Evaluating the sensitivity of Eurasian forest biomass to climate change using a dynamic vegetation model

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Abstract
Climate warming could strongly influence the structure and composition of the Eurasian boreal forest. Temperature related changes have occurred, including shifts in treelines and changes in regeneration. Dynamic vegetation models are well suited to the further exploration of the impacts that climate change may have on boreal forests. Using the individual-based gap model FAREAST, forest composition and biomass are simulated at over 2000 sites across Eurasia. Biomass output is compared to detailed forest data from a representative sample of Russian forests and a sensitivity analysis is performed to evaluate the impact that elevated temperatures and modified precipitation will have on forest biomass and composition in Eurasia. Correlations between model and forest inventory biomass are strong for several boreal tree species. A significant relationship is shown between altered precipitation and biomass. This analysis showed that a modest increase in temperature of 2°C across 200 years had no significant effect on biomass; however further exploration with increased warming reflective of values measured within Siberia, or at an increased rate, are warranted. Overall, FAREAST accurately simulates forest biomass and composition at sites throughout a large geographic area with widely varying climatic conditions and produces reasonable biomass responses to simulated climatic shifts. These results indicate that this model is robust and useful in making predictions regarding the effect of future climate change on boreal forest structure across Eurasia.

Keywords: boreal forest, gap model, climate change, validation

1. Introduction
A clear understanding of boreal forest dynamics is critical to developing an accurate representation of the Earth’s response to climate change. Boreal forests represent 30% of global terrestrial biomass and approximately two-thirds of this forest is in Russia (Conard et al 2002). Since 1966, temperatures in Eurasia have increased at nearly twice the global rate (Serreze et al 2000, Groisman et al 2009). In certain parts of Siberia, temperature increases have been documented which exceed predictions made by global climate models (Soja et al 2007). This unprecedented rate of climate warming strongly influences the structure and composition of Eurasian boreal forests. In particular, these temperature increases have led to the shift of treelines northward or upslope of previous climate limits, and a reduction in cone and seed yield for Larix sibirica and Pinus sylvestris ultimately changing forest composition and structure (Kharuk et al 2009, Soja et al 2007). These changes are important indicators of how boreal forests across Eurasia may respond to, and ultimately amplify, increases in the average global temperature.

Global climate model simulations indicate that the Northern Hemisphere’s boreal forests and, in particular, the Siberian boreal forest zone, may not only respond to climate change but may affect the Earth’s climate through feedbacks involving changes in the regional surface albedo. Bonan
et al (1992) altered surface albedo in order to simulate the clearing of the boreal forest in the National Center for Atmospheric Research (NCAR)’s Community Climate System Model version 1.0 (CCSM1). This substantially cooled the Earth not only in the boreal zone but across the Northern Hemisphere. Betts (2000) used the Hadley Center Atmosphere Model (HadAM3) to simulate the climatic consequences of albedo changes from growing more trees. He found that the surface albedo changes associated with the growth of coniferous evergreen trees led to significant increases in the average global temperature. These increases were large enough to overshadow the effect of the carbon storage that occurred as a result of growing evergreen forest in that region. Bioclimatic modeling, which utilizes changes in basic climate requirements to assess the re-distribution of ecosystem ranges, further supports this idea of albedo shift in response to climate change. Input climate variables for a Siberian bioclimatic model were derived from the Hadley Center’s global climate model HadCM2GGal output. The results of the bioclimatic model predicted that by 2090 vegetation change across Siberia would create an albedo shift and increased overall net radiation producing enhanced warming above that predicted for the high latitudes; additionally a replacement of taiga with forest-steppe and/or steppe environments is predicted across southern Siberia (Vygodskaya et al 2007).

Field observations provide further evidence that changes in the boreal forest may impact the global climate. Larch forest, dominated by both Larix sibirica and L. gmelinii, covers extensive regions in Siberia. Shifts from larch to dark conifer forests, dominated by trees such as spruce or fir that are tolerant of higher temperatures, have been documented (Kharuk et al 2007). Because larch is a deciduous conifer, this shift in forest composition would lead to the same albedo change as the evergreen tree growth simulation presented by Betts (2000). This reduction of albedo associated with a documented shift in forest type (larch to dark conifer) indicates that warming temperatures may lead to a positive feedback response: a warmer climate accelerates the natural succession from larch to dark conifer forest; the resultant albedo change promotes additional warming.

Dynamic vegetation models, specifically forest gap models, are ideally suited to an exploration of the impacts that climate change may have on the structure and composition of boreal forests and the existence of a climate/land-cover feedback in this region. The impact that a changing climate has on forests at local and regional scales has been explored with several different forest gap models (Shugart 1984, Lasch and Lindner 1995, Bugmann 1996, Yan and Zhao 1996, Bugmann and Solomon 2000, Zhang et al 2009). Forest gap models established on the approach of Botkin et al (1972) and Shugart and West (1977) are based upon the concept of ‘gap phase’ replacement (Watt 1947). Specifically, gap models simulate the growth of individual trees on a patch the size of a mature tree crown and account for competition among trees for light and resources. The outcome of this competition determines the composition and structure of the forest through aggregation of homogeneous mosaic patches through time (Shugart 1984).

Gap models have been validated and verified for a range of forests world-wide (Botkin et al 1972, Shugart and West 1977, Shugart 1984 and its reprinting 1998, 2003, Kienast 1987, Leemans and Prentice 1989, Kienast and Krauch 1991, Bugmann 2001). The individual-based gap model FAREAST (Yan and Shugart 2005) was developed to simulate forest dynamics on Changbai Mountain in China, an area famous for its rich tree species and forest type diversity. The initial tests of the FAREAST model included a simulation of forest composition and basal area at different elevations on Changbai Mountain and then at other sites in China, the Russian Far East, and Siberia (Yan and Shugart 2005). Further testing of the model at 223 sites across Russia (Shugart et al 2006) indicated that FAREAST accurately simulates patterns in leaf area and forest biomass across a large, climatically diverse area.

In this study the model is further expanded to simulate forest composition and biomass at over 2000 sites across the former USSR. Model output is then compared to detailed forest structure data from Russia and a climate sensitivity analysis is performed in order to test the ability of this model to simulate changes in forest structure and composition in response to climate change. In particular, we evaluated the ability of the model to accurately simulate biomass at different forest successional stages by comparing model output from different sites at different ages to inventory data collected in forests that had been disturbed at different times and where therefore different ages. This exercise is intended to reveal how far the model can be extrapolated from the area of initial development and, in particular, whether it is appropriate to apply this model to boreal forests across Russia, for this reason no efforts have been made to ‘tune’ the model. If the model accurately simulates forest conditions over a large geographic area with widely varying climatic conditions, then the model will likely be useful in making predictions regarding the effect of future climate change on forest structure at a particular location.

2. Methods

2.1. Model simulation across Eurasia

FAREAST was run at a total of 2083 sites across the former USSR. FAREAST uses monthly climate parameters derived from historical station data to compute daily temperature and update soil water. In particular, at each site, the model’s climate inputs are drawn from a statistical distribution of monthly values for minimum and maximum mean temperature and precipitation which is derived from 60 years of data recorded at local weather stations (NCDC 2005a, 2005b). The model also uses values for soil field capacity and soil carbon and nitrogen which were obtained from Stolbovoi and McCallum (2002) for each site.

The birth, growth, and eventual death of individual trees are determined in response to local site parameters such as soil moisture and nutrient availability, which are updated annually with bio-environmental conditions, soil moisture and available nutrients (Yan and Shugart 2005). Individual trees compete for light and nutrients with stochastic processes governing the birth and death of trees in a circular twelfth hectare plot, which approximates the size of a mature tree crown. Forty-four individual tree species are included in...
FAREAST simulations, and can be grouped into ten genera (Abies spp., Betula spp., Larix spp., Picea spp., Pinus spp., Populus spp., Tilia spp., Quercus spp., Fraxinus spp., and Ulmus spp.) and two collections of less common species (other deciduous and other coniferous). These species represent the genera which dominate Northern Eurasian forests. Each species is characterized by 25 parameters which describe the species’ fundamental silvics and determine which species has an advantage in terms of competition for light or nutrients, or tolerance to lack of water (Yan and Shugart 2005). At each of the 2083 sites, 200 independent twelfth hectare plots were simulated and then the modeled biomass values were averaged for each species in each year of the model run.

2.2. Validation of the model output

Biomass values produced by the model were validated at sites in proximity to forests with available inventory data, 82 of the 2083 model sites, (Shuman 2010) using independent, field collected inventory data from 43 Russian forests. This forest inventory data is drawn from areas with a broad range of climatic conditions and offers a representative sample of different geographic regions and forest types within Russia (Krankina et al. 2005). Field measured values for total aboveground biomass of trees in different age cohorts within stands dominated by Abies spp., Betula pendula, Larix spp., Picea spp., Pinus sibirica, Pinus sylvestris and Populus spp. were compared with model output via linear regression analyses. Model data was matched to inventory data based on geographic proximity of the inventory and weather station sites and on the age and species of the field measured trees. Data for Abies spp., Larix spp., Picea spp., and Populus spp. are summarized by genus in accordance with the measurement style of the inventory data.

2.3. Climate sensitivity analysis

The climate sensitivity analysis evaluates the response of total forest biomass at 2083 sites across Eurasia to six climate change scenarios (table 1). These climate scenarios are based on more conservative predictions of temperature and precipitation increase that are made by General Circulation Models (GCM) for portions of Eurasia (IPCC 2001). For the first scenario, no changes are made to values drawn from the distributions of monthly temperature and precipitation data that were derived from the records for 2083 weather stations and are described above. For the other climate scenarios a linear increase in temperature or precipitation or both takes place from year zero to year 200 of the simulation. This is followed by an additional 300 years of simulation during which the climate stabilizes around the conditions attained in year 200. For each model run, biomass values for different species were summed to obtain a total, average value for biomass for each site.

A non-parametric factorial ANOVA was used to assess differences in total forest biomass (tCha⁻¹) output among model runs that employed different climate scenarios at ten year intervals (SAS v. 9.1, SAS Institute Inc 2002). This ANOVA is an extension of the Kruskal–Wallis test devised by Scheirer et al (1976). The procedure tests the sums of squares from the ranks of data divided by the total mean square and considers the ratio, which is identified by the variable ‘H’, as a χ²-distributed variable with degrees of freedom pertaining to the sum of squares in the numerator (Sokal and Rohlf 1995). Total biomass values obtained for scenario 1 were subtracted from the values obtained for the other five scenarios and the calculated differences were displayed in ArcGIS in order to explore regional differences in the impact of climate change on forest biomass.

3. Results and discussion

3.1. Validation of the model across new geographic area

Correlations of model biomass to forest inventory biomass are strong for multiple species suggesting that the model is accurately simulating species biomass at different forest ages, and therefore at different stages of forest succession, across the Russian region (figure 1). The average $R^2$ ($p < 0.05$) across all species is 0.75 for 85 comparisons. The model shows particularly strong performance for accurately simulating Larix spp. with an average $R^2$ of 0.75 for 46 comparisons ($p < 0.05$). Since Larix spp. is not harvested for timber, the inventory measured biomass is a reflection of natural biomass accumulation for Larix spp. As a result, the linear regression analysis for Larix spp. indicates that the model is accurately simulating natural biomass accumulation for this genus in response to successional patterns within mixed species forests. Overall, results of this model validation increase confidence that FAREAST is a robust model of Russian forest dynamics and therefore appropriate for use across the Russian region. This and other studies (Bugmann and Solomon 2000, Zhang et al 2009) show that composition and aboveground biomass for forests in broad environmental conditions can be predicted successfully using a single forest model.

3.2. Climate sensitivity analysis

The non-parametric factorial ANOVA results showed that the scenarios which involved either an increase or decrease in precipitation (scenarios 2, 3) were significantly different from scenario 1 (i.e. the baseline simulation, $p < 0.05$) at multiple time points. More specifically, this difference is significant starting at year 160 and extending to the end of the simulations. However, the temperature effect alone (scenario 4) and the interaction between a change in temperature and precipitation (scenarios 5 and 6) were not significantly different from the

| Scenario no. | Changes in temperature (%C) | Changes in precipitation (%C) |
|--------------|----------------------------|-------------------------------|
| 1            | No change                  | No change                     |
| 2            | No change                  | +10%                          |
| 3            | No change                  | −10%                          |
| 4            | +2                         | No change                     |
| 5            | +2                         | +10%                          |
| 6            | +2                         | −10%                          |

Table 1. Climate change scenarios used in sensitivity analysis.
Figure 1. Linear regression R-squared results of model to inventory species biomass (tCha\(^{-1}\)) for Abies spp. (pink), Betula pendula (green), Picea spp. (red), Pinus sibirica (blue), Pinus sylvestris (purple), Populus spp. (white), Larix spp. (yellow). All comparisons are significant to \( p < 0.05 \).

Figure 2. Simulated total forest biomass for baseline scenario 1, which uses temperature and precipitation data derived from historical weather station records. Biomass values range from 0 to 222 tCha\(^{-1}\) for mixed species forests at 2083 sites 200 years from bare ground.

baseline and altered precipitation (scenarios 2, 3) simulations, respectively. Results from the scenarios involving an increase or decrease in precipitation suggest that a shift in the precipitation pattern has a long lasting impact on the total forest biomass. The timing of the significant precipitation effect (year 160) may be explained in terms of the patterns of maturation and mortality within forest stands. In particular, the forests may be undergoing shift in dominance from mature individuals of one species to juveniles of another that makes the system more sensitive to an increase or decline in precipitation. Such mixed species forests may therefore be most sensitive to climate change during transition points within their successional history. Further exploration of the sensitivity of the forest total biomass and succession dynamics to temperature change is warranted, as this study utilized a modest temperature rate increase spread across two centuries. In particular, it would be useful to increase the amount of warming or decrease the time in which warming occurs. The results of this study, which finds a response to water stress, but no response to modest temperature change, are in agreement with previous studies on the effects of climate change on north and south-facing slopes of boreal forests in Fairbanks, Alaska. There, the colder north-facing slopes were largely unaffected, but the relatively warmer south-facing slopes were strongly affected by the change in climate. On south-facing slopes the limiting condition appeared to be moisture stress and not a direct consequence of temperature change (Bonan et al 1990). Analysis on tree rings to determine the effects of the current run of warmer than usual decades in the Fairbanks area on White Spruce stands found evidence which confirmed the predicted moisture-stress-mediated effect as suggested by the modeling study (Barber et al 2000). Climate change studies must therefore address temperature warming in conjunction with associated precipitation changes.

The results for the baseline simulation (climate scenario 1) indicated high values of biomass across the Russian Far East and European Russia after 200 years of simulation (figure 2). This corresponds to the pattern noted by Houghton et al (2007) in maps of forest biomass created by combining inventory data and remote sensing data from the MODIS land-cover product.
Figure 3. For all figure parts, decreasing biomass is shown in pink and increasing biomass is shown in green. Figure shows difference in magnitude of total forest biomass (tCha$^{-1}$) for year 200 between baseline scenario 1, no change in climate, and: (a) climate scenario 2, +10% precipitation, overall pattern is towards increasing biomass; (b) climate scenario 3, −10% precipitation, the pattern is toward decreasing biomass; (c) climate scenario 4, 2 °C increase, decreasing biomass in response to increasing temperature is seen at western and southwestern sites, but response across the region is not consistent.

(MOD12Q1) (Schaaf et al 2002) and the GLC2000 land-cover product (Bartalev et al 2003). The results of climate scenarios which altered precipitation by either increasing or decreasing precipitation by 10%, scenarios 2 and 3 respectively, showed little similarity to one another. Climate scenario 2, which increased precipitation, induced an increase in total biomass across most of Russia with some locations in the southwestern areas showing no change in biomass when compared to the baseline simulation (figure 3(a)). Alternately, climate scenario 3, which decreased precipitation by 10%, led to an overall decrease in biomass across most of Russia (figure 3(b)). The patterns of biomass change in response to increased temperatures (scenario 4 figure 3(c)), are similar to, but less consistent and widespread than, those seen for scenario 3.
 Specifically, a decrease in biomass is seen at western and southwestern sites, but the response to increased temperatures in the remaining sites is not uniform and shows no clear pattern.

The overall response of Russian boreal forests to climate change when the effects of changes in temperature and precipitation are separated show higher average precipitation leads to increased biomass (figure 3(a)), lower average precipitation results in decreased biomass (figure 3(b)), and warming decreases in biomass for certain regions, though in parts of Siberia, where average temperatures are extremely low, warming induces an increase in forest biomass (figure 3(c)). There are also genera specific patterns in the shifts in biomass that occur across Russia. Specifically, there are different patterns of change for Larix spp. and Pinus spp. in response to temperature warming. Both genera display a decrease in biomass in western and southwestern Russia and the Russian Far East. The number of sites that experience a biomass decrease for Larix spp. is larger than the number of sites that show a decline in Pinus spp. In particular, the sites that show a decline in Larix spp. extend further northward in both European Russia and the Russian Far East. A more detailed analysis is required to determine whether these patterns are the result of a replacement of Larix spp. with Pinus spp.

There are sites which are not consistent with the general response to changes in precipitation and temperature. These inconsistent results may be explained in terms of the species that are simulated in the FAREAST model. The Russian Far East and northern China, where the model was created, are famous for their rich tree species diversity (Yan and Shugart 2005). As a result, the model has information on 44 tree species, several of which are not found outside the area where the model was developed and therefore do not occur at a large percentage of the 2083 sites used in this study. Six genera of trees (Pinus, Picea, Abies, Larix, Betula, and Populus) cover 87.4% of the forested areas in Russia, and, of those six dominant genera, four coniferous genera cover 71.1% of this forested area (Shvidenko and Nilsson 2003). The differences between the large number of tree species in the Russian Far East bordering China and the low diversity of tree species across the remainder of Russia are the result of cooling during the late Tertiary and subsequent glaciations during the Quaternary period which vastly reduced tree species diversity across much of Russia (Hytteborn et al 2005, Qian et al 2003). Therefore, in this study by using the model with a species set representative of the Russian Far East some of the species were simulated well outside their natural range and, at some sites, species whose ranges do not overlap in nature were competing with one another in the model runs. As a result sites which show inconsistent changes in biomass in relation to altered climate may be explained in terms of the presence of species, within the model, which are not naturally occurring in that region. These species may not be adapted to local climatic conditions and may therefore respond to an altered climate in an unexpected fashion.

4. Conclusion

We have expanded the geographic range of the FAREAST model across Eurasia using extensive climate and soil datasets and have validated this expansion with forest inventory data. The model retains its original species list and was not adjusted in order to improve its performance. The model in this original format successfully captures the natural biomass dynamics of mixed species forests across the vast geographic area and varied climatic conditions of Russia. Results of the climate sensitivity analysis indicate that changes in precipitation have an impact on total forest biomass relatively early in the successional history of the forest. Furthermore, mixed species forests may be particularly sensitive to climate change during shifts in species dominance or other key points in their succession. The effect of moderately increased temperature and the interaction between a change in temperature and precipitation were not found to be significantly different, respectively, from the baseline simulation and simulations which altered precipitation only. Examination of maps of changes in the magnitude of total biomass associated with the precipitation and temperature treatments showed that biomass increased with increasing precipitation and decreased with water stress and warming. Areas which do not follow these biomass trends highlight the need to re-parameterize the model to reflect species ranges across Russia. The geographic expansion and validation of the model along with our climate sensitivity analysis indicate that it is appropriate to apply this model in future tests of a feedback between climate and land-cover change in the boreal forest. In particular, this model can be used to perform a detailed analysis of forest species composition shifts in response to elevated atmospheric CO2 levels and global temperatures.

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