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A Spatially Explicit Simulation of Forest Dynamics in a Landscape Characterized by Complex Terrain and High Ecological Heterogeneity

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Abstract: Because of the large spatial scale and long-term dynamics involved, it is extremely difficult to conduct real-world experiments to assess how forest landscapes will respond to future changes in various natural disturbances, such as fire, windthrow, insect outbreak, and other anthropogenic disturbances. Forest landscape modeling can be a useful tool to understand such phenomena. However, there are limited studies on how forest landscape models behave with different levels of spatial heterogeneity. In this study, we use a neutral landscape modeling approach to assess how a forest landscape model, LANDIS-II, responds to varying degree of spatial heterogeneity in ecoregions, and to identify key model parameters. Our results showed that landscape response was particularly sensitive to propagule availability, disturbance, and light competition. We discuss that parameters associated with species establishment should be carefully determined, and that natural disturbance (especially fire) should be modeled in association with fuel dynamics and changing management to better simulate the dynamics.

Keywords: *forest landscape modeling, heterogeneity, neutral landscape, LANDIS*

1. Introduction

Forest landscape models have been widely used to understand landscape processes occurring at large spatial and temporal scale (He et al., 2011; Mladenoff, 2004). Spatially explicit and dynamic forest landscape models is a useful approach for understanding the effects of succession, natural disturbances such as fire, insect outbreak, windthrow, and anthropogenic disturbances such as harvesting and fuel treatments on forest landscape and ecosystems (Mladenoff, 2004). Because of the large spatial scale and long-term dynamics associated with the phenomenon, the impacts of such processes is nearly impossible to test as real world experiments (Bugmann et al., 1996; He et al., 2011).

However, despite its application across a wide geographical range, there is limited study on how spatial heterogeneity of landscape structure may influence the forest landscape model outcomes. Numerous studies have shown the importance of landscape structure to human- and ecological processes, such as habitat suitability for wildlife, natural disturbances such as fire and insect outbreak, succession of plant communities, and land-use pattern and development, to name a few (Chen et al., 1992; Devictor et al., 2008; Di Giulio et al., 2009; McGarigal and McComb, 1995; Wilcove, 1985). Since many forest landscape models are based on how ecological principles play out and spatially interact in different environmental settings, the complexity of the spatial template on which the model operates can have profound impacts on model behavior.

Therefore, using forest landscape models can be challenging especially when target areas are characterized with complex terrain and heterogeneous landscape. In addition, evaluating such effects can help us prioritize data collection and refinement for parameterizing the model.

In such case, application of neutral landscape models can be a useful approach, which can be used to represent realistic complex spatial patterns in the landscape and to evaluate the effects of landscape structure and spatial heterogeneity on ecological processes (Gardner et al., 1987; Morales and Ellner, 2002). Neutral landscape model are based on percolation theory, and can be used to provide a general model of spatial complexity controlled by the user (Gardner et al., 1987; With, 1997). Applying the simulated spatial complexity to forest landscape models may provide us with insights on how spatial heterogeneity contributes to forest landscape model outputs, and how to improve the model.

The main objective of this study is to evaluate the influences of landscape heterogeneity to forest landscape models and to identify key parameters that are important in landscapes with high complexity. We use a neutral landscape modeling approach and apply virtual landscapes with varying levels of landscape heterogeneity to a spatially explicit forest landscape model, LANDIS-II, and analyze the outcomes to gain insights to this problem.

2. Methods

2.1 LANDIS-II Description

LANDIS-II is a spatially explicit forest landscape model that can simulate disturbance, dispersal of propagules, and succession (He et al., 1999; Mladenoff, 2004; Scheller and Mladenoff, 2004; Scheller et al., 2007). In LANDIS, forest type and composition dynamics are simulated as species spatially interact with each other over time through life history characteristics, such as longevity, shade tolerance (or competition for light resource), likelihood of establishment, maturity, and tolerance to various disturbance events (Figure 1). LANDIS operates on a raster-based landscape, with each pixel representing homogeneous light condition, and ecoregions are used to specify disturbance regimes (such as fire, wind, etc) and establishment conditions for tree regeneration. Tree species and their age cohorts are defined for each pixel, and there can be multiple species and age cohorts contained in a single pixel. LANDIS is a widely used model which has been used to address effects of fire (He et al., 2004), forest management (e.g., harvesting and reforestation) (Gustafson et al., 2000), climate change (Scheller and Mladenoff, 2005; Scheller and Mladenoff, 2008), and biological disturbances (Sturtevant et al., 2004).

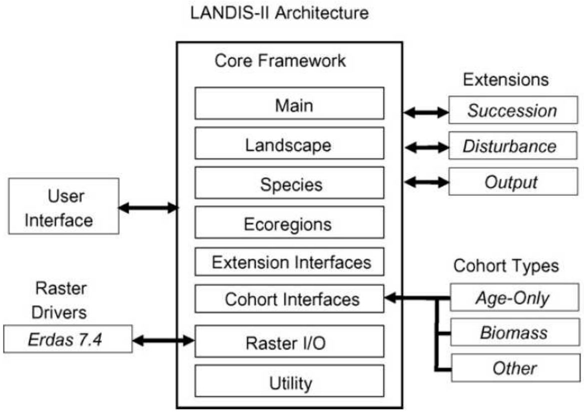

Figure 1. Architecture of LANDIS-II, showing the core modules and additional extension modules (Scheller et al., 2007)

2.2 Setting up LANDIS Parameters

2.2.1 Creating Ecoregions with Varying Spatial Heterogeneity

The specific ecoregions used in this study were based on simplified realization of a forest stand survey result from Jumbong mountain in South Korea. Jumbong mountain is at the southern-most edge of Seorak mountain national park, and is designated as a UNESCO biosphere reserve, with its approximate location at 38°02´ latitude and 128°26´ longitude (Ko, 1999).

Three different ecoregions were specified: 1) north-east facing aspect, 2) south-west facing aspect, and 3) mesic valley. Simmap (Saura and Martínez-Millán, 2000) was used to create spatial patterns of ecoregions with varying degree of spatial heterogeneity (or aggregation). Simmap uses modified random clusters method to create realistic landscape patterns, and the user can control the degree of aggregation by specifying initial percolation probability (p), neighborhood method, and minimum patch size (*m*).

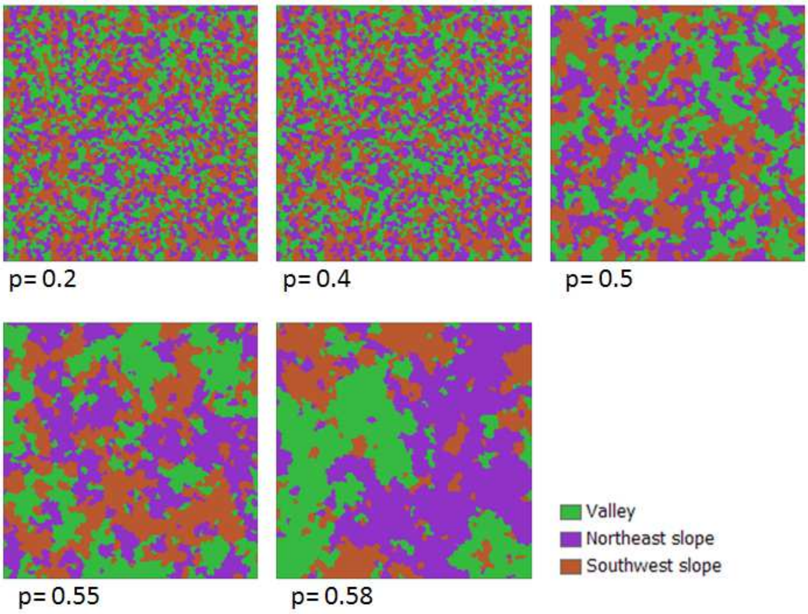

Figure 2. Ecoregions with varying degrees of heterogeneity used in the simulation

We used 5 different initial percolation parameter values of p to simulate the ecoregion maps: 0.2, 0.4, 0.5, 0.55, 0.58. Landscape size (*L*) was fixed to 200x200 pixels, with the pixel size of 30 meters, resulting in total landscape size of 3600 ha. Minimum patch size M was specified as 10 pixels (approximately 9 ha), and 4-neighborhood rule was used (Figure 2).

2.2.2 Initial Species Distribution

We used a simple configuration of initial forest canopy tree species distribution of conifer, deciduous, and mixed stands, based on the survey of Jumbong mountain (Ko, 1999). We selected Mongolian oak (*Quercus mongolica*), Korean maple (*Acer pseudo-sieboldianum*), and Korean pine (*Pinus koraiensis*) as representative species. Each of the ecoregions created from Simmap was randomly designated as old or young stand, and the age cohort for each stands were determined based on the median age of trees estimated by tree ring counts (Ko, 1999). The resulting initial species distribution for each of the ecoregion maps are visualized in Figure 3.

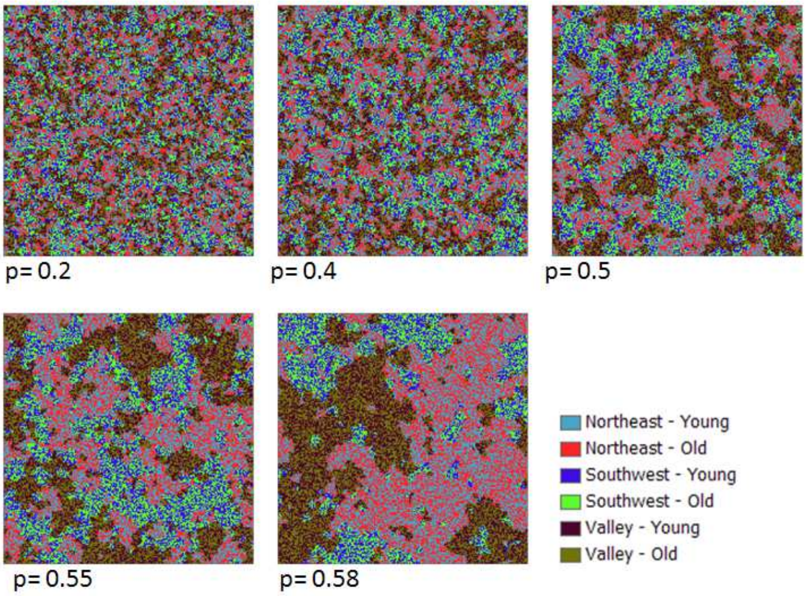

Figure 3. Initial distribution of forest composition with various degrees of heterogeneity used for simulation. Young and old stands were randomly designated within the ecoregions specified in Figure 2.

2.2.3 Species Life History Attribute

Parameters for species life history characteristics were determined based on previous studies. Mongolian oak and Korean pine were derived from a previous study based on northeast China (Bu et al., 2008), and parameters for Korean maple was based on literature of other maple species and expert opinion.

2.3 LANDIS-II Simulation

We used the base fire and wind disturbance, age-only succession, but did not use management extension of LANDIS-II. Base fire and wind disturbance parameters were based on previous study in north-east China (Bu et al., 2008) so that the ecoregions had a disturbance gradient. We ran the simulation for 30 decadal timesteps for succession and 60 5-year timesteps for disturbance with each of the ecoregion heterogeneity settings. Output maps for the disturbance events, individual species distribution and reclassified forest type distribution, and age-class distribution (maximum age) were recorded for every decadal timestep, and details of the disturbance events were logged for each 5-year timestep, which were later used for analysis.

2.4 Analysis

The influence of spatial heterogeneity and complexity was evaluated by comparing species composition, age structure, and spatial pattern of forest types, species distribution and age cohorts. For each of the heterogeneity level of the ecoregions, the temporal trajectory of species composition was graphed and compared with each other. In addition, the area of old growth stands (age > 200 years) were separated for each heterogeneity levels and compared. Disturbance regime was evaluated by observing fire occurrence and wind occurrence trend and total disturbed area.

The spatial patterns of each tree species and old growth stands were analyzed by calculating several landscape metrics through FRAGSTATS (McGarigal and Marks, 1995). FRAGSTATS can calculate a variety of landscape metrics for categorical spatial data. The outputs are used to quantify several aspects of spatial characteristics of the overall landscape or specific categories, which is useful to compare the spatial patterns. To quantify the resulting landscape structure, we calculated we calculated aggregation index (He et al., 2000) for overall landscape heterogeneity (or level of aggregation across the landscape).

3. Results and Discussion

3.1 Species Composition

Species composition changed dramatically over time, however the effect of heterogeneity was moderate at most (Figure 4). All species showed dramatic change in dominance over simulation time, regardless of heterogeneity level of ecoregions. The abrupt change in composition around simulation time of approximately 70 years is notable. This is due to a massive die-out of Korean maple around that time, triggered by its shorter longevity (150 years) compared to others (350 and 400 years for Korean pine and Mongolian oak, respectively). This event triggered widespread new establishment of Mongolian oak and Korean pine. However, Korean pine quickly lost its dominance thereafter, most likely due to the low shade tolerance and very high maturity age which effectively limited the number of effective propagules. While Mongolian oak lost its dominance relatively slowly over time, Korean maple, due to its high shade tolerance, gradually regained its dominance towards the end of the simulation.

The effect of ecoregion heterogeneity was most distinguished for Korean pine, and is related to interactions between its long dispersal distance for propagule, relatively low disturbance area, and low shade tolerance. With low fire regime, only limited burned areas occur in small patches, and given its low shade tolerance, it may be difficult for the thinly spread Korean pine propagules to find a disturbed patch to successfully establish. Landscape structure of each species showed small differences among ecoregion heterogeneity levels, with only slightly higher level of aggregation with less heterogeneity in ecoregions (Figure 5).

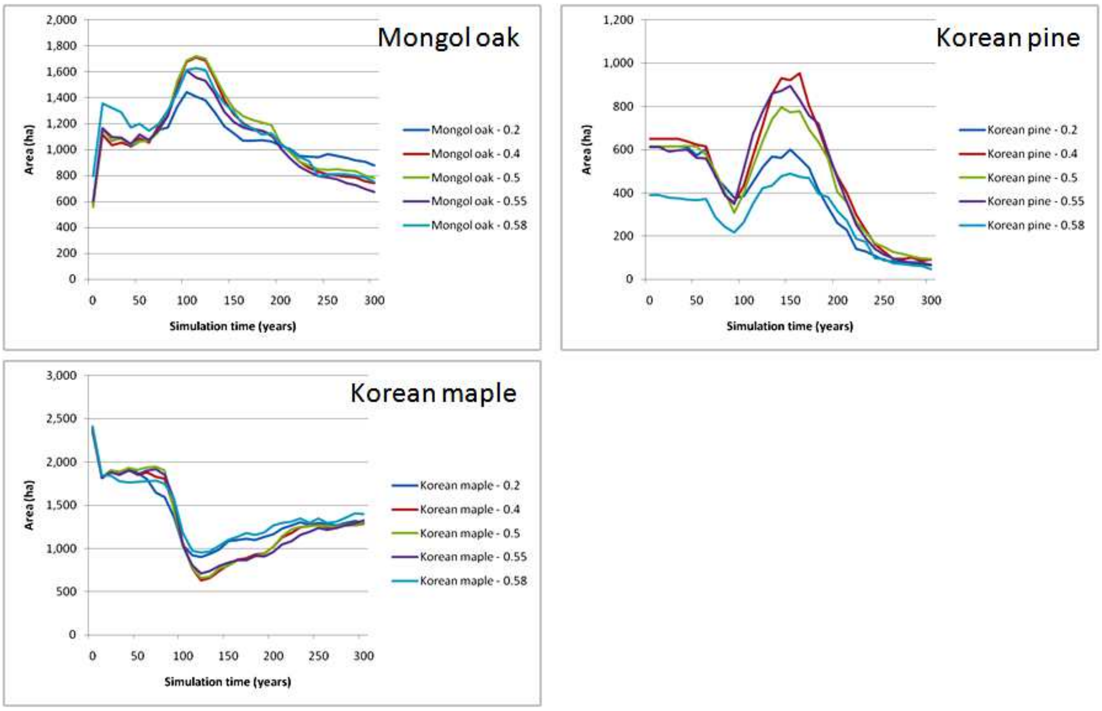

Figure 4. Simulated change in species composition over a simulation time of 300 years. Each graph represents three different species and heterogeneity levels specified by p values (degree of heterogeneity, lower p value means fragmented ecoregion and higher value means aggregated ecoregion).

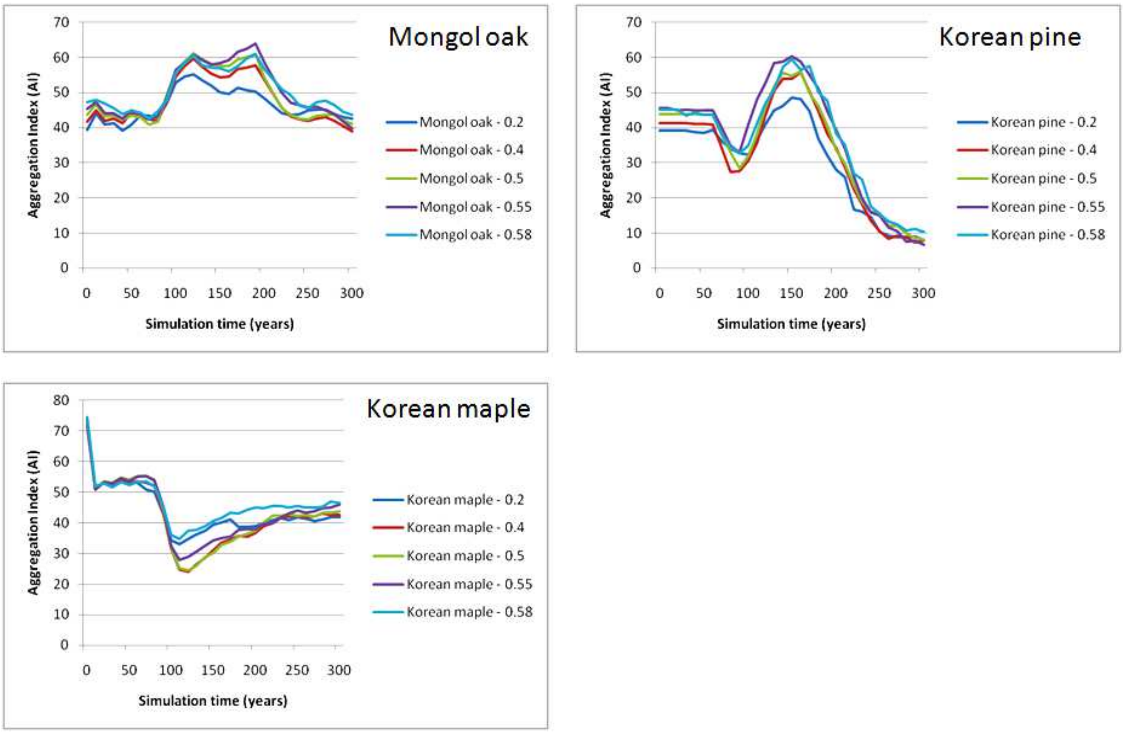

Figure 5. Change of Aggregation Index (AI) of each of the tree species stands. Higher AI indicates greater level of aggregation.

3.2 Old Growth Stands

Old growth stands (> 200 years) increased dramatically around 70 years, which is a result from most younger stands reaching 200 years at the same time (Figure 6). However, the amount of change differed among ecoregion heterogeneity. Old-growth stands with higher heterogeneous ecoregions showed almost no increase during this period, while those with less heterogeneous ecoregions showed a sharp increase. This is partly related to the limited level of Korean pine regeneration described in species composition change (Figure 4). However, the total area of old-growth stands quickly decreased over time, which is consistent with the overall decrease in species composition of both Mongolian oak and Korean pine which are long-live species and require disturbance for regeneration, while short-lived Korean maple can successfully establish under canopy due to high shade tolerance, but cannot reach age old enough to form old-growth stands. Aggregation index of the old growth stands did not show meaningful difference among ecoregion heterogeneity levels (Figure 6).

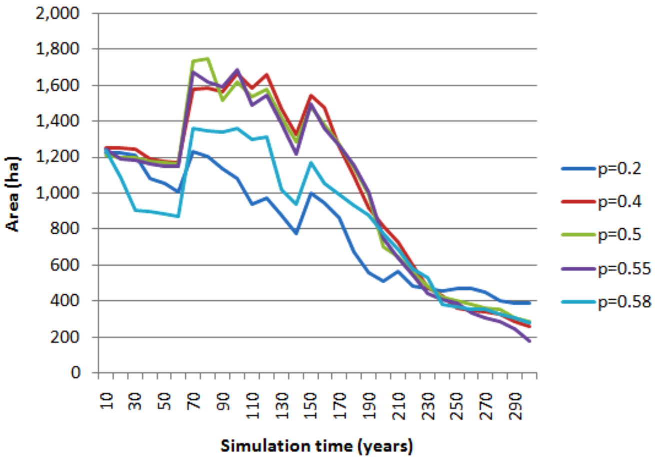

Figure 6. Area of old-growth stands over simulation time. p is the degree of heterogeneity of the ecoregion (lower value indicates greater heterogeneity and higher indicates less).

3.3 Disturbance regime

Fire regime did not show any difference among heterogeneity levels (Figure 7). Fire was randomly simulated based on fire probability and fire size derived from random probability distribution.

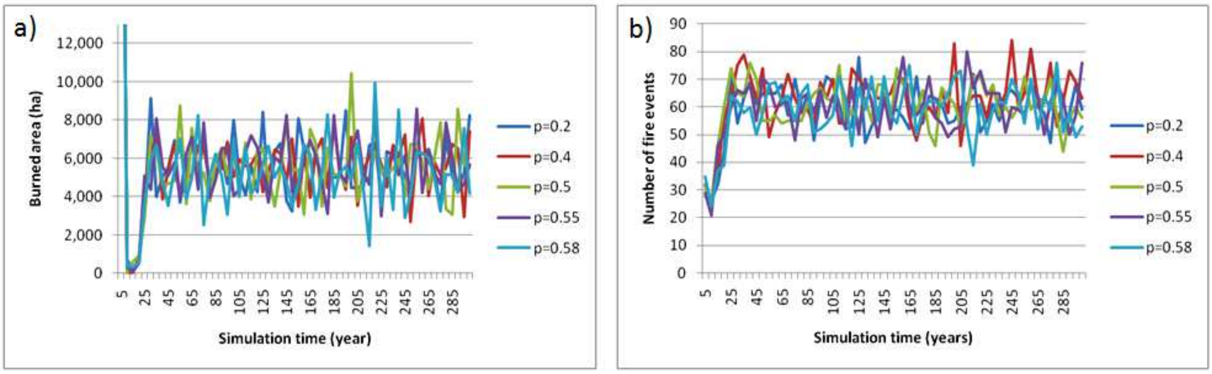

Figure 7. Burned area (a) and fire events (b) throughout simulation time.

Overall, the results suggest there are meaningful differences in forest composition change generated by ecoregion heterogeneity. It is apparent that spatial interaction of tree species and ecoregion area is playing a role in the landscape dynamics. However, the differences among ecoregion heterogeneity were not so clear for the area of old-growth stand or for the landscape structure (as quantified by aggregation index). Nevertheless, the results suggest that parameters associated with establishment (especially species establishment coefficient) are very important, and need to be improved for better representation of the dynamics.

In addition, the consistency in disturbance regime is something that has to be improved: especially, fire should be modeled in conjunction with biomass dynamics, since fuel condition are critical factors in determining fire patterns and severity, which in turn will influence how species response to fire events (He et al., 2004). Management is another important factor that should be included, especially considering that fire management policies can rapidly change with acute intensity (e.g., from complete fire suppression to active fuel reduction policies) (Stephens and Ruth, 2005).

Finally, given that LANDIS-II is a stochastic model, the presented differences (or the lack of) may be simply resulting by chance. Numerous simulations for each of the heterogeneity scenario are necessary to better differentiate the influence from ecoregion heterogeneity from that by mere chance.

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