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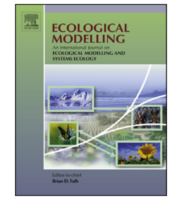

SIBBORK: A new spatially-explicit gap model for boreal forest

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ABSTRACT

Climate change is altering forests globally, some in ways that may promote further warming at the regional and even continental scales. In order to predict how forest ecosystems might adapt to a changing climate, it is important to understand the resilience and vulnerabilities that each species within that current ecosystem might have to a modified future environment. Complex systems that occupy large spatial domains and change slowly, on the order of decades to centuries, do not lend themselves easily to direct observation. A simulation model is often the more appropriate and attainable approach toward understanding the inner workings of large, slow-changing systems, and how they may change with imposed perturbations. We report on a new, spatially-explicit dynamic vegetation model SIBBORK developed for the purpose of investigating the effects of climatological changes on the long-term dynamics, structure and composition of the Siberian boreal forest.

1. Introduction

There is uncertainty in forecasts of how global forests will be affected, but we know that changes in forest extent, type and structure have the potential to feedback to the atmosphere and intensify climate change at the regional, continental and even global scales (Bonan et al., 1995; Pielke and Vidale, 1995; Cox et al., 2000; Bonan, 2008; Jackson et al., 2008; Hollinger et al., 2010; Groisman and Gutman, 2013; Kuusinen et al., 2014). Moreover, changes in vegetation structure and composition can reduce or accelerate the rate of carbon exchange between the atmosphere and the biosphere in boreal ecosystems (Kolchugina and Vinson, 1995; Krankina et al., 1996; Betts, 2000; Kulmala et al., 2004; Randerson et al., 2006; Ma et al., 2012). In order to understand what changes may be expected in a forest based on changes in environmental conditions, we have developed a new ecological model, called SIBBORK, that is robust and easily parameterized to represent dynamics of different forest ecosystems using publically available datasets, such as the World Meteorological Organization (WMO) temperature and precipitation records, and information routinely collected in forestry surveys and reflected in forestry yield tables. The purpose of SIBBORK development rests in the desire for (1) better understanding of forest response to climate change based on tree process responses to the surroundings and (2) more explicit parameterizations of environmental conditions, which depend on the tree's position on the landscape at the smaller scale. Few gap models incorporate effects of surroundings some distance away (20–100 m) on tree processes. SIBBORK can be used to investigate biome shifts and successional trajectories in forest ecosystems, to understand the likely compositional and structural changes a forest may experience with climate change, to test potential mitigation approaches, such as introduction of new species and expansion of timber plantations, assist with planning for habitat changes or shifting the economy to/from the timber sector, and assessing ecosystem services. We focus here on describing this new model, the functionality that provides advances over other models, and the testing of the model output against multi-dimensional time-series data.

2. Methodology

SIBBORK was developed to tease out the dependencies and interactions between trees and environmental conditions. We are interested in understanding the internal forest processes and their potential responses to disturbances, because forest structure and composition have a significant effect on how energy and carbon are cycled through the ecosystem (Bonan et al., 1995; Liu et al., 2005; Bonan, 2008; Ashton et al., 2012). Due to the large extent, recent climatological changes, and potential large (spatial scale) forcings that the Eurasian boreal forest can exert on the global climate, we focused specifically on this ecosystem. Like many individual-based gap models, SIBBORK simulates the establishment, growth and mortality of individual trees on plots approximately the size of a crown of a canopy dominant tree (100 m^2). Canopy size of each tree is limited by the plot size. However, unlike Monte Carlo type

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simulations of independent plots (e.g. FAREAST, Yan and Shugart, 2005), the plots in SIBBORK are arranged in a grid and connected to each other. Trees on each plot can interact with trees on adjacent and nearby plots through shading. The shadow of a typical canopy dominant from central Siberia (22–24 m, Simard et al., 2011) can extend up to 100 m, depending on foliage density and sun elevation angle. Trees within a plot also interact with each other via shading of diffuse light from directly overhead as a function of cumulative leaf area above each 1 m vertical level. In contrast, the shading capacity of a tree on an independent plot in FAREAST is limited to the plot size (500 m^2). Environmental conditions are computed and specified at the plot level and reflect the edaphic, hydrologic, and climatological gradients associated with relief. Since trees do not have explicit *x*,*y* position on the landscape, the uncertainty of a tree's location on the terrain is limited to a specific plot. Certainly, it is possible to give each tree an assigned location within the simulated domain and get rid of plot designation, however, the plots are retained for specification of environmental conditions and stem density at the plot level and for ease of aggregating stand characteristics at different spatial scales. The horizontal resolution of environmental conditions and vegetation structure is 10 m × 10 m, and the vertical resolution of the light environment and canopy structure is 1 m. Species-specific parameterizations and generation of climate conditions synthesize our current knowledge of boreal ecosystems, climatology, and numerical modeling. This model highlights important progress in ecological modeling via simulation of 3-dimensional space above a real landscape. The model simulates the environmental conditions at the plot level, and the vertical and horizontal distribution of vegetation across a 3-dimensional landscape, which renders it fit for the application toward simulation of what has already been observed as heterogeneous changes in temperature and precipitation across the spatial and temporal domains, and the associated response of vegetation to this spatially and temporally heterogeneous climate change.

2.1. Development from ZELIG

ZELIG was derived from FORET (Shugart and West, 1977), which is a more generalized version of JABOWA (Botkin et al., 1972). It was originally developed for temperate forests of North America (Urban et al., 1991; Weishampel and Urban, 1996), but has since then been used in investigations of coastal forest (Urban et al., 1993), dry tropical forest in Puerto Rico (Holm et al., 2012), upland and bottomland forests in the arid Midwest of the U.S. (Acevedo et al., 1997; Holcomb, 2001), northern hardwood forests (Larocque et al., 2006, 2011), and Amazonian forests (Holm et al., 2014). Like JABOWA, ZELIG is based on the assumption of landscape homogeneity at the plot level and within the simulation domain. ZELIG, however, presents one of the first departures from the standard gap model by introducing the idea of simulating several adjacent plots to represent a transect on a landscape. We substantially expanded the functionality of ZELIG (Urban, 1990, 2000; Urban et al., 1991, 1993) through modification to the 3-D light subroutine, simulation of canopy architecture and terrain representations, species-specific parameterization and specification of the simulation area and plot size. We modified the governing equations for soil hydrology and climate, and introduced species-specific allometry. The optimal diameter increment in SIBBORK is computed based on observed maximum annual diameter increments from the yield tables (Shvidenko et al., 2006) and the Usolsky timber enterprise inventory (Ershov and Isaev, 2006), using methodology described by Bragg (2001, 2003). This is in contrast to the JABOWA-based calculation employed in ZELIG (Botkin et al., 1972), which depends on a set maximum age for each species—a variable that depends on environmental conditions and is difficult to estimate. Soil hydrology in SIBBORK utilizes the modified Penman equation, which incorporates solar radiation and air temperature inputs and is more appropriate for high latitude environments. Soil fertility in SIBBORK acts as a cap on gross primary productivity (GPP), and annually limits actual biomass accumulation rather than maximum potential biomass accumulation based on optimal diameter increment computed in ZELIG (Urban, 1990). Soil fertility is specified at the plot level for each location based on soil type (Stolbovoi and McCallum, 2002) and a map of biological productivity for Russia (Isachenko, 1985). We built on the plasticity of ZELIG with simplified re-parameterization to different site and species characteristics using georeferenced matrices as input files for plot-level specification of environmental conditions (radiation, elevation-based temperature adjustment, soil fertility) for enhanced portability to simulation of other ecosystems.

As in ZELIG, the simulated trees in SIBBORK are fully coupled to the light environment and soil moisture (e.g. light affects trees, trees affect light), partly coupled to the soil fertility (soil fertility affects trees, but trees don't affect soil fertility), and uncoupled from (do not affect) air temperature. SIBBORK differs from ZELIG via modifications to how the spatial domain of the simulation is specified, the ability of the light regime to be computed above varied terrain, the computation of soil hydrology, the optional inclusion of permafrost and several parameterizations for tree growth and environmental conditions. SIBBORK simulates heterogeneous landscapes and different environmental conditions at the resolution of the plot, and builds more plasticity into the specification of environmental conditions and aggregation of results at different spatial scales. The enhanced simulation of the environmental conditions allow for wider application of SIBBORK, including the study of boreal forests with complex light and soil moisture regimes[1].

The simulation inputs include allometric equations and species-specific tolerances to environmental conditions, as well as initialization conditions, maximum stem density, climatological trajectory (stable or changing), and simulation duration. Additionally, the user specifies the simulation domain using a georeferenced digital elevation model (DEM) file. This can be artificial user-created terrain for testing purposes (e.g. flat or N- and S-facing slopes along an E–W ridge), or real terrain, such as from ASTER DEM (METI and NASA, 2011). During pre-processing, the DEM will need to be resampled at the desired plot size. Using the DEM and the environmental lapse rate, temperature is computed for each plot that is at a different elevation than the reference weather station. The ArcGIS Area Solar Radiation tool (Fu and Rich, 2002) is used to compute monthly incident solar radiation, and includes published cloud fraction and direct-to-diffuse radiation fraction for the simulated region, where available. Potential evapotranspiration (PET) is computed as a function of monthly temperature and solar radiation for each year of the simulation. In this manner, environmental conditions are either specified at the start or computed within the simulation at the plot level. This allows us to resolve variability in conditions associated with topographic gradients, simulate transition zones, and aggregate output at different spatial scales or via masks by terrain features, e.g. slope aspect or elevation.

The model can be initialized from bare ground or an initial stand condition. Bare ground symbolizes the complete absence of any trees on the landscape and represents the conditions following a disturbance, such as an intense wildfire, clear-cutting, or a landslide. Establishment of trees into the disturbed area is assumed to occur from seeds from nearby stands. Stump-sprouting and regeneration by layering are not currently parameterized in SIBBORK. Alternatively, to begin the simulation with a stand of a

[1] SIBBORK source code available at www.github.com/sibbork/SIBBORK.