Other regions have been experimenting with their own principles. I am aware of groups in Colorado, Oregon, and Montana working on collaborative principles. Finally, the U.S. Forest Service (2008) has released a new "Ecological Restoration and Resilience" directive that codifies restoration as a responsibility for Forest Service managers. Taskforce members from the Forest Service point to the New Mexico Restoration Principles as an important influence in the development of this national directive.

Defining a zone of agreement for forest restoration at a statewide scale has created opportunities to develop new scientific syntheses and policies and is helping agencies and their partners articulate restoration objectives across jurisdictional lines.

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Modeling Long-Term Effects of Altered Fire Regimes following Southern Pine Beetle Outbreaks (North Carolina)

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Periodic fires are an important factor shaping the species-rich southern Appalachian forest landscape, and fire regimes in this region have changed significantly over time. The role of fire in maintaining Appalachian forests has been debated and increasingly studied (Delcourt and Delcourt 1998). Experimental studies have shown that pine regeneration increases following prescribed fire (e.g., Vose et al. 1997), and researchers have suggested that reintroducing fire may help to maintain the decreasing natural pine forests (Lafon et al. 2007).

In addition to fire, southern pine beetle (*Dendroctonus frontalis*, SPB) is a major biological disturbance agent affecting pines in this region. For example, from 1999 to 2003, over 400,000 ha (timber value > $1.5 billion) of pine forests were damaged in the southern Appalachians and adjacent Cumberland Plateau. While prescribed fire is increasingly utilized as a means to restore decadent pine forests, the long-term effects of fire following SPB outbreaks are still unclear.

To investigate the synergistic effects of fire and SPB, we used LANDIS-II, a spatially explicit landscape simulation model of forest succession and disturbance. Specifically, we simulated changes in the abundance of pines under SPB disturbance and two fire scenarios: 1) fire suppression, and 2) historic fire regimes prior to fire suppression. Our goal is to understand the long-term effects of fire regimes in pine forest recovery and to provide insights into the effectiveness of post-SPB restoration strategies for the region.

We used the Grandfather Ranger District (GRD) of the Pisgah National Forest of western North Carolina, USA, as our study area. This mountainous region (ca. 777 km^2) consists of diverse environmental conditions and high plant diversity and is characterized by extensive hardwood forests. However, pine-oak and pine forests cover about 14.2% of federally managed lands, predominately on dry slopes and ridges. The natural pine species in this region include shortleaf pine (*Pinus echinata*), pitch pine (*P. rigida*), Table Mountain pine (*P. pungens*), Virginia pine (*P. virginiana*), and white pine (*P. strobus*).

This GRD landscape is divided into 11 ecozones (large areas of similar temperature, moisture, and fertility conditions), including the three pine-oak forest dominated ecozones that we focused on in this study (Table 1): I, shortleaf pine-oak forest, which is found primarily at low elevations on broad, exposed landforms in areas with low growing-season rainfall; II, xeric pine-oak and oak forests, on all upper slopes in areas with low dormant-season rainfall and at lower elevations on broad, gentle slopes and ridges; and III, white pine–oak forest, largely at lower

Table 1. Characteristics of three pine-oak ecozones (following Simon et al. 2005) and parameters for two fire regimes (historical fire scenario vs. current fire suppression scenario) in the Grandfather Ranger District, Pisgah National Forest, North Carolina, USA. Fire regime values are estimated means at initiation of LANDIS-II simulations; FRI is fire return interval.

	Ecozone I	Ecozone II	Ecozone III
Dominant Vegetation	Shortleaf pine-oak forest	Xeric pine-oak forest and oak forest	White pine-oak forest
Indicator species	shortleaf pine (*Pinus echinata*) sourwood (*Oxydendrum arboretum*) scarlet oak (*Quercus coccinea*) southern red oak (*Q. falcata*) post oak (*Q. stellata*)	Table Mountain pine (*P. pungens*) scarlet oak pitch pine (*P. rigida*) chestnut oak (*Q. prinus*) mountain laurel (*Kalmia latifolia*)	white pine (*P. strobus*) scarlet oak sourwood chestnut oak blackgum (*Nyssa sylvatica*)
Historic FRI (yr)	5–7	5–7	15–20
Historic Size (ha)	50	50	30
Current FRI (yr)	50	70	90
Current Size (ha)	5	5	3

elevations in areas with higher growing-season rainfall and also exposed upper slopes (Simon et al. 2005).

LANDIS-II simulates large-scale (> 10^5 ha) landscape dynamics and interactions among ecological processes, including succession, seed dispersal, abiotic disturbances (fire and wind), biological disturbance agents (insect outbreaks), and forest management (harvesting) in a forested landscape over long-term (50–500 years) time scales. The landscape in the model is represented as a two-dimensional grid of equal-sized cells (30 × 30 m in our study), which we divided into a simplified mosaic of four existing major forest types (pine, pine-hardwood, hardwood-pine, and hardwood forest) as a starting point for the simulations.

Succession in the model is based on life history attributes of each species, the composition of different species within a cell, and the composition of species in surrounding cells. We parameterized a pool of the 36 most dominant trees and 3 common shrub species within GRD for this simulation using the double exponential algorithm (Scheller et al. 2005) to model seed dispersal. A key parameter for species in LANDIS is an establishment coefficient, which controls the likelihood that a species will establish in a particular cell. We used a finer scale ecosystem process model (LINKAGES) to calculate the establishment coefficients based on the growth and competitive ability of species during first 10-year simulations. In turn, LINKAGES was parameterized using species-specific life history and environmental factors such as temperature, precipitation, growing season degree-days, soil organic matter, nitrogen, and moisture (Xi et al. 2008).

The Biological Disturbance Agent module in LANDIS-II was parameterized to represent the temporal and spatial pattern of SPB outbreaks in this area (Waldron et al. 2007). As a base scenario, we ran simulations with SPB as the only disturbance. This baseline was compared to two fire management and SPB outbreak scenarios: 1) historic fire regime with a mean fire-return interval of 5–20 years; and 2) current fire suppression regime with a mean fire-return interval of 50–90 years (Table 1). Fire regimes, including fire event sizes, ignition probabilities, and fire spread ages for different ecozones, were parameterized based on the published literature and communications with fire experts. Each simulation was run for 500 years.

Our results (Figure 1) indicate that SPB outbreaks alone (i.e., without fire) lead to the disappearance of all pine species from the landscape. Fire suppression promotes the increase of white pine within the landscape, but leads to the reduction of all other pine species. In contrast, historic fire regime favors the natural restoration of shortleaf pine, Table Mountain pine, and pitch pine and reduces the frequency of white pines in the landscape. Our findings are consistent with the hypothesis that SPB and fire disturbance have historically driven succession of pitch pine and Table Mountain pine forests in a beetle-fire-growth cycle, and wildfires are an integral part of the long disturbance regime that forms and maintains pine woodlands in the southern Appalachians (Williams 1998). They also help explain recent (ca. 50 years) increases in the abundance of white pines, which likely benefit from modern fire suppression policies.

Our studies help forest managers and landowners better understand the effects of multiple disturbances on the composition and structure of forests and the potential problems caused by long-term fire suppression policies. Although SPB damage is largely a natural, uncontrollable phenomenon, we have shown that historical fire and fire suppression lead to very different forest compositions. In particular, our projections suggest that frequent fires may assist regeneration and restoration of pine forests damaged by SPB outbreaks, especially species such as shortleaf

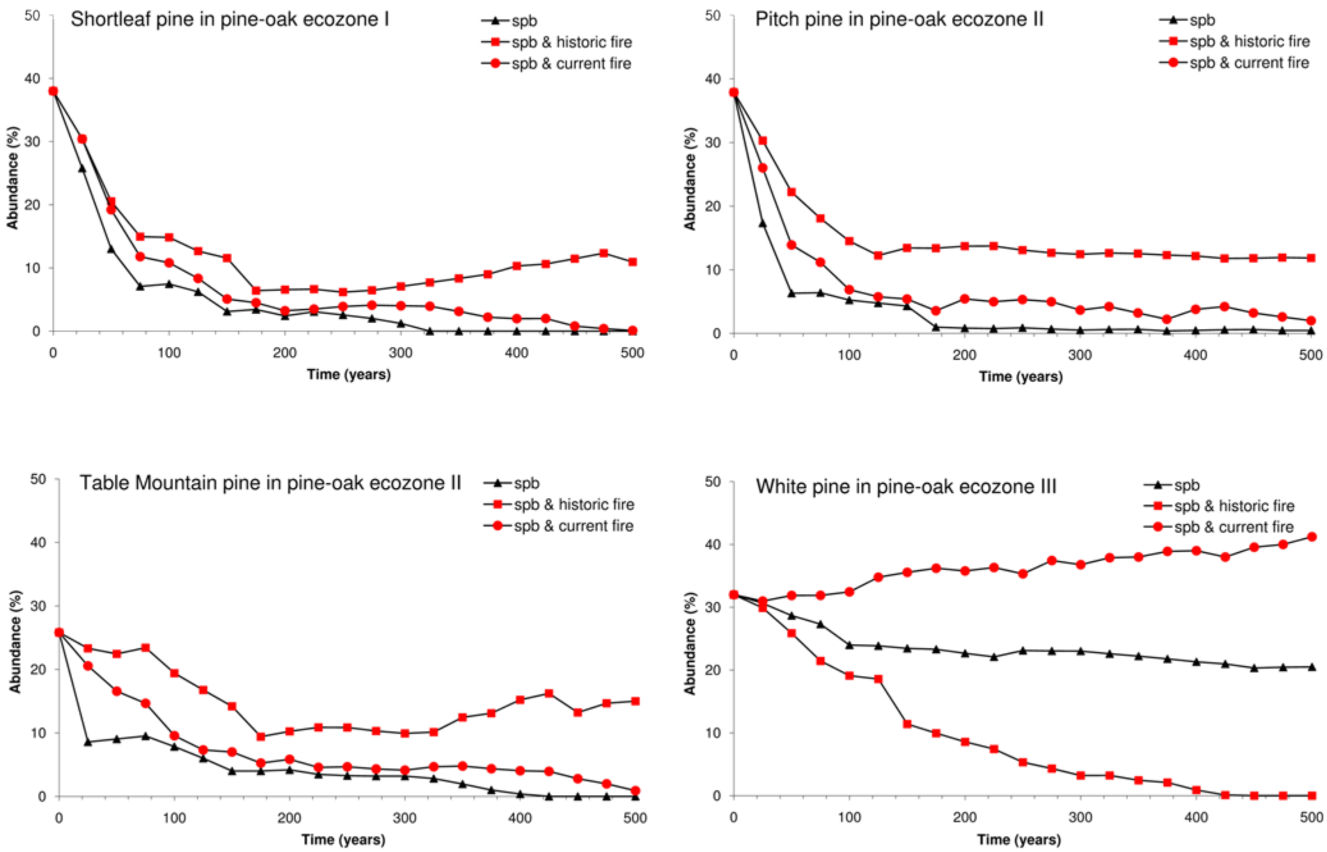

Figure 1. Changes in species abundance (percentage of landscape covered) for four pine species in three pine-oak ecozones over 500 years under two fire regimes in the Grandfather Ranger District, Pisgah National Forest, North Carolina, USA, in a LANDIS-II computer simulation.

pine, Table Mountain pine, and pitch pine, thought to be underrepresented in the present day southern Appalachian landscape. Moreover, fire-based restoration efforts should focus on the shortleaf pine-oak forest, and xeric pine-oak forest, and oak forest ecozones.

Further information about our restoration project is available at http://landscape-restoration.tamu.edu.

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