

Assessment of carbon stores in tree biomass for two management scenarios in Russia

Jacquelyn K Shuman^{1,3}, Herman H Shugart¹ and Olga N Krankina²

¹ Department of Environmental Sciences, University of Virginia, Clark Hall, 291 McCormick Road, PO Box 400123, Charlottesville, VA 22904-4123, USA

² Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR 97331, USA

E-mail: jkshuman@virginia.edu, hhs@virginia.edu and olga.krunkina@oregonstate.edu

Received 31 May 2013

Accepted for publication 14 October 2013

Published 30 October 2013

Online at stacks.iop.org/ERL/8/045019

Abstract

Accurate quantification of terrestrial carbon storage and its change is of key importance to improved understanding of global carbon dynamics. Forest management influences carbon sequestration and release patterns, and gap models are well suited for evaluating carbon storage. An individual-based gap model of forest dynamics, FAREAST, is applied across Russia to estimate aboveground carbon storage under management scenarios. Current biomass from inventoried forests across Russia is compared to model-based estimates and potential levels of biomass are estimated for a set of simplified forestry practices. Current carbon storage in eastern Russia was lower than for the northwest and south, and lower than model estimates likely due to high rates of disturbance. Model-derived carbon storage in all regions was not significantly different between the simulated 'current' and hypothetical 'even-aged' management strategies using rotations of 150 and 210 years. Simulations allowing natural maturation and harvest after 150 years show a significant increase in aboveground carbon in all regions. However, it is unlikely that forests would be left unharvested to 150 years of age to attain this condition. These applications indicate the value of stand simulators, applied over broad regions such as Russia, as tools to evaluate the effect of management regimes on aboveground carbon storage.

Keywords: modelling, boreal forest, biomass, carbon, validation

1. Introduction

Russia contains half of the global area of boreal forest (FAO 2006) and its forests are the largest in area of any nation. Because of this vast extent as well as the important global role of the Russian boreal forest, multiple estimates have been made of its carbon stores. These estimates for average biomass range from 72.6 to 167.4 Mg ha⁻¹ (Dixon *et al*

1994, Krankina and Dixon 1994, Isaev *et al* 1995, Krankina *et al* 1996, Turner *et al* 1998, Alexeyev and Birdsey 1998, Shvidenko and Nilsson 2002, 2003, Houghton *et al* 2007), and net flux of carbon estimated over a range from a source 0.5 PgC yr⁻¹ to a sink of 1.02 PgC yr⁻¹ in a review of 15 studies by Shvidenko *et al* (1996) and Goodale *et al* (2002). While several comparative studies have attempted to resolve these differences in estimates (e.g., Krankina *et al* 1996, Houghton *et al* 2007), Russia remains the nation with the most divergent estimates of carbon stores and fluxes from forest ecosystems. This variation contributes significantly to the uncertainty of global estimates. Improved quantification of aboveground biomass and the impact of management policy



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](http://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

³ Author to whom any correspondence should be addressed.

decisions on forests is an important part of informing policy decisions of the Kyoto Protocol, which was ratified by Russia in 2004, and the follow-on international agreements from the Kyoto Agreement.

Towards the objective of improved quantification of the Russian forest-carbon storage and dynamics, we are applying a forest gap model (Shugart and West 1980) called the FAREAST model (Yan and Shugart 2005) and using a comparison to current biomass inventory to explore the impacts of disturbance and management on the structure and composition of Russian forests. Gap models are a class of individual-based models (IBMs) that simulate the dynamics of individual trees on an idealized set of forest survey plots (Shugart 1984, Porté and Bartelink 2002). The parameters of the FAREAST model quantify well-appreciated biological processes (e.g., death, regeneration, and individual growth as influenced by environmental conditions) and straight-forward representations of element cycling (Pastor and Post 1988, Hobbie *et al* 1998), moisture dynamics (Yan and Shugart 2010), and radiation fluxes in plant canopies (Gu *et al* 1999a, 1999b).

Output from the FAREAST model, as with other gap models, resemble vegetation field survey data—inventories of numbers, sizes and species of each tree on a plot of land. Thus, both detailed and summarized field survey data are useful for testing simulation results. The FAREAST model has been validated against independent data for its ability to simulate: species composition and basal area changes on altitudinal gradients and for composition over a wide geographical region in eastern Russia (Yan and Shugart 2005); Successional dynamics for forest locations in China and Russia (Yan and Shugart 2005); biomass dynamics for multiple locations in Russia (Shuman *et al* 2013).

An assessment of the impact of stand management regimes on forest biomass requires that the model accurately reflect biomass accumulation within the forests measured, so successful performance in past model validation, as detailed above, is an important component of this exercise. Stand management controls and alters the stand age distribution of forests which in turn alters aboveground carbon storage. The structure of the boreal forests of Eurasia is highly dynamic with significant differences across this region driven in large part by disturbance history. In more densely populated areas of Russia (primarily western parts) logging is the primary forest disturbance factor that shapes the pattern of carbon sources and sinks (Krankina *et al* 2002, 2004). The time since disturbance that initiated a forest stand, and thus age class structure, is an essential control on the role of forests in carbon exchange with the atmosphere that is not accounted for in most models, but is included explicitly in gap models and a necessary component of projecting carbon dynamics in this region. The objective of this analysis is to use FAREAST to quantify and compare aboveground tree carbon in regions with variable disturbance histories for three management scenarios characterized by various age cohort distributions. These comparisons will help to explore the impact of management on aboveground carbon storage. The aboveground biomass storage derived using the model when

compared to the current forest condition is used to answer three questions. (1) Is the simulated estimate of biomass for the current mix of age classes significantly different from actual current biomass? (2) Would a change in management needed to produce equal areas of each age class of forest result in a simulated forest with significantly different biomass than the current actual biomass or simulated current biomass? (3) If the forests could be shifted to maturity, would the biomass be significantly greater than for the current actual, current simulated or uniform age distributions?

2. Methods

2.1. Model description and justification

In the past 20 years, IBMs have been used to provide increasingly accurate simulations of forests for current and past conditions (Mladenoff 2004). Applications of these models include investigation of forest disturbance and succession, evaluation of stand management, and for predictions of forest response to altered climate. The individual-based gap model FAREAST (Yan and Shugart 2005) was developed to simulate the forests of Changbai Mountain on the border of the People's Republic of China and the Democratic People's Republic of Korea, an area famous for its rich tree species and forest-type diversity. Yan and Shugart (2005) found that FAREAST simulated forest composition along an elevation gradient on Changbai Mountain in China. It also matched compositional features in Chinese forest inventory data and agreed with independent, more qualitative comparisons to observed forest types at 31 sites in the Russian Far East. Linear regression analysis comparing simulated to inventory measured biomass for application of FAREAST at over 2000 sites across Russia without limiting species to their range limits (i.e. all species present at all sites) showed that model and inventory biomass were statistically similar; these results suggested that range limits and species mix or presence were not controlling biomass levels across the region, and climate was theorized to be the regulator (Shuman and Shugart 2009). Validation utilizing independent data from sites across Russia and with the added modelling restraint of limiting species to their published ranges showed that the model accurately captures natural biomass accumulation rates for the Russian forest (Shuman *et al* 2013). These results greatly expands the area from that previously analysed by Yan and Shugart (2005) and confirms their qualitative results comparing simulated and observed forest types for the Russian Far East through the use of quantitative, independent forest inventory biomass data for a comparison.

For this study, simulation is used to estimate the aboveground tree carbon biomass of each of three regions under different age cohort distributions as a proxy for various management scenarios. Inventory sample estimates of the current percentage of forest cover by age cohorts and simulated biomass for each of the stand ages is used to calculate the biomass contribution per cohort for each inventoried forest. These cohort biomass estimates are

summed to obtain a total biomass value for the forest. In separate calculations the cohort age distribution is adjusted to represent a heavily managed forest condition by using an equal percentage of forest land area in each 10 year age cohort and a condition without management where the forests are allowed to attain a mature state. Forest biomass values are calculated using the derived stand age distributions and simulated biomass values. This application reveals the potential capacity for increased aboveground biomass storage across the Russian regions under different management schemes.

A general description of sub-routines and parameters from the FAREAST model is included below; a more detailed description can be found in Yan and Shugart (2005). The model is initiated from bare ground for independent sample plots found at a geographic site, and tracks individual trees through time at each plot. FAREAST uses monthly climate variables 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). Values for soil variables including field water holding capacity, carbon and nitrogen are derived from Stolbovoi and McCallum (2002) for each site. The birth, growth, and eventual death of individual trees are determined in response to local variables initialized with site conditions for soil field capacity, soil carbon for the top two layers (Ao and humus layers) and plant available nitrogen pool, which are all updated annually in response to changing bio-environmental conditions, soil moisture and available nutrients. In gap models, individual trees compete for light and nutrients with stochastic processes governing the birth and death of trees on a circular plot. Within FAREAST nutrient competition among individual trees determines biomass accumulation and annual leaf and fine root renewal. This competition is computed annually according to a mass balance approach which tracks the movement of carbon and nitrogen from the soil into the individual trees for growth, which contributes to litterfall which then returns to the soil to again be included in the available nutrient pool. Without sufficient nutrients on the plot, the growth of trees according to the diameter increment is cut back accordingly. The plot size must be large enough for the effect of large trees suppressing the growth of subordinates and the death of a large tree to be manifested as an abrupt and significant change in the plot micro-environment. This size is a function of tree height, crown width and latitude (Kuuluvainen 1992) and the one-twelfth hectare plot size used in the FAREAST model is in the size range in which both competitive suppression and stand release occur in this class of models (Shugart and West 1979).

Fifty-seven individual tree species are included in this version of the FAREAST model, 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. 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, the four coniferous genera cover 71.1% of this forested area (Shvidenko and Nilsson 2003). Species are included in simulation for each location, hereafter called sites, from range maps created for this study in ESRI ArcGIS (2008) using range information adapted from Nikolov and Helmisaari (1992) and Hytteborn *et al* (2005). At the start of simulation for each site, all potential species whose range indicates their presence are available for colonization. Individual species characteristics, including light, nutrient and water demands, define which species establish and survive during succession. For example, *Larix* spp. are strongly light demanding, and so colonize in early succession, but once the canopy becomes fully mature, *Larix* spp. are slowly replaced by shade-tolerant evergreen conifers.

Twenty-five parameters describe each species' fundamental silvics and determine which species has an advantage in terms of competition for light or nutrients, or tolerance to lack of water. Individual species growth and demography are characterized by allometric equations for growth, with a separate rate for early and late growth that is responsive to the vertical light environment, as well as site values for the flux and storage of water, organic carbon, and plant available nitrogen. Successional dynamics are therefore a result of competition between tree species for light and nutrients, as well as limitations to growth imposed by local environmental conditions.

At each of the sites, 200 independent twelfth hectare circular plots (replicates) were simulated starting from bare ground and then the biomass values were averaged for each species in each year. Estimated biomass for a given age cohort is therefore an average of the standing biomass for all 200 plots at the same simulated time since stand initiation. The biomass accumulation results are the integral of the difference between the growth rate and the mortality rate of all the plants on each simulated plot. The plots are independent from one another but are responding to the same climate conditions. This is a Monte Carlo simulation of a landscape of indeterminate size sampled with a system of independent sample plots with the same climate and soil conditions. Thus, the average of the simulation corresponds to a shifting-mosaic steady-state landscape. Analysis of convergence of average species-specific biomass values finds that 150–200 replicate plots are necessary to provide a sample which approximates the landscape response of the forest (Bugmann *et al* 1996).

2.2. Comparison of regional aboveground tree biomass

Simulation with the FAREAST model was completed for 82 sites with meteorological data within 125 km to forests with available independent, field collected inventory data from 40 Russian forest management enterprises (further called inventoried forests; Krankina *et al* 2005) (figure 1). Inventoried forest data for total stem volume of trees within stands dominated by *Abies spp.*, *Betula pendula*, other

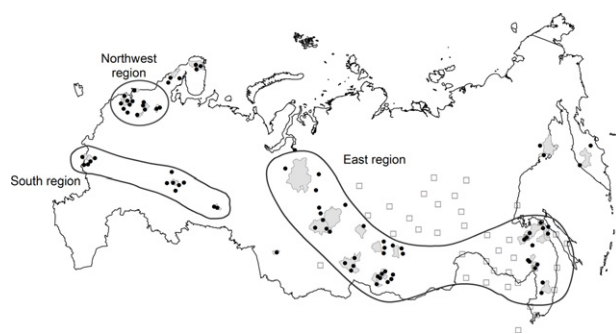


Figure 1. Map of Russia with locations of forests, model simulation sites, and region groupings for standing biomass analysis. Forests shown shaded in grey, model simulation sites shown as black circles, and sites from Yan and Shugart (2005) shown as open squares. Regional analysis sites circled in grey with northwest, south and east regions labelled.

Betula spp., *Larix spp.*, *Picea spp.*, *Pinus sibirica*, *Pinus koraiensis*, *Pinus pumila*, *Pinus slyvestris*, *Populus tremula* and other *Populus spp.* were averaged for 10-year age cohorts and converted to stand biomass using conversion factors differentiated by tree species, vegetation zone, and geographic region from Alexeyev and Birdsey (1998) as described in Krankina *et al* (2005). The standard practice for these forest inventories was based on field census of trees on plots of a given age. Field crews measure all of the trees on a number of individual forest stand polygons (a homogeneous patch of forest vegetation), ranging in size from 0.3 to 100 ha to obtain an overall forest inventory. This process is repeated at intervals ranging between from 10 to <20 years. The standard set of data gathered included site productivity and drainage, tree species composition, mean height, diameter and age (rounded to the nearest 10 years for stands older than 50 years), canopy structure, wood volume, and characteristics of different types of land without tree cover (clearcuts, bogs, meadows). The average biomass values in the 10-year age classes form a set of sequences of expected biomass inventory as a function of stand age and major dominant tree species. Even though the stands of different ages all exist at the current time they can—approximately—represent the biomass in stands over time in 10-year increments. This is termed a substitution of space (stands of many ages over a landscape)-for-time (viewing the stands as occurring over time rather than space). The sources of variation in a space-for-time substitution (different soils, prior weather history, etc) introduce additional error variability to the biomass/time relationship. These inventoried forest data were drawn from areas with a broad range of climatic conditions and provide a representative sample of geographic regions and forest types within Russia.

For each site biomass values produced by simulation were weighted by the area of 10-year age cohorts for three different cohort age structures: (1) a ‘current’ age distribution according to the stand age distribution as provided by independent inventoried forest data collected from 40 inventoried Russian forests described above from Krankina *et al* (2005), (2) an ‘even-aged’ distribution, or managed forest

condition, where the percentage of biomass contribution of each 10 year age cohort is equal, and (3) a ‘mature’ forest condition which is taken from the simulation results for a mature forest after 150 years of growth from bare ground. These simulated mature forests do not have external disturbances, such as fire, but internally the death of large trees produces a landscape which is a mosaic of forest stand ages. The inventoried forests were grouped into three regions: the northwest, south, and east, each of which have distinctive historical disturbance and harvest regimes (figure 1). These disturbance regimes are discussed in more detail in the results section 3.1.

The ‘current’ age distribution is based on data from inventoried forests which provide the percentage of forest cover in each 10 year age cohort; regional patterns are shown in figure 2. The simulated total biomass for each 10 year interval was derived by using the percentage forest cover per age cohort as described by the data from inventoried forests multiplied by the simulated biomass to calculate the biomass contribution per cohort for corresponding simulation sites and inventoried forests. In an inventoried forest with 100-year old stands making up 5% of the total forest area, the matching simulated biomass is adjusted according to this 5%. So, at the matching simulation site if total simulated biomass 100 years after stand initiation is 60 tC ha⁻¹, then the biomass contribution for the 100-year age cohort is 60 × 5% or 3 tC ha⁻¹. This procedure is repeated for each 10 year age class, and the cohort biomass contributions are summed to obtain a total biomass value for the forest. The ‘even age’ distribution has the same percentage of age cohorts present (equal areas of each age class) in the forest to a maximum cohort age of 150 years (a 150-year sustainable harvest rotation) as one case and up to 210 years in another. The ‘mature’ biomass value is the simulated total biomass for an unmanaged mature forest 150 years from bare ground applied across the region. Analysis of variance with a Duncan’s test was completed by region to assess differences in aboveground biomass by treatment: inventory current actual, current simulated, even distribution to a maximum age of 150 years, even distribution to a maximum age of 210 years, and mature. All calculations were completed in SAS v9.1 (2002).

3. Results and discussion

3.1. Quantification and comparison of regional aboveground tree biomass

3.1.1. *Is the simulated estimate of biomass for the current mix of age classes significantly different from actual current biomass?* The inventory measured aboveground biomass for the east region (table 1, figure 3) was significantly different from the simulation estimate of current biomass, while the south and northwest inventory measured biomass values were not significantly different ($p < 0.05$) to the simulation estimate of current biomass. The current pattern of forest stand age cohort distribution in the boreal forest across Russia is a result of the effects of anthropogenic and natural disturbances over a range of time scales (Krankina *et al* 2005).

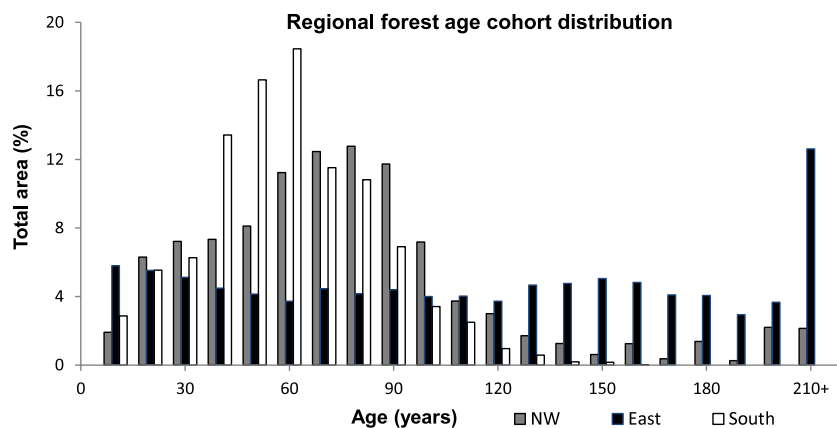


Figure 2. Average age cohort distribution for forests from regions in the northwest (grey), east (black) and south (white).

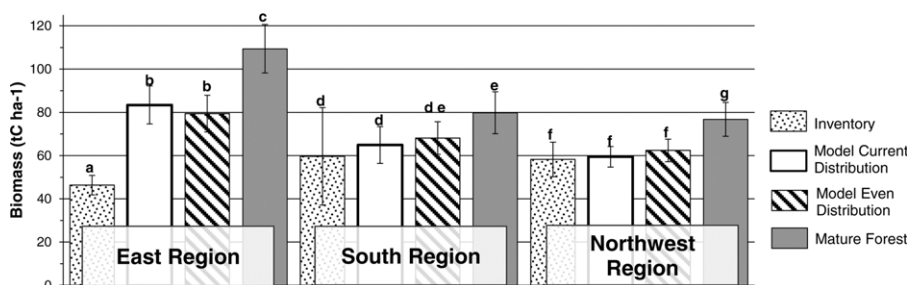


Figure 3. Average forest biomass for the east, south, and northwest regions shown with 95% confidence intervals for 40 inventoried forests from Krankina *et al* (2005), which are shown as stippled light grey, simulated current-age cohort distribution (solid white), simulated even-aged cohort distribution with a maximum stand age of 210 years (black diagonal), and a simulated 150-year old unmanaged mature forest condition (solid grey). Analysis of variance with a Duncan test was completed by region to assess differences in aboveground biomass. Within the regions a difference of letters indicates significantly different biomass values ($p < 0.05$).

Table 1. Average biomass (tC ha⁻¹) for regions and age distributions.

Region	Age distribution	Data source	Mean biomass	N	Standard deviation	Lower 95% CI	Upper 95% CI
East	Inventory	Inventory	46.37	24	10.75	41.83	50.91
East	Current	Modelled	83.42	55	32.41	74.66	92.18
East	Even (150 max)	Modelled	69.21	55	29.95	61.11	77.30
East	Even (210 max)	Modelled	79.42	55	31.53	70.89	87.94
East	Mature	Modelled	109.41	55	41.47	98.20	120.62
South	Inventory	Inventory	59.65	5	18.14	37.12	82.18
South	Current	Modelled	64.89	13	14.16	56.33	73.44
South	Even (150 max)	Modelled	62.12	13	11.10	55.41	68.83
South	Even (210 max)	Modelled	68.11	13	12.42	60.61	75.62
South	Mature	Modelled	79.81	13	16.08	70.10	89.53
Northwest	Inventory	Inventory	58.25	7	8.60	50.30	66.20
Northwest	Current	Modelled	59.45	14	8.20	54.71	64.18
Northwest	Even (150 max)	Modelled	56.20	14	7.07	52.11	60.28
Northwest	Even (210 max)	Modelled	62.41	14	9.02	57.20	67.62
Northwest	Mature	Modelled	76.72	14	13.57	68.89	84.56

Unlike harvest, which has preferential selection of stands of a particular age or size for stem removal, fire is stochastic and can remove stems at all age classes (Krankina *et al* 2005). Within the regions analysed the distribution of age cohort distribution suggests variable disturbance regimes (figure 2). The disparity between the inventory measured and simulated results for the east region is likely caused by disturbance regime effects captured in the inventory and not included in the modelling processing.

The east region, dominated by Siberia, is characterized by frequent wildfires of variable intensity and size, insect outbreak and increasing rates of harvest (Bonan and Shugart 1989, Lyamzev and Isaev 2002, Vandergert and Newell 2003, Sukhinin *et al* 2004, Soja *et al* 2004, 2007). There are studies which highlight the growing problem of illegal logging in Siberia and the Russian Far East, theorized to be connected to increased demand from China (Vandergert and Newell 2003, Newell 2006, Henry and Douhovnikoff 2008). Except

for the preponderance of very old stands, the rest of the age class distribution is nearly even-aged with equal areas of the age classes in the east region and reflects the stochastic nature of these different disturbances (figure 2). Old growth stands within inventoried forests are likely to have gone through disturbance events (fire, insect outbreak, and logging) which will remove understory and select trees therefore reducing overall standing biomass. Disturbance effects of fire, insect damage and logging are not explicitly included in these simulations using the FAREAST model; therefore the model can produce higher biomass estimates compared to the inventory-based estimates (table 1, figure 3). The model calculates the statistical properties of an age cohort as the predicted forest composition and structure following a stand initializing event. Over time trees are removed within the model by natural mortality events, but the decrease in biomass is not similar to the removal characterized by illegal harvest or large wildfires. Thus, simulated stands of ages 150 years and older have higher levels of biomass relative to the inventoried stands. Results for the east region highlight the importance of incorporation of disturbance history in carbon accounting methods and projections.

The inventory and simulated current biomass values for the northwest and south regions are statistically similar. The high proportion of older stands found in the east are not found in the northwest and south regions (figure 2) and do not produce the overestimate of biomass when compared *in toto* to the simulation. The northwest and south regions include the forests of European Russia, which historically had intense harvest during the post-war period continuing into the early 1970s thus removing a large portion of the forest from the cohort which would now be classified as 'older stands' greater than 100 years old (Pisarenko and Strakhov 1996, Henry and Douhovnikoff 2008). This period of intense and sustained harvest during wartime followed by a period with a lack of harvest during the economic collapse of the Soviet Union resulted in a larger than normal percentage of stands between 50 and 70 years in the south and northwest respectively (figure 2). The structure of these forests in the south and northwest of Eurasia will be highly dynamic with significant differences across this region driven in large part by disturbance history and future management scenarios.

3.1.2. Would a change in management needed to produce equal areas of each age class of forest result in a simulated forest with significantly different biomass than the current actual biomass or simulated current biomass? For a forest with an even distribution of age cohorts and rotation age of 210 years, the aboveground biomass was significantly different from the current actual biomass in the east region only; comparisons between regional biomass for the simulated current in the east, and current actual and simulated current in the south and northwest were statistically similar (figure 3). The results indicate that a conversion from the simulated current forest state to a managed forest condition with an even distribution of age cohorts, with a maximum age of a 210-year-old stands, would not significantly alter aboveground biomass values compared to simulated current

distributions in any of the regions measured. In the south and northwest, this similarity between the biomass for the current actual and the even-aged distributions suggests that natural disturbance and harvest have resulted in aboveground biomass similar to that of simulated active forest management without natural disturbance. A management scenario of even-aged harvest maintains an equal proportion of trees in stands across all stand ages, but the biomass is heavily concentrated in the older stands. Though the overall biomass contributions are collectively similar between the current and even-aged distribution, the exploitation and unsustainable wood production generates forest stand age distributions that are not stable and thus not suited for long term harvest in these regions (Angelstam *et al* 1995, Pisarenko and Strakhov 1996, Krankina *et al* 2004). An example of this type of unstable forest stand age distribution in the vicinity of St Petersburg shows a large cohort of 60–70 year stands as a result of extensive logging and agricultural land abandonment in early 20th century (Krankina *et al* 2004). This largest cohort of forest stands is at or past peak carbon accumulation in biomass. Increased accumulation of carbon in tree biomass will only occur if timber harvest rates increase to reduce this largest cohort and replace it with younger trees capable of sequestering more carbon (Krankina *et al* 2004). Concentration of biomass in a small number of cohorts limits the ability of the forest to generate and maintain carbon biomass accumulation, as younger stands are not present in enough quantity to replace older stands.

Decreasing the rotation age for an even-aged distribution from 210 to 150 years does result in decreased biomass in all regions, but this decrease is only statistically significant in the east region. Within the east region the simulated average total standing biomass (tC ha^{-1}) is 69.21 for the 150-year rotation which is significantly lower than the current simulated biomass of 83.42, whereas the 210-year rotation has a simulated biomass of 79.42 (table 1). These results suggest that only the east region has sufficient forest present at these highly mature ages, beyond a stand age of 150 years, to show a response of standing biomass to these differences in rotation periods.

3.1.3. If the forests could be shifted to maturity, would the biomass be significantly greater than for the current actual, current simulated or uniform age distribution? A conversion to a landscape with mature forest condition on all the elements of the landscape would result in increased biomass in all regions, with the greatest increase in the east region. The biomass increase was statistically significant when compared to the current inventory and current simulated for all regions and even-aged distributions for the east and northwest regions ($p < 0.05$) (table 1, figure 3). The simulated mature biomass values are theoretical estimates of the maximum possible carbon storage. The increase seen here for the mature condition would be smaller if natural disturbance was included. Thus, the capacity for increased aboveground biomass in the regions analysed is limited. Given the fire and insect disturbances indigenous to the region, it would be very difficult to maintain extensive landscapes of

mature phase forest for the purpose of accumulating carbon across Russia. The development of management plans with the unusually long rotation periods of 150 or 210 years or maintaining a forest without preferential harvest is unlikely. Even so, these results suggest that such a management, if it could be attained, shows limited capacity for additional aboveground carbon storage.

This analysis does not consider the sink resulting from build-up of downed and dead trees that one might expect in a mature forest mosaic landscape. It does capture the changes in forest stand age distribution that are identified as an important factor in whether a forest acts as a carbon source or sink (Caspersen *et al* 2000, Magnani *et al* 2007). Natural disturbance and forest management strongly affect the size of carbon pools with differences in the rates of carbon release for decomposition and the uptake of regeneration acting as important contributors to changes in carbon pools (Houghton *et al* 1999, 2000, Houghton and Hackler 2000, Luysaert *et al* 2008). There are inherent challenges in quantifying the continued carbon storage in old growth forests and the transition between a forest being classified as a source or sink, as the source or sink transition is tied closely to the stage of growth within the forest and the ratio of growth to senescence. This is made more difficult by disturbance and management schemes. Old growth forests, which have been spared from large stand-replacing disturbances, have been demonstrated to continue to accumulate carbon, though this effect is more pronounced in temperate compared to boreal forests (Luysaert *et al* 2008).

More accurate carbon accounting is an important part of assessing the contribution of the Russian forest to the global carbon budget, and its classification as a source or sink. This requires the forest to be assessed in as much detail as possible across as much area as possible. The data used in this study, though extensive for its coverage of forest types, geographic, and climatic conditions, cannot be easily adapted for coverage across all of Russia. Availability of inventoried forest data which provide the age cohort distribution for the 'current' picture of standing biomass is the primary limiting factor. For simulation of current biomass storage outside of inventoried areas, assumptions regarding disturbance history by region according to surrounding inventoried forests, or application of historical disturbance as characterized by remote sensing data are necessary. Inclusion of disturbance data will likely noticeably improve estimates of biomass for the eastern region, by correcting overestimation in this region. Application of the FAREAST model across Russia for simulation of even-aged and mature standing biomass is not limited by the availability of inventory data, and only requires appropriate climate and soils data which are readily available and data processing capabilities for such a large simulation area.

Large scale simulation for carbon accounting is commonplace, and often utilizes more generalized models for coverage of large areas. This generalization varies based on the model and application. Dynamic global vegetation models (DGVMs) use broad classifications of vegetation as plant functional types (PFTs) which represent simple aggregations

such as broadleaf versus needleleaf or tropical versus temperate, whereas gap models utilize individual species parameters. Purves and Pacala (2008) highlighted the need for improvement of DGVMs and their simulation of forests, and suggested the use of models based around the dynamics of individual trees. There have been examples of cohort-based models, which have the ability to simulate individual species, applied within the boreal forest for the purpose of improved carbon accounting: STANDCARB in St Petersburg (Krankina *et al* 2004), LANDIS-II in a south-central Siberian forest (Gustafson *et al* 2010) and ED2 across northeastern USA and Quebec (Medvigy and Moorcroft 2012). These models are constrained or calibrated against empirical data and use cohort-based dynamics which simplify the physiological responses in the model. These cohort-based models are not intrinsically competitive with IBMs, such as FAREAST: for example, Moore and Noble (1993) developed an automatic system to develop cohort-type models from IBM detailed output and the ED model was initially developed using a gap model to generate the demography (Moorcroft *et al* 2001). Since cohort-based models are based on data derived from or summarized from IBMs, this leads to a generalization of results in cohort-based models.

FAREAST was not calibrated to empirical data and does not use cohort-based dynamics; rather it was parameterized for each individual tree species and considers the life-cycle of each individual tree. We know from paleo-ecological reconstructions in the quaternary have clearly indicated that under past climate conditions novel vegetation that is not found in the present is observed (and vice versa). This presents a challenge in using model calibration as a sole methodology to predict future forests under novel climates. There is no reason to expect such novel vegetation with not occur in the future. FAREAST is of a class of vegetation models that have been used to reconstruct these past novel vegetation types, which give hope that they may be able to do so for future vegetation (see Shugart *et al* 1992, Shugart and Woodward 2011 and many references therein). Of course, there is not a guarantee that past model performance will predict future performance. The point here is *testing* against empirical data (rather than *calibration* to available data) is an alternative procedure. Procedurally, it is a hypothetical-deductive rather than an empirical approach. Given the challenges we face in making future predictions at present, a multiplicity of approaches is likely in order.

The current study's modelling of individual tree birth, growth and death dynamics can be used for simulation of forest biomass change over very large areas and implies that the generalization of these results by cohorts is not necessary. It nonetheless might be potentially expedient, for large scale simulation for carbon accounting. Results for application of FAREAST across all of Russia at over 30 000 simulation locations have already been completed and are being analysed for biomass and productivity in comparison to those results from dynamic global vegetation models. Therefore, simulation at the scale of competition amongst individual trees is possible across this vast region. Given that many of the approaches used for calculations of forest

biomass and composition change compute average changes expected in forests, they necessarily average out some of the variability of the responses of forests. The simulation of all individual trees and their dynamics for hundreds of thousands of plots potentially provides a more complete carbon accounting of the complex dynamics of change within the forest system by capturing the detailed change in the system. The problem of capturing carbon dynamics and forest change at the level of the individual tree applied across large geographic regions does not appear to be computationally limited on modern computers.

4. Conclusion

Quantification of standing biomass across an area as large as Russia is a continued source of uncertainty in global estimates of carbon. The use of a model which has been shown to demonstrate the biomass accumulation for the region provides a powerful tool in evaluating the impact of management on aboveground carbon storage. Modelled biomass accurately reflects aboveground carbon storage as described by the inventory for the current forests in both the south and northwest regions, but overestimates biomass in the heavily disturbed east region. The disparity for the east region is likely explained by the lack fire and insect outbreak in the model, which allows more biomass accumulation across all age classes. Using an even-aged distribution to describe a heavily managed condition, simulation results show that there is not a significant change in aboveground standing biomass compared to current conditions under the assumption that these older age classes will not incur increased effects from landscape disturbance. This reaffirms that the forests are already heavily harvested and a change in management is unlikely to significantly increase standing carbon stores. Within all regions a transition to a mature forest characterized by a 150-year-old unmanaged forest does significantly increase biomass, but the increase is limited and a transition to a fully unmanaged forest condition in these forests is highly unlikely given the economic importance of wood harvest. More active management, however, will alter carbon flux within the forest, with changing carbon pools resulting from harvest and carbon storage in maturing trees. These results suggest that active management of the Russian forests has the capacity to maintain aboveground carbon stores, but that significant increases in aboveground carbon are unlikely.

Acknowledgments

This work was funded by the following NASA grants to H H Shugart: 10-CARBON10-0068, and Climate Change/09-IDS09-116. We are grateful to A D McGuire and the anonymous reviewers who provided detailed helpful comments on earlier versions of this paper.

References

Alexeyev V A and Birdsey R A (ed) 1998 Carbon storage in forests and Peatlands of Russia *General Technical Report NE-244* (Radnor, PA: USDA, Forest Service, Northeast Research Station)

- Angelstam P, Majewski P and S Bondrup-Nielsen 1995 West-east cooperation in Europe for sustainable boreal forests *Water Air Soil Pollut.* **82** 3–11
- Bonan G B and Shugart H H 1989 Environmental factors and ecological processes in boreal forests *Annu. Rev. Ecol. Syst.* **20** 1–28
- Bugmann H, Fischlin A and Kienast F 1996 Model convergence and state variable update in forest gap models *Ecol. Model.* **89** 197–208
- Caspersen J P, Pacala S W, Jenkins J C, Hurtt G C, Moorcroft P R and Birdsey R A 2000 Contributions of land-use history to carbon accumulation in US forests *Science* **290** 1148–51
- Dixon R K, Brown S, Houghton R A, Solomon A M, Trexler M C and Wisniewski J 1994 Carbon pools and flux of global forest ecosystems *Science* **263** 185–90
- ESRI 2008 *ESRI ArcGIS Version 9.3* (Redlands, CA: ESRI)
- FAO (Food and Agricultural Organization of the United Nations) 2006 *Global Forest Resources Assessment 2005* (Rome: FAO)
- Goodale C L *et al* 2002 Forest carbon sinks in the Northern Hemisphere *Ecol. Appl.* **12** 891–9
- Gu L, Fuentes J D, Shugart H H, Staebler R M and Black T A 1999b Responses of net ecosystem exchanges of carbon dioxide to changes in cloudiness: results from two North American deciduous forests *J. Geophys. Res.* **104** 31421–34
- Gu L, Shugart H H, Fuentes J D, Black T A and Shewchuk S R 1999a Micrometeorology, biophysical exchanges and NEE decomposition in a two story boreal forest: development and test of an integrated model *Agric. Forest Meteorol.* **94** 123–48
- Gustafson E J, Shvidenko A Z, Sturtevant B R and Scheller R M 2010 Predicting global change effects on forest biomass and composition in south central Siberia *Ecol. Appl.* **20** 700–15
- Henry L A and Douhovnikoff V 2008 Environmental issues in Russia *Annu. Rev. Environ. Resour.* **33** 437–60
- Hobbie J E, Kwiatkowski B L, Rastetter E B, Walker D A and McKane R B 1998 Carbon cycling in the Kuparuk basin: plant production, carbon storage, sensitivity to future changes *J. Geophys. Res.* **103** 29065–73
- Houghton R A, Butman D, Bunn A, Krankina O N, Schlesinger P and Stone T A 2007 Mapping Russian forest biomass with data from satellites and forest inventories *Environ. Res. Lett.* **2** 045032
- Houghton R A and Hackler J L 2000 Changes in terrestrial carbon storage in the United States. 1. The roles of agriculture and forestry *Glob. Ecol. Biogeogr.* **9** 125–44
- Houghton R A, Hackler J L and Lawrence K T 1999 The US carbon budget: contributions from land-use change *Science* **285** 547–78
- Houghton R A, Hackler J L and Lawrence K T 2000 Changes in terrestrial carbon storage in the United States. 2. The roles of fire and fire management *Glob. Ecol. Biogeogr.* **9** 145–70
- Hytteborn H, Maslov A A, Nazimova D I and Rysin L P 2005 Boreal forests of Eurasia *Coniferous Forests (Ecosystems of the World vol 6)* ed F Andersson (Amsterdam: Elsevier) pp 23–99
- Isaev A, Korovin G, Zamolodchikov D, Utkin A and Pryashnikov A 1995 Carbon stock and deposition in phytomass of the Russian forests *Water Air Soil Pollut.* **82** 247–56
- Krankina O N and Dixon R K 1994 Forest management options to conserve and sequester terrestrial carbon in the Russian Federation *World Resour. Rev.* **6** 88–101
- Krankina O N, Harmon M E, Cohen W B, Oetter D R, Zyrina O and Duane M V 2004 Carbon stores, sinks, and sources in forests of northwestern Russia: can we reconcile forest inventories with remote sensing results? *Clim. Change* **67** 257–72
- Krankina O N, Harmon M E and Winjum J K 1996 Carbon storage and sequestration in the Russian forest sector *Ambio* **25** 284–8
- Krankina O N, Houghton R A, Harmon M E, Hogg E H, Butman D, Yatskov M, Huso M, Treyfeld R F, Razuvaev V N and Spycher G 2005 Effects of climate, disturbance, and species on forest biomass across Russia *Can. J. Forest Res.* **35** 2281–93

- Krankina O N et al 2002 Coarse woody debris in forest regions of Russia *Can. J. Forest Res.* **32** 768–78
- Kuuluvainen T 1992 Tree architectures adapted to efficient light utilization: is there a basis for latitudinal gradients? *Oikos* **65** 275–84
- Luyssaert S, Detlef Schulze E, Börner A, Knohl A, Hessenmoller D, Law B E, Ciais P and Grace J 2008 Old growth forests as global carbon sinks *Nature* **455** 213–5
- Lyamzev N and Isaev A 2002 Forest natural hazards—insects *CD-ROM Land Resources of Russia* ed V Stolbovoi and I McCallum (Laxenburg: International Institute for Applied Systems Analysis and the Russian Academy of Science)
- Magnani F et al 2007 The human footprint in the carbon cycle of temperate and boreal forests *Nature* **447** 848–50
- Medvigy D and Moorcroft P R 2012 Predicting ecosystem dynamics at regional scales: an evaluation of a terrestrial biosphere model for the forests of northeastern North America *Phil. Trans. R. Soc. B* **367** 222–35
- Mladenoff D J 2004 LANDIS and forest landscape models *Ecol. Model.* **180** 7–19
- Moorcroft P R, Hurtt G C and Pacala S W 2001 A method for scaling vegetation dynamics: the ecosystem demography model (ED) *Ecol. Monogr.* **74** 557–86
- Moore A D and Noble I R 1993 Automatic model simplification: the generation of replacement sequences and their use in vegetation modeling *Ecol. Model.* **70** 137–57
- NCDC (National Climate Data Center) 2005a *Global Synoptic Climatology Network C The Former USSR Version 1.0* TD-9290c-1 (Asheville, NC: NOAA National Climatic Data Center)
- NCDC (National Climate Data Center) 2005b *Daily and Sub-daily Precipitation for the Former USSR Version 1.0* TD-9813 (Asheville, NC: NOAA National Climatic Data Center)
- Newell J P 2006 Timber in the Russian Far East and potential transborder conflict *Russian Business Power: The Role of Russian Business in Foreign and Security Relations* ed A Wenger, J Perović and R Ortung (New York: Routledge) pp 239–59
- Nikolov N and Helmisaari H 1992 Silvics of the circumpolar boreal forest tree species *A Systems Analysis of the Global Boreal Forest* ed H H Shugart, R Leemans and G B Bonan (Cambridge: Cambridge University Press) pp 9–84
- Pastor J and Post W M 1988 Response of northern forests to CO₂-induced climate change *Nature* **334** 55–8
- Pisarenko A I and Strakhov V V 1996 *Socio-Economic Assessment of the Russian Boreal Forests Working Paper* WP-96-58 (Laxenburg: International Institute for Applied Systems Analysis)
- Porté A and Bartelink H H 2002 Modelling mixed forest growth: a review of models for forest management *Ecol. Model.* **150** 141–88
- Purves D and Pacala S 2008 Predictive models of forest dynamics *Science* **320** 1452–3
- SAS Institute Inc 2002 *SAS Release 9.1* (Redlands, CA: SAS Institute Inc)
- Shugart H H 1984 *A Theory of Forest Dynamics the Ecological Implications of Forest Succession Models* (New York: Springer Verlag) (Caldwell, NJ: Blackburn Press) (reprinted in 2003)
- Shugart H H, Smith T M and Post W M 1992 The potential for application of individual-based simulation models for assessing the effects of global change *Annu. Rev. Ecol. Syst.* **23** 15–38
- Shugart H H and West D C 1979 Size and pattern in simulated forest stands *Forest Sci.* **25** 120–2
- Shugart H H and West D C 1980 Forest succession models *Bioscience* **30** 308–13
- Shugart H H and Woodward F I 2011 *Global Change and the Terrestrial Biosphere: Achievements and Challenges* (Oxford: Wiley–Blackwell Press) p 242
- Shuman J K and Shugart H H 2009 Evaluating the sensitivity of Eurasian forest biomass to climate change using a dynamic vegetation model *Environ. Res. Lett.* **4** 045024
- Shuman J K, Shugart H H and Krankina O N 2013 Testing individual-based models of forest dynamics: issues and an example for the boreal forests of Russia *Ecol. Model.* at press
- Shvidenko A Z and Nilsson S 2002 Dynamics of Russian forests and the carbon budget in 1961–1998: an assessment based on long-term forest inventory *Clim. Change* **55** 5–37
- Shvidenko A Z and Nilsson S 2003 A synthesis of the impact of Russian forests on the global carbon budget for 1961–1998 *Tellus B* **55** 391–415
- Shvidenko A Z, Nilsson S, Rozhkov V A and Strakhov V V 1996 Carbon budget of the Russian boreal forests: a systems analysis approach to uncertainty *Forest Ecosystems, Forest Management and the Global Carbon Cycle (NATO ASI Series I vol 40)* (Berlin: Springer) pp 145–62
- Soja A J, Cofer W R, Shugart H H, Sukhinin A I, Stackhouse P W, McRae D J and Conard S G 2004 Estimating fire emissions and disparities in boreal Siberia (1998–2002) *J. Geophys. Res.* **109** D14S06
- Soja A J, Tchepakova N M, French N H, Flannigan M D, Shugart H H, Stocks B J, Sukhinin A I, Parfenova E I and Chapin F S III 2007 Climate-induced boreal forest change: predictions versus current observations *Glob. Planet. Change* **56** 274–96
- Stolbovoi V and McCallum I (ed) 2002 *CD-ROM Land Resources of Russia* (Laxenburg: International Institute for Applied Systems Analysis and the Russian Academy of Science)
- Sukhinin A I et al 2004 AVHRR-based mapping of fires in Russia: new products for fire management and carbon cycle studies *Remote Sens. Environ.* **93** 546–64
- Turner D P, Winjum J K, Kolchugina T P, Vinson T S, Schroeder P E, Phillips D L and Cairns M A 1998 Estimating the terrestrial carbon pools of the former Soviet Union, conterminous US, and Brazil *Clim. Res.* **9** 183–96
- Vandergert P and Newell J P 2003 Illegal logging in the Russian Far East and Siberia *Int. Forest Rev.* **5** 303–6
- Yan H and Shugart H H 2010 An air relative-humidity-based evapotranspiration model from eddy covariance data *J. Geophys. Res.-Atmos.* **115** D16106
- Yan X and Shugart H H 2005 A forest gap model to simulate dynamics and patterns of Eastern Eurasian forests *J. Biogeogr.* **32** 1641–58

Reproduced with permission of copyright owner. Further reproduction prohibited without permission.