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Model sensitivity to spatial resolution and explicit light representation for simulation of boreal forests in complex terrain

Ksenia Brazhnik*, H.H. Shugart

Department of Environmental Sciences, 291 McCormick Rd., University of Virginia, Charlottesville, VA, 22902, USA

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ABSTRACT

A model is a simplification of our understanding of reality, but how much simplification is too much? We assessed model sensitivity for a new spatially-explicit individual-based gap model (IBM) SIBBORK to determine how spatial resolution (*i.e.*, plot size) and explicit representation of light and space affect the simulated vegetation characteristics (*e.g.*, structure and composition). The 3-dimensional (3-D) representation of light is the most computationally-expensive part of the simulation, so it is worthwhile to evaluate whether the time, resource and effort of spatial explicity improve predictive capabilities. In the simulation, gap dynamics occur at the plot-level, wherein a certain level of spatial homogeneity is assumed. Therefore, for the simulation of each ecosystem it is imperative to select the appropriate scale at which gap dynamics are simulated, *i.e.* the plot size. We conducted these sensitivity analyses and qualitatively compared model output to the descriptions of forest structure and composition at two different sites in central and southern Siberia. We systematically varied the plot size (100–900 m^2) and found that a 100 m^2 plot is most appropriate for the simulation of the central Siberian boreal forest ecosystem. Moreover, we found that the forest structure and composition simulated under the light environment generated using a 3-dimensional light ray tracing subroutine more closely resembled local and regional forest characteristics at both sites, whereas the growth and stand processes computed based on the simplified (1-D) light conditions approximated only large-scale (continental) average forest structure and biomass for the Eurasian boreal forest.

1. Introduction

Model sensitivity in an individual-based gap model may be limited by the underlying assumptions of vegetation responses to environmental forcings or by the computational domain selected. Parameters may affect model output differently based on the spatial scale (*e.g.*, domain, resolution) of the simulation (Huston, 1991). Although environmental and species parameters may be specified by the user, the plot size and the simulation domain area are often hard-coded by the developer and may not be revisited by subsequent model users. It is possible that computations on smaller or larger plots do not yield output that compares well to observed stand structure and composition due to an inaccurate quantization of the resource utilization area (*e.g.*, zone of influence) for arboreal species in the model, or that simulation of smaller areas using edge-to-edge wrapping results in numerical instability or periodicity that is an artifact of the model algorithm rather than the simulated terrain or vegetation.

The new spatially-explicit individual-based gap dynamics model SIBBORK presents a unique platform for assessing the importance of spatial explicity in the simulation of forest processes, because it can be operated in independent and interactive plot modes, without changing any of the other conditions. SIBBORK has been verified and validated against several multi-dimensional datasets using 100 m^2 plots and simulation domains ranging in size from 9-ha to almost 70-ha (Brazhnik and Shugart, 2015; Brazhnik and Shugart, 2016). Although calibrated to a central location in Siberia (57°N, 95°E) east of the Yenisei River, SIBBORK appropriately reproduces observed vegetation structure and composition in the southern, middle, and northern taiga ecotones without subsequent tuning, demonstrating the generalizability of the model algorithms within central Siberia. This robust model also accurately simulated the geographic location of the historical northern, southern, and altitudinal boreal treelines, including the elevation ranges for the upper and lower extents of expositional forest steppe on south-facing slopes near the southern boundary of the boreal forest, as well as the recent climatologically-driven shifts

* Corresponding author.
E-mail address: ksenia@virginia.edu (K. Brazhnik).

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in treeline location (Brazhnik and Shugart, 2015). However, it is important to understand how certain user-specified parameters may affect model output. Specifically, does spatial explicity enhance predictive capabilities? *i.e.*, Does model simulation using independent non-interacting plots and calculation of available light only from directly overhead (1-D) yield different results than a spatially-explicit and more computationally-expensive light calculation above a terrain comprised of interactive plots (3-D)? How do the spatial resolution (*i.e.*, plot size) and the size of the simulation domain affect model output? Furthermore, model application toward understanding how the central Siberian boreal forest may respond to climate change and how this response is different in the 1-D and 3-D modes are also explored in this manuscript.

SIBBORK, like other IBMs, tracks the establishment, growth, and mortality of individual trees over the course of the simulation. The individuals are simulated on plots approximately the size of the crown of a canopy dominant tree. Multiple trees sprout, grow, and die on a plot over the course of the simulation. Successional dynamics are simulated as a transition from one species to another through species-specific tolerances and competition for resources, such as light. Gap models are grounded in the assumption that plot-level patch dynamics can be abstracted to the landscape scale (Shugart, 1984) and that the average dynamics from 150 or more independent replicate plots (Bugmann et al., 1996) represent the larger landscape dynamics. In gap dynamics theory, the forest is comprised of a mosaic of patches of stands at different stages of succession, resulting in heterogeneous age structure. The size of the simulated patch can have an effect on both the behavior of the simulated stand as well as the individual trees in the simulation (Shugart and West, 1979), because it defines the area of resource utilization or the zone of influence for individual trees (Coffin and Urban, 1993; Larocque et al., 2006) and limits the extent of each tree's canopy. Gap dynamics are driven by the availability of light through the opening created in the canopy when the dominant tree dies and falls to the ground. Gap size affects regeneration processes and succession trajectories, so in order to appropriately reproduce the patchiness of a mature forest, the size of the patches needs to be accurately estimated. The availability of light and other resources below the canopy and at the ground level that facilitate growth of previously suppressed trees and the establishment of new saplings changes based on the size of the gap created (Bradshaw, 1992). Variation in plot size alters the patch size at which the forest dynamics are simulated and, at some point, the average plot-level dynamics may no longer represent the landscape-scale dynamics because of misalignment between the plot size and the scale at which important forest processes occur.

Zhu et al. (2015) point out that regeneration trajectories depend on the size of the break in the main canopy, which affects the light environment within and near the gap. The size of the gap sufficient to alter the regeneration environment depends on the height of the surrounding trees and the solar elevation angle during the growing season. Gap size significantly alters the availability of photosynthetically active radiation (PAR) at different levels within the canopy near the gap, especially at higher latitudes (Canham et al., 1990). Previous studies explored how plot size affects the model's ability to capture gap dynamics (Shugart and West, 1979; Coffin and Urban, 1993), and the species-specific resource utilization area (*e.g.*, zone of influence) of individual trees (Larocque et al., 2006), as well as scale-dependent aggregation of variables from gap dynamics models (Smith and Urban, 1988). These studies found that plots approximately 400–800 m^2 most accurately represent the patch scale of resource utilization in simulations of temperate and northern hardwood forests in North America. Typical gaps in northern forests may range in cross-sectional area from 40 m^2 to hundreds or thousands of square meters (Drobyshev, 1999). In a simulation, typical plot sizes need to be congruent with typical gap sizes, because in order to capture gap dynamics both are supposed to be approximately the size of the crown of a canopy dominant tree, and range across IBMs from 100 m^2 to >1000 m^2. Herein, we assess the sensitivity of model output to plot size selection for the central Siberian boreal forest by systematically varying plot size from 100 m^2 to 900 m^2.

Classical (Monte Carlo type) gap dynamics models simulate individual plots collocated in space that experience the same input parameters and environmental conditions in any given year of the simulation (Urban and Shugart, 1992; Yan and Shugart, 2005; Larocque et al., 2006, 2011). The patch dynamics simulated on each plot are averaged across several model runs to obtain average landscape dynamics. SIBBORK differs from these models via operability in the independent and interactive plot modes. In contrast to classical gap dynamics models, however, the 1-D mode in SIBBORK retains the plot position on the landscape, allowing for different environmental conditions to be specified at the plot level, and simply not permitting the trees on the plots to interact (*e.g.*, shade trees on adjacent and nearby plots). In the independent plot mode, individual trees are limited to within-plot interactions, whereas in the interactive plot mode trees on one plot can affect tree growth on adjacent and nearby plots through competition for light. Intercomparison of model output from simulations in these two modes allows for the evaluation of the importance of spatially-explicit representation of light and space and interactions between trees within one model, rather than across models. The ability to simulate the same spatial domain with plot-level environmental conditions in 1-D and 3-D modes allows for a direct assessment of whether the spatial complexity expands the model's predictive capabilities.

In the independent plot mode, light attenuation is computed along a single ray trace of diffuse light from directly overhead using the Beer-Lambert Law and leaf area index (LAI) at 1 m vertical steps throughout and below the canopy, similar to the computation employed in other gap dynamics models (FORET: Shugart and West, 1977; FAREAST: Yan and Shugart, 2005). In the interactive plot mode, trees on one plot have the ability to shade trees on adjacent and nearby plots, and the effect of a gap can extend across multiple plots, which is more congruent with observations (Canham et al., 1990). The light environment is computed based on attenuation of direct light along ray traces from seven compass directions (no direct light from the north in the extratropical northern hemisphere) and diffuse light from eight compass directions and directly overhead, also using the Beer-Lambert Law and LAI at 1 m vertical resolution (see Brazhnik, 2015; and Brazhnik and Shugart, 2016 for detail). Although sun flecks are not considered in the simulation, foliage surrounding each simulated gap experiences significant spatial heterogeneity in light availability due to the fine resolution (horizontal: plot size; vertical: 1m) of the light ray tracing algorithm.

Light may arguably be the most important environmental factor affecting tree growth (Huston, 1991; Purves et al., 2008; Purves and Pacala, 2008), especially in environments with harsh and complex light regimes, such as the high-latitude boreal forests. Therefore, the representation of light in the simulation is likely to play an integral role in how stand structure and composition evolve within the simulated domain. We assessed how the representation of light the simulated forest processes and the resulting plot-level and aggregate model output for the simulation of central Siberian and southern Siberian boreal forest under historical and potential future climates.

2. Methodology

The 3-D light subroutine in SIBBORK (described in detail in Brazhnik (2015), Brazhnik and Shugart (2015) computes the avail-