SPATIALLY-EXPLICIT MODELING OF SIBERIAN BOREAL FORESTS

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Abstract. Circumpolar boreal forests contain one half of the terrestrial carbon stores, and have been shown to be susceptible to climate change. As climate regimes shift, the total biomass and species composition may change in ways that may promote further warming on the regional level through atmosphere-vegetation feedbacks. The purpose of this project is to develop a spatially explicit model for simulation of structure and dynamics of boreal forest through space and over time. The current model builds on previous forest gap models, and incorporates additional functionality, both, in the programing and the modeling realms. With the new model, we will be able to study the long-term and large-scale responses of the boreal forest to climate change, through the simulation a grids of plots, each approximately 0.1 hectare in size. The spatially-explicit aspect of the model will enable studying the propagation of insect outbreaks and wildfires across the landscape, as both of these types of disturbances are expected to increase in frequency, intensity, and duration with climatic shifts. The model output – changes in the sizes of trees on the plots, the total and species-specific biomass and basal area, as well as species composition, will be imaged and georeferenced in GIS software.

Introduction

Siberian Boreal Forest

Boreal forests are located between 50°N and 70°N latitude on the continents of Eurasia and North America, with some regional variability along the southern and northern boundaries. Approximately one third of the global carbon storage is in the above-ground and below-ground biomass within the boreal forests. The largest continuous expanse of forest is found in Russia and constitutes over approximately two thirds of the total boreal forest biome. Boreal forests are floristically simple, which renders their biomass and species diversity more susceptible to climate change. Due to the warming predicted and observed in Eurasian boreal forests, this ecosystem potentially plays a significant role in the planetary carbon cycle, as the changes in forest dynamics may further propagate regional and global warming of ambient air temperatures through a complex system of vegetation-atmosphere feedbacks. Predicting future changes in the Russian boreal forest is intrinsically a modeling issue, as the spatial expanse of the forest and the temporal scale of patterns and processes do not lend themselves to direct measurement or observation. Herein, the approach of spatially-explicit model-based synthesis of forest dynamics will be utilized to study the structure and processes of this vast boreal landscape on multiple levels and over time, including an exploration of forest response to climate change.

Beyond the large stores of carbon, there are complex internal interactions within the boreal ecosystem. Regional changes in vegetation can lead to changes in regional albedo, which may affect regional climate through atmosphere-vegetation feedbacks. Of great concern is the replacement of deciduous Larch species (Larix spp.) with evergreen conifer species (Abies spp., Picea spp., Pinus spp.) accompanying an increase in ambient winter temperatures. Larch is a deciduous conifer and, as such, loses foliage in the fall. Consequently, the regional albedo of larch-dominated forests in the winter is closer to that of snow, and reflects a significant portion of the incoming solar radiation. In contrast, evergreen trees maintain the same albedo throughout the year. Figure 1 shows a comparison of annual average albedo of conifer (pine) versus deciduous larch stands in a snow-free environment (redrawn from [14]); the albedo of larch is greater than any other conifer. Needle-leaf forests absorb more insolation, while broad leaves reflect more and, hence, have a higher albedo. Albedo also depends on foliage nitrogen content. There is evidence that the large-scale replacement of larch and a shift to evergreen dominance by dark conifers, decreases the average regional albedo and drives a positive feedback loop between the ambient temperature and vegetation cover, which may result in further warming and climate changes through alteration of the radiation budget on the regional level, generating a positive radiative
forcing of approximately 5W/m$^2$. Dark conifers include spruce and fir – species that are more tolerant of higher temperatures. Field studies have shown that alterations in land cover (tree line, forest composition) and vegetation processes (regeneration, seed dispersal) are already occurring in the Siberian boreal forest, alongside greater warming in Siberia than was observed elsewhere or predicted by climate models.

The dark conifers in Siberia are affected by insect outbreaks and fires – both types of disturbances that may become more significant with increasing conifer dominance in the region. Coniferous trees are also more susceptible to insect damage and exhibit higher mortality during insect outbreaks. Direct observation of forests in North and South America revealed that climate-related and insect outbreak disturbances cause structural changes in forests, including alterations in density, spatial distribution, dominant species, and species composition, because trees have different susceptibilities to selective mortality based on size and life stage of the individual and the life history of the species. Changes in forest structure and species composition in the large boreal ecosystem may have significant implications for net primary productivity and carbon balance in the region. Additionally, insect outbreaks may be linked to increase in wildfire spread and frequency, which would further decrease the carbon storage and productivity of the region in the short term. It has been reported that an increase in the wildfire and insect-related disturbances in the boreal forests in Canada have already converted those forests to a source of atmospheric carbon.

Additional feedbacks include an increase in the decomposition rate of the carbon-rich organic mat on the boreal forest floor and peatbogs, release of carbon dioxide and methane during permafrost thaw, and enhanced exchange of carbon between the biosphere and the atmosphere due to predicted and already observed increases in wildfire frequencies and extent. Remote sensing and satellite products are necessary to monitor the regional changes in species composition, albedo, and large-scale disturbances, while numerical models are needed to predict future forest structure and dynamics, and the associated implications for regional climate and the carbon cycle.

**Forest Modeling**

A forest is a large, continuous expanse of trees that spans climatologic, geologic, topographic, and environmental gradients. Within the Siberian boreal forests, there is large temporal and spatial variability in insolation, moisture, as well as air and soil temperatures. Forests are spatially extensive, and the components of the forest (namely, trees) change over long periods of time, with most lifetimes of trees longer than human life expectancy. For these reasons, numerical
modeling of forests lends itself as a tool for examining forest responses to environmental factors and disturbances. Forests and other landscapes have been modeled by an array of approaches \(^{24}\), including homogeneous landscape models, Markov and Semi-Markov models, mosaic landscape models, such as a Monte Carlo simulation for point locations \(^6\), interactive \(^{25}\) and nested landscape models \(^{26}\). It is hypothesized here that a spatially explicit interactive landscape model is better at simulating and predicting responses of large heterogeneous landscapes to abrupt disturbances (fires, insect outbreaks), as well as more gradual changes in environmental parameters related to climate change.

A gap model simulates plots the size of the crown of a dominant tree (0.05-0.1ha), and the establishment, growth and mortality of each tree on each plot, including the effects of environmental factors on those processes, based on the species-specific tolerances and competition for resources \(^{24}\). The growth response of trees to the environmental factors of light availability, soil moisture, ambient temperature, expressed as growing degree days, and soil fertility (N content) are shown in Figure 3 \(^{22}\). Current generation of individual-based gap models (IBMs) are based on the FORSKA and JABOWA models developed in the 1970’s \(^{27,29}\). Growth refers to an increase in diameter, height, cumulative leaf area, and biomass of individual trees with time, establishment denotes the seedling germination and sapling establishment, and mortality may be natural or stress-induced. The model computes the maximum potential growth and establishment rates for trees of specified species and sizes, and modifies them by the environmental factors and available resources, with light serving as the factor most limiting to growth. It has previously been found that various environmental factors are limiting to different species and at different periods in their lifetime. The environmental parameters considered are light availability, air temperature, soil moisture and soil fertility; the latter is gauged from the simulated productivity of the plot limited by a maximum productivity for the site specified in the data input file (Driver). The simulation of multiple plots represents the average forest dynamics over time \(^{24,30,31}\). The model considers age structure, diversity, and geometry of individual trees on a plot (independent mode), or a transect or aggregate of plots (interactive mode), and computes the three-dimensional canopy interactions among trees \(^{20}\).

A model can be verified by comparing the output of the model to the data on which it was “trained” – which was used to parameterize the model and create the Driver (input) files for the simulation. Verification assesses how well the numerical model aligns with the conceptual model of the phenomena simulated. A model can be validated by comparing the model output to an independent data set, information from which is used to initiate the model, but which was not employed in parameterizing the model. Validation tests the accuracy of the concept map and how well the model can be generalized to new scenarios and environments/locations. The model may need to be revised several times in order to achieve the desired accuracy and realism in representation of the forest growth and responses, and to better match the computer simulation to the concept map of the forest processes, feedbacks, and interactions modeled.

Herein, the approach of model-based synthesis of forest dynamics is utilized to study the structure and processes of this vast boreal landscape on multiple levels and over time. Different versions of ZELIG have been compared with other models \(^{32}\), but validation against data is a stronger test. JABOWA \(^{33}\) and FAREAST model (Monte Carlo simulation) \(^{33,34}\) have been used for the investigation of the role of the forests in the global carbon cycle and the potential response of these

![Figure 2. A single plot approximately the size of the crown of the canopy dominant tree (0.05-0.1ha). A forest landscape is made up of a mosaic of similar patches, with vertical structure and species composition as shown in this sample plot. In a boreal forest, canopy dominance is determined by the light regime and shading perimeter.](image)
forests to the changing climate conditions, and associated disturbance regimes. The current project utilizes the ZELIG model, which is described in detail below.

ZELIG simulates a stand of trees on a grid of cells, each roughly the size of the shading influence of the canopy dominant tree. The model can be run in an independent plot mode or in an interactive plot mode. The former simulates plots that do not interact in space (Monte Carlo simulation): trees from one plot do not shade trees on adjacent plots, and runoff from one plot does not become runon on adjacent plot(s) downslope. In the interactive mode, the model simulates the grid of cells with spatial interactions between the cells: trees on one plot shade adjacent plots. When the plots are aggregated together, they simulate an area on a forest landscape, from which stand composition and structure can be determined. The optimal size for each simulated plot was determined to be 0.04 to <0.2 ha in size\(^{35}\), which is large enough for the canopy dominant tree to achieve its maximum size and for gap replacement to (be observed to) occur upon the mortality of the dominant tree. Nonetheless, the aggregate mosaic of plots is representative of the large-scale forest structure and can be used to generalize about a much larger landscape than is actually simulated. ZELIG has a spatially explicit interactive mode, which will be used to explore the phenomena associated with forest components that depend on spatial variability on the landscape. The model will also be used to explore phenomena that propagate in space, such as wildfire and insect outbreaks. These phenomena are intrinsically spatial. For example, a plot that is near a plot that is on fire is more likely to also catch on fire, than a plot that is not adjacent to or surrounded by plots with fire. Therefore, it is hypothesized that a spatially explicit model, such as ZELIG, would have better predictive capabilities with regards to spread of fire, insect outbreaks, and other phenomena that depend on spatial variability or propagate in space.

Some processes in ZELIG are modeled stochastically (monthly temperature, tree mortality), and others – deterministically (tree height, optimal growth diameter). Homogeneity is

Figure 3. The response of tree growth to environmental parameters of (a) available light, (b) soil fertility, (c) soil moisture, and (d) temperature expressed in growing degree days. A tree of a given species will respond to environmental stresses based on its tolerance level (to drought, heat stress)\(^{35}\).
scale-dependent, and is assumed for some parameters in the model, such a soil type at the plot or simulation level\textsuperscript{36}. When we want to understand forest responses at the stand or landscape level, modeling plots the size of gaps in the forest (the scale of gap dynamics) allows for better scaling up of the model output at the plot level to the landscape level, than models that simulate responses at the leaf level, because the plot size in ZELIG better represents the vertical and horizontal structure of the forest\textsuperscript{37}. Proposed improvements in the model include transformation of several simulation-wide parameters to plot-wide variables. This addresses the scale to which the assumption of homogeneity is applied. When elevation, slope, and aspect are plot-wide, more realistic temperature, soil moisture and PET values may be simulated, and the effect of these environmental factors on tree growth, mortality, and establishment of new saplings, may be more realistically represented in the model.

Methodology

The motivation for this research stems from the need for developing predictive capabilities for the simulation of terrestrial ecosystem dynamics and incorporating projections of regional and global changes. This project undertakes the understanding of the forest dynamics in the ecosystem that comprises the largest carbon reserve on the Earth’s surface via a spatially-explicit modeling approach. The manner in which a landscape may respond to climate change depends on spatial interactions between the different components of the landscape\textsuperscript{9}. Some components of the forest functions and processes, such as evapotranspiration, soil moisture, spread of insect outbreaks and wildfires, depend on spatial parameters, such as topography and whether the neighboring trees are infected or on fire. I will test whether the ZELIG-BORK model in the spatially-explicit mode has better predictive power with regards to species composition, total biomass (carbon storage), total and species-specific basal area, and other stand aggregate and species-specific parameters in a boreal forest, as compared to the independent point-plot mode.

To narrow down the scope and to focus the parameterization of the ZELIG-BORK model, I will use meteorological, soil, and silvicultural data, and forest inventories from the Krasnoyarsk Region of Russia (highlighted red in Figure 4a). For model verification, I will use data from Krasnoyarsk Region, whereas for model validation I will use data from the Usol’sky forest (Figure 4b), as defined in [17]. The Usol’sky forest includes six regions (Figure 4c), each of which is subdivided into dozens of quartals, which are further subdivided by dominant species stands. The database is extensive, and contains information regarding forest structure and insect outbreaks. Therefore, a portion of the data will be used to validate the ZELIG-BORK model, and another portion will be used to validate the ZELIG-BORK model with insect module.

My main question concerns special explicit: does it add to predicting ability of the model? 1. Is there a statistically significant gain in the accuracy of model prediction for such parameters as forest biomass and species composition, from inclusion of interactions between model plots (light and soil moisture variables) and geospatial information regarding terrain (temperature, soil moisture, insolation)?

2. How do climate change responses in the vegetation differ on an interactive transect of plots compared to independently modeled plots?

3. Is a spatially explicit model better able to model and predict propagation of an insect outbreak in a boreal forest landscape?

4. Does a spatially explicit model have better capabilities of simulating the spread of fire across the boreal forest landscape?

Though the FAREAST model performs strongly\textsuperscript{5}, it does not explicitly resolve disturbances that spread in space, such as large fires or insect infestations, both of which are expected to increase in frequency and magnitude with alterations in local and regional climate\textsuperscript{38-41}. Insect outbreaks often depend on short-term climatic changes, which are not resolved with tree growth and regeneration subroutines that depend on longer-term climate parameters. Recently, a module has been developed by A. Kovalev for the FAREAST model to account for possible disturbance by the Siberian Silkworm (Dendrolimus sibiricus)\textsuperscript{42}. The FAREAST model utilizes a Monte Carlo simulation to simulate independent plots, whereas ZELIG-BORK can be run as an aggregate of interacting plots – a mode that explicitly resolves large spatial extents (numerous plots the size of a mature tree crown...
aggregated into a simulation area), eliminating the need for interpolation between site values.

The main question is whether the spatially explicit model has stronger predictive capabilities than the simulation of independent points or plots, as can be achieved with the FAREAST or the independent plot mode in ZELIG-BORK. To couple the insect module with the ZELIG-BORK model, the weather subroutine in ZELIG-BORK needs to be modified to simulate daily weather (temperature and precipitation). ZELIG-BORK, with its spatial capabilities (interactive plot mode) may be more optimal for the assessment of the effect of changing climate on disturbance regimes at finer spatial and temporal scales, including the effects of topography on runoff and potential evapotranspiration, as well as the cumulative effect of climate change and disturbances on the forest structure and composition.

A comparison between FAREAST and ZELIG-BORK output will be conducted for several locations in the Krasnoyarsk Region boreal forest.

I have developed a Python-based version of this model, and am in the process of encoding the 3-D light subroutine developed by Weishampel.
and the topography-related modifications described by Acevedo\textsuperscript{45}. The Python-based ZELIG-BORK model utilizes open-source libraries associated with Python language and an iPython notebook for fast visualization of intermediate model outputs, such as the simulation of monthly temperature and total biomass for each year. ZELIG-BORK contains tree silvics for boreal species, soil functions from the ZELIG v 2.3 model\textsuperscript{45}, a potential evapotranspiration function more appropriate for high latitudes, and environmental parameters for simulation of the boreal forests in the Krasnoyarsk Region.

Due to the timber economy of the region, ample forest inventory data are available for the boreal forests around Krasnoyarsk, including yield tables\textsuperscript{46}, which were used in the parameterization of the ZELIG-BORK model and generating the silvics Driver file, and will be used for the verification of the model. An independent dataset from the Usol’sky forest, located at 55-57.5°N, 94.5-98°E, will be used for validation, and will serve as the stronger of the two tests. Meteorological data for the Driver file were obtained from the seven WMO stations located nearest to and within the forest boundaries of the forest of interest\textsuperscript{37,48}, and soil data (type, field capacity, wilting point, nitrogen content) for different parts of Krasnoyarsk Region were obtained from [20]. Species present in the region were determined from species range maps\textsuperscript{6}, and arboreal silvicultural data were obtained from previous reports\textsuperscript{1,6,50}. The species of greatest interest – Larix sibirica – does not have commercial timber value, therefore forest inventories represent its natural abundance, percent composition, and biomass.

Soil properties in Siberia are unique, due to the distribution of permafrost, and the extremely inland location. This combination of factors creates conditions in which evapotranspiration annually exceeds precipitation\textsuperscript{1}, with average annual precipitation of around 400mm and annual evapotranspiration of 500mm\textsuperscript{51}. However, the presence of permafrost inhibits drainage, so for many tree species the soil moisture is adequate. Permafrost extent influences soil moisture and soil temperature, which affects the decomposition rate and, thus, content of the organic mat on the forest floor, as well as tree growth and sapling establishment\textsuperscript{52}. To better represent the unique ground properties of the Siberian boreal forest, I plan to update ZELIG-BORK to include several soil layers, with thermal and moisture properties simulated for each layer down to the level of permafrost, as described in by Acevedo\textsuperscript{45}. To include permafrost extent in the model, I plan to wrap ZELIG-BORK around an existing permafrost module from Bonan\textsuperscript{5,19,52}.

Some tree models (e.g. ZELIG v1.0\textsuperscript{25}, ZELIG-TROP\textsuperscript{53}) set a minimum growth increment that a tree may achieve over the course of a year or several consecutive years that would set the tree for mortality due to stress and reduced vigor. However, trees in extreme environments may continue to survive even with very low vigor levels\textsuperscript{54}. Therefore, I plan to modify the natural and stress-induced mortality subroutine to accommodate species-specific tolerances to environmental stresses\textsuperscript{55}.

In the second version of ZELIG-BORK, weather will be simulated on a daily basis. Temperature and precipitation will be simulated based on input means and standard deviations for each day of the year, ignoring leap days, and a normal random number generator. Temperature and precipitation will differ for different regions of the Usol’sky forest, as information from the closest WMO station will be used as input in the Driver file. Radiation data, however, is only available from one station, and will be the same for all districts in the Usol’sky forest. Once relief is included in the model, radiation, runoff, runon, PET, and soil moisture parameters are expected to be different for the various regions within the Usol’sky forest based on terrain slope and aspect.

The start, end and duration of the growing season were determined for each year of the simulation from the simulated monthly temperature values with a degree day base (DDBASE) of 5°C\textsuperscript{1}. The monthly temperature and precipitation values are additionally used to compute the monthly soil moisture content and potential evapotranspiration (PET), as well as drought days within the growing season. The original model employed the Thornthwaite equation\textsuperscript{56} to compute PET based on average monthly temperature and correction coefficients for each month and latitude. The Thornthwaite equation had not been validated for the calculation of potential evapotranspiration at high latitudes (above 50°N)\textsuperscript{57}, and correction factors are not
available for those regions. Therefore, a modified Penman equation was utilized for the computation of PET in the boreal forest:

$$\text{PET} = a^* (T_a + b)^* S_\lambda / \lambda \quad (1)$$

where $\lambda$ is the latent heat of vaporization ($2430 \text{ J/g}$), $a$ and $b$ are coefficients, with typical values of 0.025°C and 3°C, respectively, $T_a$ is the average monthly air temperature (°C) and $S_\lambda$ is the solar radiation ($\text{W/m}^2$)\(^5\). Monthly mean temperature and radiation data were used to compute PET on a monthly basis, which is employed in determining the monthly water balance for the plot. Radiation data for the PET calculation were obtained from the World Radiation Data Centre, for the Vanavara station (#249080), located at 60°N 102°E in the Krasnoyarsk Region, which is 200 miles from the Usol’sky forest.

The mortal subroutine activates two mortality functions, which stochastically select individual trees for natural and stress-dependent mortality. Natural mortality is based on the assumption that 1% of individuals of a given species reach the maximum age (AGEMAX) specified in the Driver file. A stressed tree is one that has grown less than 10% of the maximum possible increment for the species and the age of the individual due to species-specific shading, drought or nutrient stress tolerances. A tree that has been stressed for two consecutive years has a 37% chance of dying in the following year. The age-related mortality function:

$$P = 1 - e^{-4.605/\text{AGEMAX}} \quad (2)$$

where $P$ is the species-specific probability of mortality\(^4\), and AGEMAX is specified in the Driver file for each species, is very similar to the one used in ZELIG v1.0.

In Development

Spatially Explicit Modeling of Insect Outbreaks in the Siberian Boreal Forest

Insect outbreaks are an important disturbance regime in the boreal forest of Siberia. An array of pests, from defoliators, such as the Siberian Silk Moth (*Dendrolimus sibiricus*), the European Gypsy Moth (*Limantria dispar*)\(^2\), and the Pine Looper (*Bupalus piniarius*)\(^6\), to borers, such as the sawyer beetles (*Monochamus urussovi*)\(^6\), to the nematodes that the borers introduce into the tree cores, affect the health, and therefore the structure and dynamics of boreal stands. The Siberian Silk Moth is the major defoliator in Siberia; it feeds on foliage of larch, pine and spruce trees. Aspen and birch may be hosts to the European Gypsy Moth. *Pinus sylvestris* is particularly susceptible to Pine Looper attacks, which may additionally affect larch and spruce trees, whereas the sawyer beetle can affect many types of conifers. To narrow down the scope of the insect outbreak study, I will focus on the major Siberian boreal forest defoliator – the Siberian Silk Moth.
Spatially Explicit Modeling of Wildfire Propagation: Current Conditions and Climate Change Scenarios

Wildfire is the dominant disturbance regime in the Siberian boreal forest, and is the major agent in stand replacement. Most of the fires in the Alaskan boreal forest are large (>20,000ha), and in Siberia the total area burned each year in Alaskan and Canadian boreal forests has been steadily increasing since the 1960s. Though the data reported from the continuous record of wildfire frequency and extent in Siberian boreal forests from the Soviet Union era may not be reliable, there is satellite evidence from the last few decades that the situation is similar in circumpolar boreal forests across the globe, including Siberia. This spatial extent renders fire an important disturbance process that affects the carbon storage of the boreal forest, and by which the biosphere and the atmosphere exchange carbon.

Explicitly-spatial modeling of the wildfire spread in boreal forests may provide better predicting abilities with regards to vulnerable (stressed) stands and spread of fire through space, from plot to plot. My approach will utilize a sector of the Usol’s sky forest for training of the model, and a different sector for model validation. Regions with past fires will be selected. Carbon emission estimates previously reported for Siberia will be utilized for converting the area burned (simulated as burned in the model) to carbon emissions. To employ the C emission estimates, intensity of the fire(s) needs to be known. I am currently researching and brainstorming how to address this parameter in the model.

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