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EDITORIAL

Modeling forest landscapes in a changing climate: theory and application

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Introduction

Natural phenomena occur in hierarchies across a wide spectrum of spatiotemporal scales. An equally wide range of models has been developed at each hierarchical level to model these phenomena (Wu et al. 2006). At a given level of hierarchy, a modeling system is composed of interacting components (i.e., lower-level entities) and is itself a component of a larger system (i.e., higher level controls) that influences behavior (Delcourt and Delcourt 1988; Wu and Loucks 1995; Wu 1999; Wu and David 2002; Lischke et al. 2007). Forest landscape models (FLMs) simulate forest landscape processes (FLPs) at landscape scales and stand dynamics as a function of lower-level entities operating at site-scales, while incorporating regional environments (e.g., climate) as higher level controls (Fig. 1). FLPs include seed dispersal and natural and anthropogenic disturbances such as wildfire, windstorm, insect outbreak, disease spread, timber management activities (He et al. 2011).

The fundamental difference between FLMs and other terrestrial biosphere models (TBMs) (e.g., stand dynamic, biogeographical, biogeochemical, land surface, and DGVM models) (Fisher et al. 2014) is that FLMs simulate FLPs as spatially contiguous and interacting processes at a fine resolution (He 2008). For example, in FLMs fire may spread over a group of spatially contiguous cells (pixels) as a function of vegetation, terrain, fuel, and wind on these cells, but because of the need to simulate FLPs and site-scale forest dynamics, FLMs typically operate at relatively fine spatial resolutions (e.g. 30–300 m cell size) and moderate temporal resolution (e.g., yearly). TBMs on the other hand use coarser spatial resolutions (e.g., 10,000–50,000 m) and relatively fine temporal resolution (e.g. daily or monthly). In TBMs, cell-level dynamics are simulated based on either interactions between downscaled physiological drivers and plant functional types (Neilson et al. 2005) or derived from the observed distributions of environmental variables (Pearson and Dawson 2003). These cell-level results are then aggregated to the region of simulation such

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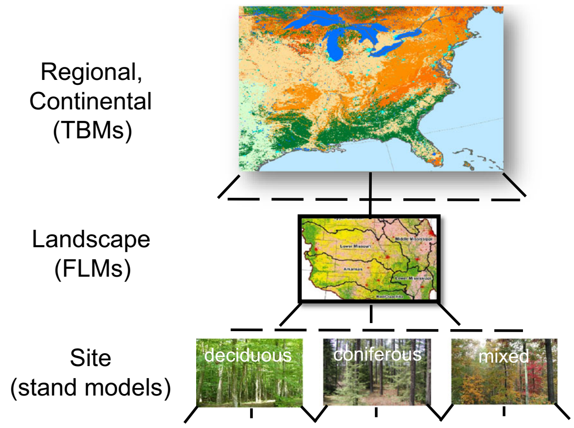

Fig. 1 Upper image is a forest cover of eastern U.S., middle image is a forested landscape in Missouri, and lower images are various forest types within the Eastern U.S. Usually, regional scale predictions (e.g., dynamics of total forest carbon of Eastern U.S.) directly use relationships between processes at stand/site scales (pixels) and climatic drivers at regional scales, completely bypassing landscape processes. The fundamental question is: Are landscape processes necessary in regional scale predictions?

that fine-scale processes are ignored or highly simplified (Purves and Pacala 2008; Elith and Leathwick 2009; Iverson et al. 2011; McMahon et al. 2011).

Increasing numbers of studies have shown that fine-scale processes may play a greater role than climate change in affecting forest composition and FLPs may accelerate shifts in species composition by providing regeneration opportunities and altering the competitive balance among tree species (Gustafson et al. 2010; Thompson et al. 2011; Li et al. 2013; Luo et al. 2014; Wang et al. 2015). In addition, studies have found that seed dispersal that links site-scale population (seed abundance and distribution), species biological traits (e.g., dispersal distance), and environmental heterogeneity is fundamental to studying tree species migration and range shifts (Lischke 2005; Thuiller et al. 2008; Doxford and Freckleton 2012; Meier et al., 2012; Corlett and Westcott 2013). FLMs are ideally designed to tackle the key processes discussed above.

Significant theoretical and technological advances have been made in FLMs over the past decade (Scheller and Mladenoff 2007; He 2008; Gustafson 2013). From the theoretical perspective, incorporating quantitative information of biomass, density, and individual trees into landscape models has improved the realism of simulated landscape dynamics, and the inclusion of altered disturbance regimes and nutrient cycling under climate change has addressed key prediction uncertainties. From the technological perspective, computer memory is no longer a severe limitation because of advanced data compressing algorithms and 64-bit operating systems. Furthermore, landscape-scale data sets for model initialization and evaluation are becoming increasingly available through systematic forest inventory and remote sensing. Thus, many FLMs have achieved a new quality of regional-scale predictions by incorporating additional site- and landscape-scale processes. Such predictions allow for comparisons with those by TBMs to reveal the effects of dispersal, disturbance and management, further reducing prediction uncertainties under changing climates.

In light of these advances, we organized the symposium, "Modeling Forest Landscapes in a Changing Climate—Theory and Application", at the Ninth International Association of Landscape Ecology World Congress held in Portland, Oregon, USA. The purpose of the workshop was to bring together scientists from around the world to share advances in this field. This special issue reflects the collective efforts of participants of the symposium. We have organized the papers of the special issue into four sections, reflecting the different foci in forest landscape modelling: (1) FLM development and comparison (2) Simulating regional-scale responses of tree and wildlife species to climate change with FLMs (3) Studying the effect of landscape disturbance and management with FLMs, and (4) FLMs and ecosystem services.

Model comparison and development

FLMs have emerged and evolved over the past 20 years. Shifley et al. (2017) provided a comprehensive review that highlighted milestones in the development of forest dynamics models. They pointed out that a great window of opportunity has opened for the development and application of FLMs because past limitations in computing capacity are easing and because data suitable for model calibration or evaluation are becoming more available. Of all the classes of models that simulate FLPs, FLMs are perhaps the most ready to transition to a central role supporting forest management, planning, and policy decisions.

Species distribution models (SDM) use empirically derived statistical relationships between the current distribution of species and key niche attributes such as climate and soil to predict future species distributions. Alternatively, process-based models predict future species distributions by simulating the physical and biological processes that determine where species will be abundant. Iverson et al. (2016) compared predictions made for 30 tree species in four regions under two climate change scenarios using an SDM (TreeAtlas) and two process models (LINKAGES and LANDIS-PRO) to increase the robustness of assessments of likely species response to climate change. Comparisons indicated a high agreement for many species, especially those near the southern edge of their range. Their analysis also uncovered a very simple diagnostic metric that can predict a species' potential to gain, lose or maintain abundance within a region under climate change.

Xiao et al. (2016) compared two versions of the LANDIS FLM family that differ in the main state variables used to represent vegetation: LANDIS PRO simulates density and size of cohorts, whereas LANDIS-II (with biomass extensions) simulates the accumulation and loss of biomass of species cohorts. For early successional species, the two models yielded similar distributions of species abundance and size, but for mid- to late-successional species, the results differed significantly. This highlights the importance of carefully scrutinizing how fine-scale processes are formulated and upscaled to a larger scale in forest landscape modeling.

Several succession modules of the LANDIS FLM family require input variables describing an environment-dependent species growth potential. To understand this potential, the physiological model LINKAGES was adapted and run in ecologically differing areas of the Central Hardwood Region of the USA under current and projected future climate (Dijak et al. 2016). Forest composition and biomass simulated by LINKAGES were plausible with respect to spatial distribution and temporal characteristics of temperature, drought and soil quality. This provides a way to derive LANDIS inputs from LINKAGES results.

Regional-scale responses of tree and wildlife species to climate change

In this section, researchers used FLMs with different designs for simulating site-level forest dynamics to examine occurrence and abundance (biomass) of tree species at regional scales.

Duveneck et al. (2016) used LANDIS II to examine how forest succession will continue to influence future forest conditions under current climate and that projected by four separate global circulation models forced by a high emission scenario (RCP 8.5) in New England. They found that the region will accumulate 34% more forest biomass and succeed to more shade tolerant species. They also found that climate change resulted in a 82% biomass increase. Continued recovery dynamics from historic land use change will have larger impacts than climate change on forest composition in New England. The large increases in biomass simulated under all climate scenarios suggest that climate regulation provided by the eastern forest carbon sink has potential to continue for at least a century.

Wang et al. (2016) used LANDIS PRO to simulate change in aboveground biomass and tree species composition throughout the northeastern United States under current climate and three climate change scenarios from 2000 to 2300, while accounting for harvest and windthrow disturbance. They found that species composition remained fairly stable for a century, but after 300 years, northern hardwood and conifer species decreased in abundance while some central hardwood and southern tree species increased. Forest biomass increased more under the two climate scenarios with greatest warming, but the patterns in biomass over time were similar among climate scenarios because biomass dynamics responded primarily to succession. These results provide evidence that climate change effects may take considerable time to unfold, and that disturbance and successional dynamics play a critical role in determining climate impacts.

Boulanger et al. (2016) projected the effects of climate change on the composition and productivity of four landscapes at the southern boreal forest transition zone in Canada. They used LANDIS-II informed by a forest patch model (PICUS). They found that productivity and total biomass would decrease especially for the dominant boreal species. This result differed from

Duveneck et al. (2016) and Wang et al. (2016), whose studies showed an overall increase in total biomass under climate change. Sensitivity analyses conducted using a mechanistic model based on physiology first principles suggest that increased respiration loads at very high temperatures more than offset biomass increases predicted under more moderately increased temperatures, which may partially explain these discrepancies. Biomass reduction in boreal regions may also be partially due a lack of temperate species adapted to warmer climates and stronger fire disturbance (Boulanger et al. 2016). They concluded conservation and forest management planning within the southern boreal transition zone should consider both disturbance-and climate-induced changes in forest communities.

LeBrun et al. (2016) linked Bayesian empirical models of bird habitat suitability with the LANDIS-PRO FLM to predict avian abundance under various climate and management scenarios. They were able to characterize bird habitats using density and size information simulated by the model. They found that management actions had a much greater impact on avian abundance than did climate, although greater climate effects may develop beyond the 100-year projection period of the study. Management strategies to increase carbon sequestration or resilience did not produce a strong collateral effect on birds, and climate effects on habitat were significant only for the northern bobwhite.

Landscape disturbance and management

Several studies revealed the importance of interacting disturbances and the necessity to include FLPs in prediction of climate change response.

Loehman et al. (2016) used the mechanistic ecosystem-fire process model FireBGCv2 to model interactions of wildland fire, mountain pine beetle, and white pine blister rust under current and future climates across three diverse study areas for 300 years. They found that while disturbances reduced overall basal area more than other disturbances. They also found that disturbances under future climate had greater effects on landscape basal area than those under the current climate scenarios. Their research highlighted the importance of understanding disturbance interactions because forest responses to wildfires, pathogens, and beetle attacks may offset or exacerbate climate influences under the interacting disturbances.

Loudermilk et al. (2016) used the LANDIS II FLM coupled to the Century carbon dynamics model to assess the effectiveness of fuel reduction treatments in wildfire-prone areas under climate change. They found that over longer periods fuel reductions were successful in terms of reduced fire severity and spread, and increased carbon storage. The latter resulted from increased tree growth after the treatments caused by decreased drought, and a change in species composition toward more drought and fire-tolerant species. This study demonstrates that forest resilience to climate change can be achieved or enhanced by appropriate management measures.

Cary et al. (2016) quantified the relationship between fuel treatment effort (planned burning) and the incidence of moderate-to-high intensity unplanned fire. To maximize generality, they used three landscape-scale fire models in two biomes to evaluate the relative importance of fuel treatment effort, ignition management and weather in reducing the area burned by moderate-to-high intensity wildfire. They found that fuel treatment effort explained less than 7% of the variation in total area burned by unplanned fire across models and biomes. They concluded that effort to control ignitions and housing development in fire-prone environments may be more effective than efforts aimed at broad-area fuel treatment, although constructed assets in a specific locale may be worth protecting with targeted fuel treatments.

Seidl and Rammer (2016) studied the effect of interacting wind and bark beetle disturbances on a forested landscape in the European Alps. They complemented the iLand FLM, which already contained a wind disturbance module, with a bark beetle disturbance module and successfully evaluated it against observations of wind-bark-beetle affected forests. A structural sensitivity analysis revealed that the effect of wind and bark beetles on the forests was much more sensitive to climate change when the two disturbances were interacting (as in reality) than when they were acting separately. This demonstrates that neglecting interactions, in this case, of disturbances, can lead to misleading results in climate change studies.

Forest landscape models and ecosystem services

Schuler et al. (2016) used the LandClim FLM and compared the ability of different tree species mixtures to provide ecosystem goods and services (EGS) at the landscape scale. They evaluated multiple EGS for two landscapes: a high-elevation alpine region (Dischma valley, Switzerland) and a lowland valley (Mt. Feldberg, Germany). They found that mixed-species forests were usually better in providing multiple EGS, although monocultures were often best for single EGS. The simulation results also demonstrated that changing environmental conditions along an elevational gradient had a strong impact on the structure of different species combinations and therefore on the provisioning of EGS. they concluded that tree species diversity alone is not a good predictor of multifunctionality of ecosystem services. Mixtures should be selected based on local environmental conditions, complementary functional traits, and the ability to provide the EGS of interest.

Li et al. (2016) developed a value-based framework to evaluate changes in a forest landscape following a disturbance through forest inventory and variables such as value-based forest product options, wood fiber attributes, and ecosystem services. They found wood density, fiber length, and pulp yield could be combined with total wood volume to derive new indices to characterize changes in landscape conditions. They found that their model can contribute to the assessment of landscape changes by indicating the values a forest can have when it is used for different conservation or utilization purposes. The model can also support improved decision-making with respect to the management of forest resources.

Conclusions

FLMs have been significantly improved in terms of increasing their simulation capacity at regional scales. Users of terrestrial biosphere model have started to compare FLM simulation results with those from species distribution models (Iverson et al. 2016) and ecosystem process models (Jin et al. 2017). Such model comparisons will help narrow prediction uncertainties. The application of FLMs of different designs to the New England region with similar species and disturbance regime resulted in agreements and discrepancies in predictions. The discrepancies suggest that users should carefully examine model behaviors and limitations before choosing a FLM in their study. Compelling studies have shown that interacting disturbances are critical in predicting vegetation response to climate change and FLMs currently offer the most sophisticated capabilities for incorporating a broad diversity of FLPs. The ultimate goal of FLMs is to assist forest planning and management. The application of FLMs to evaluate diverse ecosystem services under alternative management strategies is proving highly useful to forest managers to reduce critical uncertainties, especially in the face of an uncertain future.

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