited in this study (~10 years of fire records) and this could reduce the accuracy of our model results. In order to best represent the fire regime of a study area within a model such as LANDIS-II, data used to parameterize fire regimes should encompass the range of variability in fire regimes due to climatic variability, if sufficient data are available. Likewise, our ability to properly assess the veracity of the results of our pre-colonial scenarios is limited due to a lack of objective data sources for the study area. In other areas of New England and the Mid-Atlantic, colonial era land surveys (e.g., Cogbill et al., 2002; Russell, 1981) and palynological studies (Watts, 1979; Russell and Standford, 2000; Russell and Davis, 2001; Parshall et al., 2003) have been used to reconstruct pre-colonial era vegetation regimes. However, the colonial era land survey record for the area of the NJPB has not been carefully investigated and it is unclear whether they will provide sufficient information to resolve the vegetation patterns of the pre-colonial era. Palynological studies that include the NJPB are limited in number and either focus on the time period of the last glaciation (e.g., >10,000 years before present; Russell and Standford, 2000) or are broad-scale, rather than local, applications (e.g., Watts, 1979; Russell and Davis, 2001). Thus, due to a lack of data with which to evaluate our model results, our pre-colonial modeling scenarios can only provide approximations of potential variation of pre-colonial vegetation.

If only approximately accurate, the degree of departure seen in this study would be consistent with historic trends from the northwestern Wisconsin Pine Barrens (Radeloff et al., 1998, 1999). Although largely contiguous, the Wisconsin Pine Barrens have experienced a similar decline in fire frequency and size since the pre-settlement era and a decrease in a fire dependent pine (*P. banksiana*) with an increase in oak dominance (Radeloff et al., 1998, 1999). However, our estimates of pre-colonial conditions represent only an approximation of past variation, given our limited knowledge of past climatic conditions and Native American burn frequencies. These trends contrast with the decline of oaks often found in more mesic eastern forests (Abrams, 2005).

Our estimates of species composition change under different management scenarios (specifically scenarios B and C) are conservative, with little potential change in the Ecological System Classification. However, our most likely scenarios (B and C) show a large increase in oak as a percentage of biomass within the Upland Pitch Pine forests. Simulation results also indicate that current day management practices, if continued for the next 50 years, will generally keep the managed portions of the NJPB within our estimated range of pre-colonial vegetation dominance. Unmanaged lands, especially wetlands, however, apparently require more management than was

simulated to push the NJPB back towards either pre-colonial reference condition. The general lack of sensitivity to management, specifically burning, suggests that restoring a system like the NJPB back to pre-colonial conditions or to a desired future condition will require more extreme management than is currently underway. Nevertheless, societal and policy conflicts may prevent fire managers from continuing to meet current objectives. Specifically, air quality impacts from increasing the amount of burning might limit the continued use of fire as a primary tool for managing the NJPB. Harvesting may be another management option, but the lack of active forestry in the study area over the last ~100 years suggests that there will be considerable operational difficulties in implementing harvest at a large-scale. The land management restrictions associated with the designation of the Pine Barrens as a National Reserve may reduce the ability of land managers to use fire and harvest more intensively than current levels.

The comparison of current vegetation with historic range and variability (HRV) of vegetation to help guide management decisions has been discussed widely in the literature (Swetnam et al., 1999; Landres et al., 1999). Methods for determining the HRV range from field-based measurements (Swetnam et al., 1999) to simulation modeling (Cissel et al., 1999; Nonaka and Spies, 2005; Pratt et al., 2006). Reliable methods for determining the degree of departure from the HRV have been explored in literature (Nonaka and Spies, 2005; Steele et al., 2006). However, because we lacked pre-colonial climate and ignition data, our two estimates of pre-colonial dominance do not represent a true range of variation, which would also include broad temporal variation caused by shifts in climate (e.g., drought) and/or variable ignition rates (due to either lightning and perhaps variable ignition rates due to Native Americans burning). A direct comparison of model results to HRV estimates will require model refinements to include climatic and ignition variability over time.

Fragmentation within the NJPB has reduced the forested area, increased edge density, and reduced forest patch size (Luque et al., 1994). Fragmentation caused by housing development has also likely shifted the local economy from extractive to a more suburban ('bedroom community') orientation, similar to trends in Wisconsin and elsewhere (Radeloff et al., 2001, 2005; Clendenning et al., 2005). Such changes are often accompanied by changes in forest management away from large treatments with concomitant changes in forest succession and composition (Ward et al., 2005). However, within the narrow suite of parameters that we examined, we did not find any consistent trends that we could attribute to changes in the spatial configuration of forested patches alone. An absence of such an effect does not preclude fragmentation from potentially modifying landscape response to climate change (Scheller and Mladenoff, in review; Higgins et al., 2003) or from crossing a threshold whereby succession and composition is significantly altered (Franklin and Forman, 1987). Given the continued development and fragmentation of forest outside of the Pine Barrens National Reserve, we would expect the probability of such effects to increase. In addition, continued development will likely discourage the more

intensive management that our simulations indicate are necessary to manage areas for pre-colonial conditions.

In conclusion, our simulations provide a tool for estimating pre-colonial range of forest variation, for estimating the effects of various forest management options, and for conducting controlled landscape experiments to determine the contribution of potential driving variables (e.g., fragmentation) on overall landscape change. Although simulations are always a limited tool – limited by available data for parameterization, ecological knowledge, and available validation data – they nevertheless provide valuable information that otherwise lies outside the purview of empirical data. In the NJPB, our simulations increase our understanding of the mechanisms responsible for pre-colonial forest community composition and provide a step towards more reliable ecological forecasting (Clark et al., 2001). Our results may also help guide any changes in the goals of fire management and LANDIS-II shows promise as a model for simulating management scenarios to help guide management decisions at the landscape level. Currently, fire management is driven by the need to reduce hazardous fuels, and generally not for managing community composition. Simulation modeling is an important tool that can help direct such activities.

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