Forestry *An International Journal of Forest Research*

Institute of Chartered Foresters

Forestry 2013; **86**, 283–293, doi:10.1093/forestry/cps086
Advance Access publication 3 January 2013

Sensitivity of Russian forest timber harvest and carbon storage to temperature increase

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Received 7 August 2012

Russia is a leading exporter of industrial round wood and supplies many countries with a large share of their wood fibre. However, warming temperatures are likely to have an impact on the productivity of Russian forest stands and affect their production capacity and management. The forest gap model FAREAST was used to derive biological growth parameters of several forest types; these data were then used within an economic model to discern the response from both a timber harvest and carbon sequestration perspective. An incremental warming of 2°C resulted in an increase in the timber harvest for most forest types. A 4°C increase, however, caused nearly all projects to yield less timber and sequester less carbon than under current conditions. Only stands in northwestern Russia stocked with *Pinus sylvestris*, a fast growing heat-tolerant species, continuously increased timber harvest and carbon sequestration in parallel with extreme temperature changes; however, stands with greater species diversity were less sensitive to increased temperatures. Russian forest carbon sequestration, a process mentioned as a method to mitigate climate change, may become less effective by the same process it is hoped to assuage.

Introduction

Russia, home to nearly one-quarter of the planet's forests,[1] is the world's largest exporter of industrial round wood.[2] Russian forestry is an important part of the country's economy, contributing over $7.7 billion in 2009 (FAO, 2006)[3] and a major employer, employing 849 000 Russians in 2006 (FAO, 2006). Raw timber products from Russia are critical for countries which import a majority of their wood resources, such as China and many countries within Europe. Exports of timber to China, totalling $1.32 billion in 2002,[4] have almost doubled in recent years, reaching $2.5 billion in 2009.[2] Considering that nearly 30 per cent of Russian logging is estimated to be illegal,[5] these financial estimates are likely to be conservative and may underestimate the full economic importance of the Russian forestry industry. While Russian forestry is a major industry with far-reaching impacts, its harvest only makes up 3 per cent of the world's total.[2] This is despite the fact that Russia contains 20 per cent of global wood resources.[6] In the past decade, exports have consistently increased and indications that the forest sector will continue to grow are numerous.[7]

However, climate change and warming temperatures are an important source of uncertainty for Russian forest managers. Temperatures have been rising in much of the area that contains Russian forests. Dendrochronological records indicate that temperatures in northern Siberia are currently the warmest in over 1000 years,[8] while an analysis of global weather station data suggests that Russia has been experiencing warmer temperatures in the past half-century.[9] Data compiled from 44 regional weather stations throughout Siberia from a baseline period of 1960–1990 compared with the period of 1991–2010 indicate a 2–3°C warming during winter in northern Siberia and a 1–2°C increase during summer in Southern Siberia.[10] Both the Arctic climate impact assessment and the Intergovernmental Panel on Climate Change (IPCC)'s findings imply that the circumboreal region, an area that contains much of Russia's forests, will experience temperatures nearly 40 per cent above the global mean in the coming decades.[11]

These climate variations are expected to seriously impact nearby forested ecosystems. Modelling exercises in Russian forests have shown that underlying forest composition will change in response to projected changes in temperature.[12–15] In particular, cold-adapted species such as Siberian larch (*Larix sibirica*) may be replaced by species which can withstand warmer temperatures, like Siberian pine (*Pinus sibirica*).[12] In Eastern Eurasia, deciduous trees such as *Fraxinus*, *Ulmus*, *Quercus* and *Tilia* may extend their range at the expense of coniferous species.[14] Analyses of forest plots have detected current transition from Dahurian larch (*Larix gmelinii*) to evergreen conifers such as spruce, fir and pine in central Siberia over the past three decades.[16] To properly adapt to increasing temperatures, forest managers may have to cultivate species that traditionally were not planted or did not exist in the areas that they manage or else look for alternative sources of income from their forests.[17] In the case of Russian forestry, managers need to be aware of their stock sensitivity to warming temperatures and understand how it may influence their economic expectations.

If climate change provides economic setbacks to traditional timber management, alternative strategies for economic gain may be useful to Russian forest managers. Carbon sequestration platforms that encourage forestry plantations as a methodology to mitigate greenhouse gas levels in the atmosphere may provide such an additional strategy.[18] For example, the Kyoto Protocol's clean development mechanism (CDM) includes afforestation and reforestation as financial opportunities for forestry managers as a method of carbon sequestration. Many studies have highlighted this potential[19–21] yet very few forestry CDM projects exist[22] and none exist within Russia. Estimates suggest that nearly 50–80 million ha of currently unforested land within Russia could be reforested, yielding a 2.5 t C ha^{-1} year^{-1} carbon sink.[23] Current logging practices in these areas allow for regeneration rates of significant length, typically 120–140 years as dictated by the biology of the stand and not the economic yield.[24] By managing their forests to maximize carbon sequestration and selling credits on regulated and/or unregulated markets, Russian forest managers may have another option for the direction of their enterprises. Detailed studies regarding forest carbon sequestration projects within Russia are not present in the scientific literature; however, total carbon pool estimates suggest that Russia and its forests have been a net sink from 2000 to 2007[25] and therefore particular areas of Russian forests may be suitable candidate sites.

Detailed simulations of Russian forest responses to rising temperatures are useful for addressing uncertainties related to forest sensitivity. Traditionally, computational models have been the primary tool used to answer these types of questions. However, such models generally stem from either the economic or biological disciplines and rarely are the two disciplines combined into one model effectively. Economic models have been generally developed to incorporate carbon sequestration with timber harvest to evaluate forest management strategy.[26–28] On the other hand, ecological models often have been designed to simulate the ecological and biological processes of forests. While some ecological models have incorporated timber harvest[29] and climate change,[14,30] integrations between ecological and economic models for forestry management in the context of rising temperatures have had wide-ranging aims[18] and none have examined Russian forests in detail. Despite this absence, Aaheim *et al*.[18] suggest that dynamic biogeographical models may be appropriate for the next steps in effective model integration due to their ability to focus on the growth of biomass, the key characteristic which unites forest ecology, timber harvest and carbon sequestration. Our study fills this niche by pairing the biological and ecological simulation abilities of a proven dynamic forest gap simulator that focuses on Russian boreal forests (FAREAST)[30] with an economic forestry model.[28] With this pairing we address how several highly important Russian forest types respond to increased temperature scenarios. We then summarize the implications of this response for timber harvest and the potential for forest carbon sequestration.

Methodology

Study sites

Forested lands designated for forest management purposes constitute almost 70 per cent of the total area of Russia.[31] While only a portion of this is considered to be 'exploitable' and available for harvesting, the total area of forest that may be managed for harvest still covers 329.8 million ha.[31] Within this large area we examined statistics of annual timber extraction that had been compiled by the Russian Federal Forestry Agency and were provided by the Center for Ecological Productivity of Forests at the Russian Academy Of Sciences, Moscow (Ershov, unpublished). We chose nine sites (Table 1) which represented the main timber-producing regions of the country. A map of these site locations can be found as Figure 1. Three locations in the eastern one-third of Russia, sites 4, 7 and 9, were centred nearby Amursk, one

Table 1. The nine boreal forest types examined, their location and the tree species present.

Site #	Site name	Latitude	Longitude	Species Included	Notes
1	Central Larch	57.78	100.65	*Larix sibirica*	200 km from Bratsk, Irkutskaya Oblast
2	Pine West	61.63	38.23	*Pinus sylvestris*	40 km from Kargopol, Republic of Karelia
3	Pine Central	57.78	100.65	*Pinus sylvestris, Pinus sibirica*	200 km from Bratsk, Irkutskaya Oblast
4	Pine East	50.51	137.53	*Pinus koraiensis, Pinus pumila*	30 km from Amursk, Khabarovsky Krai
5	Spruce Fir West	61.63	38.23	*Picea obovata, Picea abies*	40 km from Kargopol, Republic of Karelia
6	Spruce Fir Central	55.99	106.22	*Abies sibirica, Picea obovata*	200 km from Severobaykalsk, Irkutskaya Oblast
7	Spruce Fir East	50.51	137.53	*Abies holophylla, Abies nephrolepis, Picea ajanensis, Picea koraiensis*	30 km from Amursk, Khabarovsky Krai
8	Deciduous Mix West	55.58	32.83	*Populus tremula, Betula pendula, Betula pubescens, Fraxinus excelsior, Acer platanoides, Tilia cordata, Ulmus glabra, Quercus robur, Alnus incana*	35 km from Beyll, 300 km from Moscow
9	Deciduous Mix East	49.45	137.24	*Populus tremula, Betula pendula, Betula pubescens, Betula platyphyll*	30 km from Amursk, Khabarovsky Krai

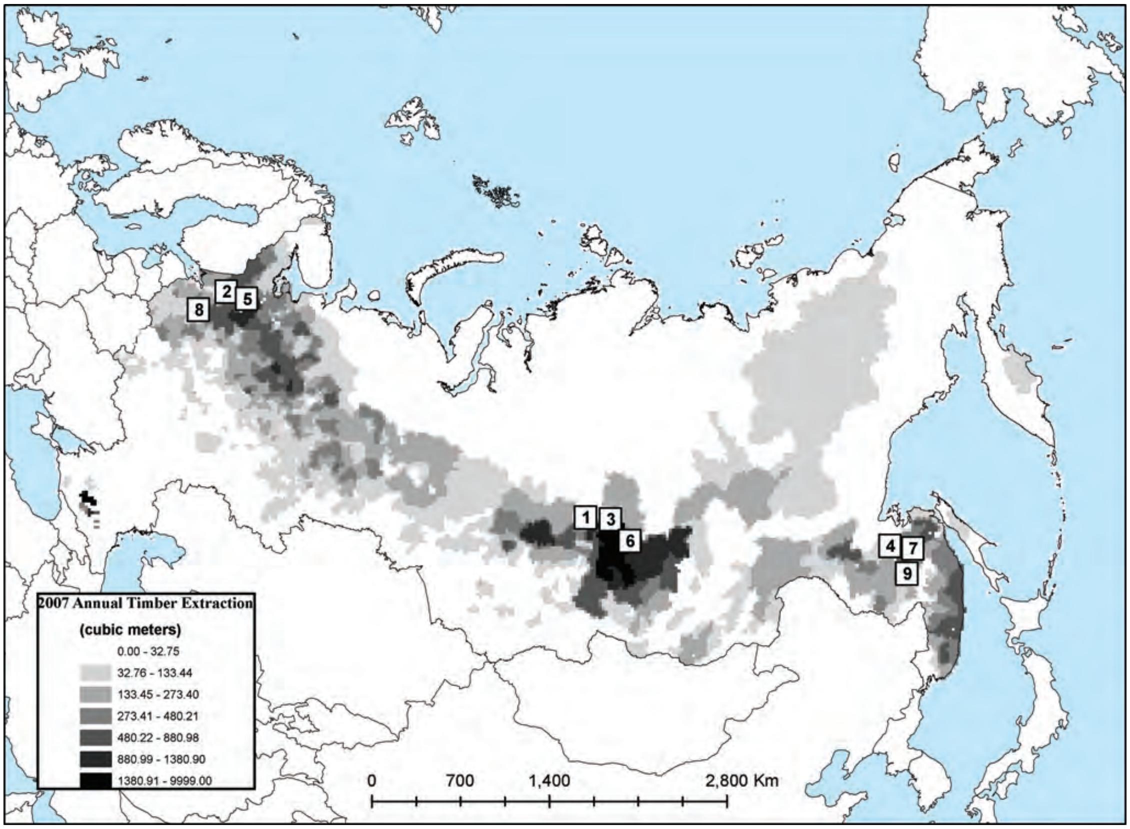

Figure 1 Locations of the nine simulated forest stands throughout Russia. Each location is indicated by a numbered icon, coordinates of which are on Table 1. Shaded black areas indicate the annual stock volume of harvestable timber as reported by the Russian Federal Forestry Agency for the year 2007.

of the dominant lumber-producing cities in the Russian Far East. Two locations, sites 2 and 5, were selected within the western Republic of Karelia, a federal subject of Russia that uses a high percentage of its allowable forests[32] and is home to a large timber industry driven by European demand. Together with a site near Beyll, site 8, these three locations were defined as 'western'. Three sites, 1, 3 and 6, were also selected within Central Siberia. These were located nearby Irkutsk, one of the dominant lumber-producing cities within Siberia. These study sites provided us with a wide diversity of the most merchantable species (*Picea* and *Abies*, *Larix*, *Pinus*, and two mixes of deciduous species containing mainly of *Populus*, *Quercus* and *Betula*). The species contained within each site and their geographic coordinates can be found in Table 1. The FAREAST model had previously been validated using field studies[12,14,30] in these areas and thus FAREAST simulations could be considered to faithfully represent actual forest structure.

Ecological model

The FAREAST model is an individual-based forest gap model created to simulate the dynamics of Eurasian forests.[30] Originally developed to focus on north-eastern China and the easternmost areas of Russia, it has since been expanded and developed to model a variety of forests in the Russian boreal zone[33] as well as investigate climate change scenarios.[14,33,34] FAREAST uses four different modules to simulate the growth and dynamics of a forest stand. A detailed description of these modules and their specific equations can be found in Xiaodong and Shugart[30] and Zhang *et al*.[35] Essentially, FAREAST simulates an area of 0.05 ha within boreal forest stands with species-level discretion, but also reports biophysical parameters of forest trees as well as biogeochemical conditions of the stand, including above- and below-ground carbon and nitrogen levels. FAREAST was parameterized through the use of the most extensive archive of Russian forest silvics.[36] FAREAST has been used for projections of carbon storage[33] and species dynamics[12,14] under warmer climates and has been validated throughout Russia by comparisons to forest inventory stands.[33]

Economic model

The economic model used in this study is a derivative of that presented by Gutrich and Howarth[28] for an analysis of NH, US forest projects. This model calculates total timber stock as a direct function of time since the previous harvest. The model runs at annual time steps and after each year, it partitions biomass into the appropriate pools of live wood, dead wood and litter, long-lived forest products, timber and soil. These quantities can thus be evaluated for economic value. Timber growth and the amount of harvestable timber is determined by the derivation of a multitude of parameters that are focused on four central equations and three groups of slightly less important yet contributing parameter sets. The model calculates total current timber volume of each stand by estimating the maximum timber volume (m^3/ha), the timber growth coefficient (per cent/year) and the minimum stand age with timber volume (years) from forest yield tables using the equation:

$$V(s) = \begin{cases} \alpha_0(1-(1-\alpha_1)^{s-\alpha_2} & s \geq \alpha_2 \\ 0 & s < \alpha_2 \end{cases} \qquad (1)$$

where the maximum timber volume is α_0, the timber growth coefficient is α_1 and the minimum stand age with positive timber volume is α_2.[28] These coefficients for the Russian species within this study were derived from biomass yield data from the FAREAST simulation runs.

Once timber is simulated within the economic model, it is divided into share coefficients for saw timber and pole timber. Following harvest, the proportion that ends up in sawn wood and pole wood products is based upon research within the Russian forest sector by Gerasimov *et al*.[37] To generate the net present values (NPVs) of forest timber projects, contemporary saw timber and pole timber prices were utilized (Wood Resources International, personal comm., 2010).[38] Stands were harvested completely within this model and were re-established with no additional planting since nearly 75 per cent of all forestry operations within Russia utilize natural regeneration methods.[24]

For the calculations of total carbon content for the stand, this model utilizes a series of equations that focus on live and dead carbon. Live carbon is simulated by:

$$C_{\text{live}} = \gamma_0(1-(1-\gamma_1)^s) \tag{2}$$

in which γ_0 is the maximum carbon storage in live biomass in tons/hectare and γ_1 is the live biomass growth coefficient in percent per year. For dead carbon, the equation

$$C_{\text{dead}}(t) = (1-\delta_0)[C_{\text{dead}}(t-1) + \delta_1 C_{\text{live}}(t-1)^{\delta 2} + D(t-1)] \tag{3}$$

is used in which δ_0 represents the decay rate of dead and downed wood in per cent per year, D signifies the slash that is left after a harvest event and $\delta_{1,2}$ represent formation coefficients. C_{dead} is the initial storage in dead and downed wood at a site in tons per hectare.[28] Live carbon storage and the carbon growth coefficient parameters were derived from FAREAST simulation data, while the decay rates of dead and downed wood were derived from U.S.F.S Evalidator data, a network of detailed measurements from long-term forest service monitoring plots. Additionally, carbon held within the soil and stored carbon in wood products is calculated within this model. The former is derived from the FAREAST simulator and the later from calculations of carbon in long-lived wood products stemming from work by Birdsey[39] and reported by the United States Department of Energy in their guidelines for reporting of emissions inventories.[40]

Precise information regarding the allocation of forest types to wood products throughout Russia is not commonly reported in the scientific literature; however, Krankina *et al*.[41] rely on national economic statistics which report 28 per cent of wood being converted to paper products, with 72 per cent used for timber, plywood and particle-board. These numbers generally mirror those assumed by Birdsey.[39] Obersteiner and Nilsson[42] used linear decay rates for long-lived forest products within the Russian Federation to estimate carbon fluxes. While there was no differentiation amongst forest type in that analysis, Obersteiner and Nilsson[42] represented sharp decay rates for pulp and paper products, nearly 5-fold that of saw products such as construction materials; these rates are similar to those used in our model, however with the caveat of slightly faster decay in pulp products due to limited recycling implementation.

The financial component of the economic model aligns with previous work by Van Kooten *et al*.[43] All parameter values for each forest type can be found in Table 2 and a more detailed description of all of the equations used within this model can be found in Gutrich and Howarth.[28]

Study design

Each forest project location was simulated using the FAREAST model using a base climate derived from a 60-year weather station record of daily temperature and precipitation measurements which were converted into monthly mean minimum and maximum temperatures and monthly precipitation values.[44] This data set was archived and a result of cooperation between the National climatic data centre and the all-Russian research institute for hydrometeorological information. In total, 223 stations across the former USSR were included in this data set, with 9 being used for this analysis. Temperature was measured eight times a day at each station and then converted to a daily minimum and maximum; similarly, precipitation was measured daily to the nearest tenth of a millimeter.[44] These monthly data were used within the FAREAST climate module to derive daily temperatures stochastically as well as update soil water levels[30]; the climate sub-module within FAREAST then directly influenced the simulation of forest growth based on species-specific parameters as described within Xiaodong and Shugart.[30] This procedure has been used in each FAREAST study to date.[12,14,30,33] Information regarding the physical and nutrient properties of soils at the project sites was taken from the land resources of Russia data set, prepared by the International Institute for Applied Systems Analysis.[45]

At each forest project location, FAREAST was run forward for 90 years, starting at bare ground with an intact seed bank. Two hundred replicate plots of 0.005 ha were simulated at each study site in order to minimize the variability inherent in the forest gap model and to effectively represent forest structure; this is a technique commonly utilized in forest gap model simulation.[12] The 2° and 4°C increase scenarios required slight modifications in the model inputs. For the FAREAST simulations, the base temperature data were incrementally increased at a rate of 0.022 and 0.0444°C year^{-1}, respectively, over the lifetime of the project until the target value was reached in the final year of the simulation. This method allowed stochastic processes to generate variability in both individual daily temperatures and inter-annual climate patterns since the FAREAST climate module inherently adds randomness.

Once each forest project was simulated with FAREAST, the necessary output including biomass, growth, carbon storage and soil carbon values were used as input to the economic model and NPV, timber harvest and carbon sequestration values were generated using current stumpage prices, carbon market prices and interest rates. Carbon forestry projects here are defined as simple reforestation projects as specified by the United Nations CDM. These were simple analyses absent a full attribution of additionality or leakage; they were meant as a first step towards understanding the fate of carbon sequestration capabilities for forest stands in these areas with basic carbon accounting techniques. We assumed a simple, consistent increase in timber and carbon prices in the same fashion as Gutrich and Howarth.[28] However, to understand the influence of the economic variables more fully, we preformed a sensitivity analysis on changes in pole timber and saw timber stumpage price, the stumpage price growth rate and the discount rate for the NPV of the timber component of the projects. Likewise, the sensitivity of the each project to changes in carbon price, the carbon price growth rate and the discount rate for the carbon component was tested using 10 per cent deviations from current values. To understand critical carbon price values for each project, we relied upon Monte Carlo scenario analysis to provide repeated randomization of starting carbon market prices.

Results

Results of the coupled FAREAST and economic model indicate that increased temperature scenarios did noticeably influence the timber harvest output of the forest projects investigated (Figure 2). Of the nine projects, several responded with gains in productivity and an increase in overall timber harvest. Notably, the central Siberian *Larix sibirica* and the northwestern Karelia *Pinus slyvestris* projects both saw an increased harvest following

Table 2. Model parameters used to simulate timber harvest and carbon sequestration capabilities within each forest stand.

Estimated parameter values Russian forests		Larch	Pine West	Pine central	Pine East	SpruceFir West	SpruceFir East	SpruceFir Central	Dmix West	Dmix East
alpha0	Maximum timber volume (m^3/ha)	209.00	402.79	207.46	742.19	137.10	65.31	145.46	160.41	163.78
alpha1	Timber growth coefficient (%/year)	0.0071	0.0184	0.0195	0.0074	0.1426	0.0946	0.0199	0.0262	0.0262
alpha2	Minimum stand age/positive timber volume (years)	2.2050	5.6700	4.7718	4.2253	12.5548	11.4200	19.3220	4.0120	2.0560
gamma0	Maximum carbon storage in live biomass (t/ha)	128.48	180.71	93.08	332.98	95.46	45.48	101.28	118.75	121.24
gamma1	Live biomass growth coefficient (%/year)	0.0071	0.0353	0.0346	0.0558	0.0484	0.0391	0.0437	0.0483	0.0479
DeadStart	Initial carbon content of dead/downed wood (t/ha)	46.0100	20.5000	20.5000	20.5000	44.2000	44.2000	44.2000	38.7000	38.7000
delta0	Decay rate of dead and downed wood (%/year)	0.0320	0.0400	0.0400	0.0400	0.0480	0.0480	0.0480	0.0650	0.0650
delta1	Formation coefficient for dead and downed wood	0.0651	0.2580	0.2580	0.2580	0.7300	0.7300	0.7300	0.3910	0.3910
delta2	Formation coefficient for dead and downed wood	0.7372	0.3580	0.3580	0.3580	0.4280	0.4280	0.4280	0.4780	0.4780
SoilCarbon	Soil Carbon (t/ha)	141.86	133.17	133.17	133.23	133.17	159.58	159.58	133.18	133.18
beta0	Saw timber share coefficient (%)	6.3600	6.3700	6.3700	6.3700	7.2700	7.2700	7.2700	1.3800	1.3800
beta1	Saw timber share coefficient (years)	2.7000	2.7000	2.7000	2.7000	1.4700	1.4700	1.4700	20.0200	20.0200
beta2	Saw timber share coefficient (%)	5.4000	5.4000	5.4000	5.4000	6.7000	6.7000	6.7000	0.5500	0.5500
epsilon1	Carbon content of softwood (t/m^3)	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234
epsilon3	Carbon content of hardwood (t/m^3)	0.357	0.357	0.357	0.357	0.357	0.357	0.357	0.357	0.357
h1	Percentage of harvest—softwood pulpwood	0.410	0.410	0.410	0.410	0.410	0.410	0.410	0.000	0.000
h2	Percentage of harvest—softwood saw products	0.550	0.550	0.550	0.550	0.550	0.550	0.550	0.000	0.000
h3	Percentage of harvest—hardwood pulpwood	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.850	0.850
h4	Percentage of harvest—hardwood saw products	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.120	0.120
phi0,1	Decay rate of softwood pulp products	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060
phi0,2	Decay rate of softwood saw products	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038
phi0,3	Decay rate of hardwood pulp products	0.0062	0.0062	0.0062	0.0062	0.0062	0.0062	0.0062	0.0062	0.0062
phi0,4	Decay rate of hardwood saw products	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042
phi1,1	Carbon percentage in softwood pulp products	0.2375	0.2375	0.2375	0.2375	0.2370	0.2370	0.2370	0.2370	0.2370
phi1,2	Carbon percentage in softwood saw products	0.2980	0.2980	0.2980	0.2980	0.2980	0.2980	0.2980	0.2980	0.2980
phi1,3	Carbon percentage in hardwood pulp products	0.2274	0.2274	0.2274	0.2274	0.2270	0.2270	0.2270	0.2270	0.2270
phi1,4	Carbon percentage in hardwood saw products	0.1871	0.1871	0.1871	0.1871	0.1870	0.1870	0.1870	0.1870	0.1870

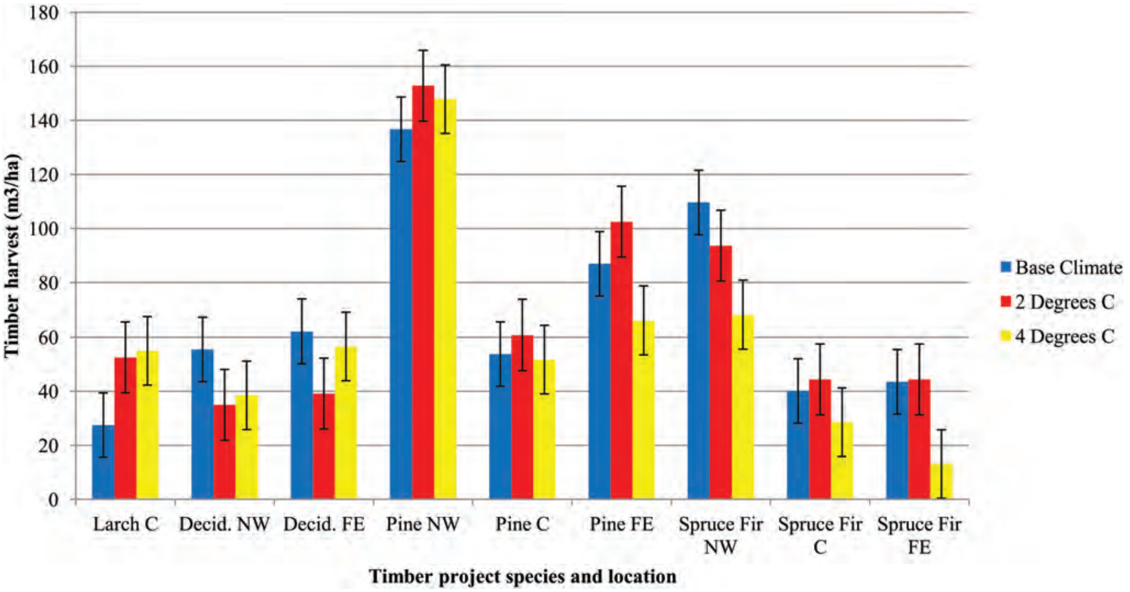

Figure 2 Timber harvest at financially optimal rotation periods for nine timber projects within Russia at varying magnitudes of climate change. Blue bars represent harvest returns under current climate conditions; yellow indicates harvest given an expected increase of 2°C by 2100 and red bars indicate harvest given a linear 4°C increase. A colour version of this figure is available on the *Forestry* website.

a 2°C increase. The *L. sibirica* project, in particular, doubled timber output from 27.49 to 54.95 m^3/ha. However, under a faster warming scenario in which temperatures eventually reached 4°C above the base, no further influence on the productivity of the stands was observed. Three projects, a Central Siberian project with two types of Pine (*Pinus Siberica* and *Pinus Sylvestris*), a Far Eastern project with two types of pine (*Pinus koraiensis* and *Pinus pumila*) and a Central Siberian project with Spruce and Fir (*Abies sibirica* and *Picea abies*), all responded to the 2°C increase scenario with more growth than the base scenario. Yet, when temperatures were increased to 4°C, these projects decreased carbon storage and timber harvest declined. In the case of the Far Eastern Pine project, harvest decreased by >20 per cent over base values.

Not all sites reacted to increased temperatures with amplified yield. Sites 5 and 7, which contained a mixture of spruce and fir, decreased timber yield by 38 and 70 per cent, respectively. The two sites containing mixes of deciduous species, sites 8 and 9, were less productive in the 2°C increase scenario; however, in the 4°C scenario, they had biomass yields more akin to those in current condition simulations. In particular, the Far Eastern deciduous broadleaf project, site 9, containing *Populus tremula* and three types of *Betula*, retained similar timber yields as the base scenario.

Forest carbon sequestration potential mimics the response of timber harvest to some extent (Figure 3). Several sites sequester more carbon as temperatures increase compared with the baseline climate scenario (the *L. sibirica* project in Central Siberia; the *P. slyvestris* project in Karelia). Yet sites located in the Russian Far East and those with temperature sensitive species such as *P. abies* collapse in the 4°C scenario and therefore sequester minimal quantities of carbon. With respect to individual species responses, Pine species, notably *P. sylvestris* and *P. koraensis*, were present in the two sites sequestering the most carbon, while those containing spruce and fir generally averaged the least. Central Siberian sites sequestered carbon slowly and, in small quantities, minimizing their potential value with respect to the ability to serve as future carbon offset projects.

Discussion

Timber yield

Overall response of forest projects to temperature increases was dependent upon the species harvested, the geographic location and the species diversity of the site. Forest projects which were shown to have a greater timber harvest with 2 and 4°C increases, sites 1, 2 and 3, often contained species with large climatic tolerances. Siberian Larch, *L. sibirica*, is known to have the largest potential distribution area of all Eurasian boreal species,[46] and previous research of its life history has shown it to be receptive to changes in climate and growing conditions,[36] particularly when it is constrained by cold temperatures. The trend of increasing productivity in this species has been documented in the field and through other modelling exercises. Kharuk *et al.*[47] observed growth increment increases and heightened regeneration in southern Siberia since the middle of the 1980's. Analysis of tree-ring patterns in western Siberian *Larix sibrica* indicates growth increases following temperature increases in the late 20th century.[48] Several modelling studies have also shown that this species will increase in potential distribution[49]; however, excessive temperature increase will cause significant population decline[12] which may explain no further yield increase above 2°C.

Scots pine, *P. sylvestris*, also responded to temperature increase by increased yield in its projects. This species has the largest range of any pine species in the world[50] and is also capable of handling temperature increase and drought stress in northern latitudes. It is often suggested as a species suitable

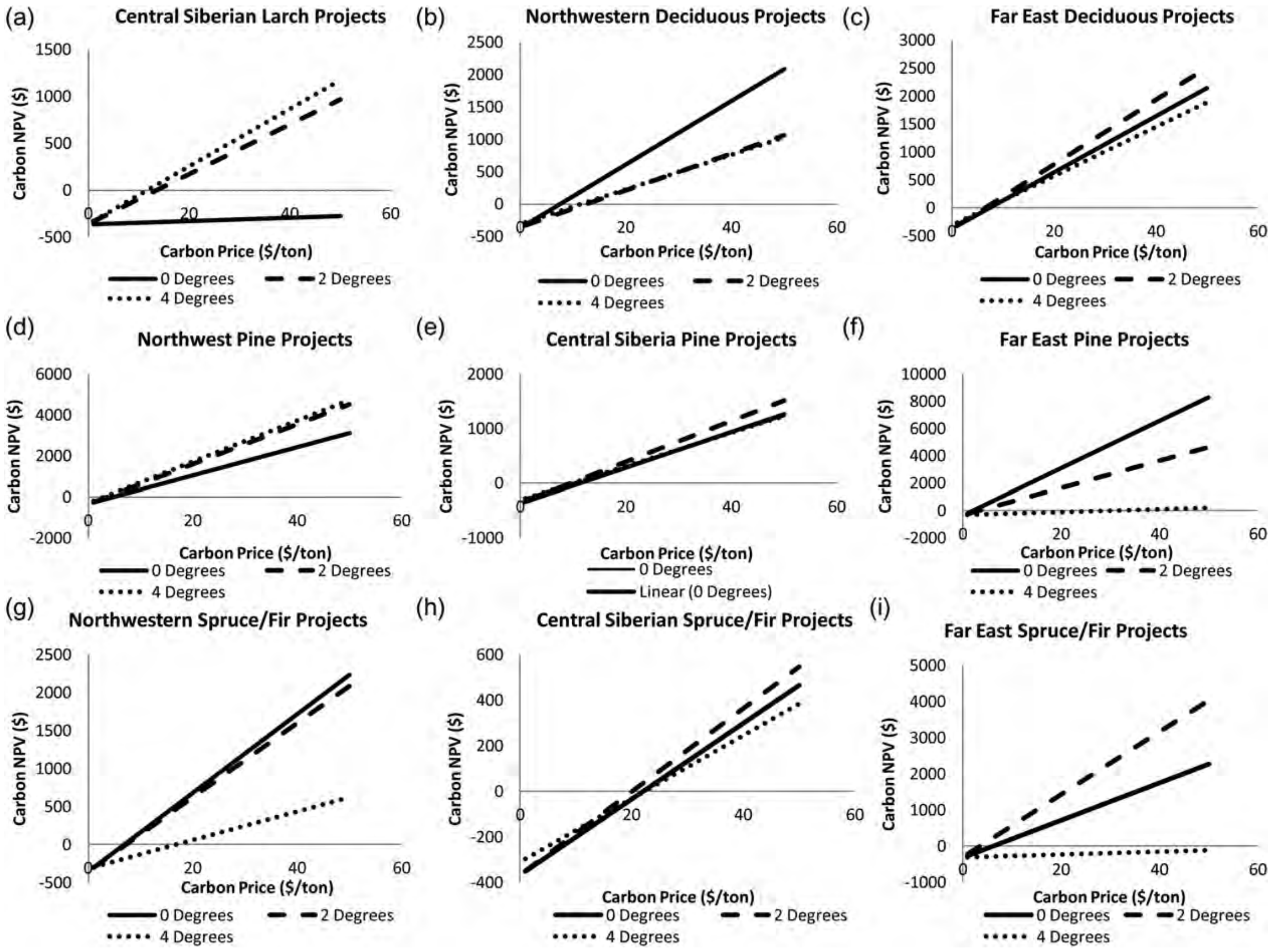

Figure 3 NPV of the nine forest carbon projects in different warming scenarios. Most projects were hampered by the most intense 4°C warming scenario (dotted line) yet were more profitable in the 2°C scenario (dashed line) than under the base climate (solid line).

for conservation forestry due to its drought tolerance.[51] Long-term observation of *Pinus sylvestris* in Eurasia and North America suggests that this species currently inhabits areas where climate is colder than that of their optimum productivity,[52] and thus temperature increases may be amenable to populations of the species and result in heightened productivity particularly in northern latitudes. Stemwood volume models also indicate that *Pinus sylvestris* will increase volume in the boreal zones of Eurasia through 2030, yet will likely have decreasing returns past 2050.[53] Our modelling results thus are consistent with previous research indicating these species responses to temperature and suggest that these projects will encounter larger short-term timber harvests.

For forest projects in other locations in Russia, particularly sites 3, 6, 7 and 9, the evidence is mixed. Very generally, small temperature increases boost productivity, while large increases cause forest stress and collapse. Coniferous forests in the Russian Far East and forests of *Picea* spp. and *Abies* spp. respond particularly poorly under the 4°C scenario. While *Picea obovata* is not temperature inhibited, it is particularly sensitive to moisture conditions,[54] and increased drought stress may be responsible for this species decline. The Siberian Fir, *Abies siberica*, is present within Central Siberian sites and is a particularly slow-growing species.[36] In this location, it responds poorly to large increases in temperature. Similarly, *Pinus koraiensis*, the pine species present in the Far East projects is not capable of handling an overall 4°C increase in temperature. While increased temperatures may boost productivity in the short-term, the long-term repercussions resulting from a partial collapse of these species in these locations may result in diminished timber harvest. It is important to note that a more thorough inclusion of precipitation changes as projected by climate models may diminish or exacerbate these effects, depending on the direction of the change. Decreases in precipitation intensify drought stress, particularly in forests already stressed by temperature increase and may lead to increased mortality and decreased growth.[55]

Broadleaved deciduous projects provided an opportunity to understand how species diversity may influence forest projects under a changing climate. While both projects, sites 8 and 9, responded to a 2°C temperature increase with an initial decline in harvestable timber, they were less affected with 4°C warming and in the case of the Far East project, had similar yields as the base scenario. Consistent yield in the higher temperature scenario is likely due to the greater diversity and complexity included in the simulations. While other forest projects consisted mainly of one or two primary species, the deciduous forest projects often contained several species of hardwoods native to the sites. While a 2°C increase in temperature was often detrimental to the dominant species and a decline in productivity and harvestable wood was noticeable, at 4°C, the dominant species was perturbed significantly enough to allow previously suppressed and heat-tolerant species to establish. Close examination of the broad-leaved project in Karelia revealed that the more extreme temperature scenario adversely affected the previously dominant Silver Birch (*Betula pendula*) which allowed for Norway maple (*Acer platinoides*) to establish. In the Far Eastern plots, *Populus tremula* was replaced by the previously minimal *Betula platyphyll*. In these cases, increased diversity within a forest plot mitigated the potential of decreased timber harvest and therefore financial loss, given changing environmental conditions.

These results follow several forest management studies which suggest that the creation of plantations with higher levels of diversity will mitigate losses due to climate change.[51,56,57] Additionally, these case studies provide evidence supporting Folke *et al.*'s[58] biodiversity insurance hypothesis, which posits that several keystone process species are critical for successful self-organization and increased system resilience. When species diversity is decreased, this may limit the ability of the system to recover or transition to an equally productive alternative state. Crépin[59] suggests that continual harvest in boreal forests using single species models may result in a loss of resilience, whereas creating management areas that increase resilience through planning at the landscape-level may be both feasible and profitable.[60]

Carbon sequestration

Despite the importance of forest and soil carbon accounting within Russian boreal forests for terrestrial carbon cycling calculations,[11,61] relatively few studies have investigated Russian forests for the potential as carbon sequestration projects at the most basic level. The results of these simulations suggest that several Russian forests may transition to an alternative state with projected increases in temperature. This may result in some cases in a diminished storage of carbon due to the combination of the inability of currently present boreal species to adapt to higher temperatures and a lack of heat tolerant species to replace them. In particular, sites containing *Picea* sp. and *Abies* sp. which sequester carbon effectively under current climate conditions, fail to maintain similar levels with large temperature increase unless adaptation measures are undertaken. Sites containing species that are heat-tolerant, particularly *P. sylvestris*, become excellent candidates for short-term carbon storage due to their fast growth rate as temperatures warm. The results of this study contrast some suggestions regarding Russian forest sector carbon storage potential. For instance, Van Minnen *et al.*[62] contend that, given the low productivity of high-latitude forests in Russia, carbon plantations there are not recommended. Similarly, Krankina *et al.*[41] mention the slow growth rates of central Siberian forests as a potential detriment to carbon sequestration projects there. However, neither of these studies incorporated the increased carbon storage potential given increases in temperature. Including forecasts of increased productivity under warmer climate suggests that these areas previously deemed as unfit for carbon storage projects may be more successful than previously expected, although considerations of additionality and leakage, as well as the influence of radiative forcing effects from albedo, need to be considered in future studies.

Conclusions

From the results of this study, we draw several preliminary conclusions regarding the response of several test sites of boreal species for both carbon and timber management:

(1) Given the speed at which warming temperatures may affect Russian forests and the relative instability of several species to warming temperatures as determined by this research, many forest management projects containing species maladjusted to thermal changes will be rendered economically less profitable given current interest rates and standard and linear growth of timber prices as temperatures rise. While most projects retain some value even at 4° warming, much of this is due to harvests made within the initial 50 years. Stands with species that are currently not limited in productivity by climate become heat stressed by the end of the simulated warming period, decreasing timber yield and carbon sequestration capability. Because of the implications of decreased yield, more intensive simulations should be created to explore the range of regional responses in combination with regional climate projections for more refined estimates.

(2) The difference between a 2 and 4°C scenario has important implications for forest management in many cases. While the more modest warming scenario results in moderate financial gain for several timber projects, the latter more severe scenario leads to stock collapse and the transition to an alternative stand composition in the absence of adaptation. This results in the inability for continued timber harvest to occur in those projects. Thus, planting strategy must regard site-level projections of temperature and precipitation change considerably since species responses vary drastically with relatively small changes in temperature increase. Because rotation periods are often long and many of the forests in Russia are remote, adaptation may be limited, thus placing more pressure on proper site planting strategies.

(3) Stand diversity may buffer losses due to the replacement of heat-stressed species by previously suppressed understory species. In particular, high-diversity deciduous broadleaved forests seem particularly well buffered against more severe warming scenarios due to the availability of replacement by other tolerant species. Low diversity stands with highly intolerant species, in contrast, may be more vulnerable to economic losses since replacement will depend on the migration capabilities of other species and their propensity to serve

market demand. These stands may be likely locations for transplant studies to find more tolerant substitution species which may retain project value. Of particular, interest may be the Russian Far East, as simulations there indicate very likely transitions to alternative compositions.

(4) Based on this modelling work, forest carbon sequestration potential in the locations we examined in Russia was also subject to climate-induced variability. As winter temperatures often limit productivity in some of these sites, warming may increase the carbon storage potential for several forests. This is particularly true for the *L. sibirica* sites in Central Siberia. The concept of adjusting additionality measurements due to carbon sequestration being modified by climate change is a topic that stems from the results of this study and warrants further discussion.

(5) Future modelling efforts are needed to more precisely calculate species vulnerabilities to increased temperatures and changing climate. Temperature ramp studies, such as this one, help us to understand systematic behaviour and forest trends under basic climate fluctuations. Pairing projects with specific scenarios from climate models is an effective way to forecast specific geographic and climatic vulnerabilities and will greatly inform Russian forest managers. Future work will incorporate precipitation more thoroughly and will include a more robust investigation into seasonal temperature change, as temperature in the region is not projected to consistently increase each month and rather will vary between summer and winter.

As a sensitivity study, this work investigated the immediate implications of higher temperatures to currently operating forest enterprises and potential carbon storage. The limitations towards a broad application of these results to all of Russian forestry include: a lack of global market influence on the economic model to modify timber prices under changing climate scenarios; the inability to account for mid-stand lifetime adaptation to warming by planting better adapted species; a robust investigation into climatic effects on forest growth including precipitation fluctuations and seasonal temperature variability; and the investigation of forest projects beginning at planting, rather than those which are currently older. Illegal logging, an issue commonly affecting forests in southeastern Russia, was not addressed either. However, this sensitivity study provides initial insight into the complications of forest management in boreal zones when temperatures change at projected rates.

It is important to note that the influence of climate on forest growth in these simulations are due to the direct consequences in the change in temperatures across Russia coupled with water-stress effects associated with temperature increases. Secondary effects of warmer temperatures were not present in these simulations but are worth mentioning. Fires, expected to increase in boreal forest areas as a consequence of a warmer climate, have become more prevalent and powerful in Siberia in the past decade.[11] An analysis of circumboreal fire projections under climate change[63] suggested that fire management agencies may not be properly equipped to respond in the next few decades. Unmanaged fire will substantially reduce the carbon storage and timber yield of these projects, thereby decreasing economic gains.

Insects commonly serve as primary forms of disturbance in boreal forest systems,[64] yet a warmer climate will also increase the prevalence of forest pest outbreak.[65] Many boreal defoliating pests are limited by winter temperatures and mild winters allow egg stages of pests to survive until the following summer, thereby increasing their populations.[66] However, increased summer temperatures will likely increase populations of pest predators, keeping their numbers regulated.[67] When large outbreaks occur, particularly those of the Siberian silk moth (*Dendrolimus superans sibiricus*), areas as large as 1 million ha can be affected in just 3 years.[68] Clearly, insect defoliation may play a large role in the future of Russian forest management and should be incorporated in further analyses.

Acknowledgements

The authors would like to thank John Gutrich and Richard B. Howarth for the use of their forest management economic model. Additional thanks go to Dmitry Ershov at the Center for Productivity and Ecology of Forests at the Russian Academy of Sciences, Moscow, Jacquelyn Shuman and Timothy Stevens for their help with the FAREAST model and Lyndele Von Schill for project coordination. Miles Silman, Rebecca Powell and Howie Epstein provided valuable suggestions to improve this manuscript. This research was funded by a grant from NASA (NASA Carbon/04-0231-0148) and a NASA award (No. NNG-05-GN69G) to H.H. Shugart. Research funding was also provided by the Civilian Research Development Foundation Multidisciplinary Climate Change Award and the Virginia Space Grant Consortium.

Funding

This work was supported by the National Aeronautics and Space Administration (Carbon NNG-05-GN69G); the Civilian Research and Development Foundation Joint Climate Change Grant; and the University of Virginia Presidential Fellowship.

Authors' contribution

D.A.L designed and performed the experiments, analysed the data and wrote the paper. H.H.S. provided FAREAST model guidance and commented on and revised the manuscript. M.A.W. provided economic model guidance, analysed the data and commented on and revised the manuscript.

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