Ecological and Economic Consequences of Climate on Eurasian Boreal Forests

David Andrew Lutz
Kennett Square, Pennsylvania

Bachelor of Science with Honors, Wake Forest University, 2004
Master of Science, University of Virginia, 2008

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Howard Epstein

ABSTRACT

This dissertation documents the use of the ecological gap model FAREAST throughout Russia, in concert with an economic timber and carbon model, and demonstrates its utility and compatibility with Dynamic Global Vegetation Models (DGVMs) for future climate-terrestrial simulations. Results from experiments performed in this dissertation showed that the leading edge of Russian forests is not the most likely location for change identification, as most changes in these areas occurred physiologically as opposed to compositionally within the stands observed. Interior forests displayed much greater levels of change, particularly with variables related to stand species composition.

Forest stands with a stand age between 75 and 150 years showed slight resiliency to warming temperatures in Siberia. These results follow Holling (1986) and his conceptual adaptive cycle framework for forests. While this resiliency is stronger for warming up to a 2 degree Celsius increase of monthly mean temperatures and therefore important for short-term management decisions, greater temperature increases hamper the ability for these forests to be resilient. Forest plantations are, due to their short life-cycle, particularly vulnerable to warming temperatures. Analysis of the net present value of several forest projects indicates that warming temperatures will lower economic returns from nearly every forestry project studied with the exception of *Pinus sylvestris* stands in northwestern Russia. While forestry projects in Russia are good candidates for carbon sequestration projects, mainly because timber operations are marginally profitable due to the low growth rates in many areas of Russia and systematic inefficiencies of Russian

infrastructure, warming temperatures will also affect the ability of these projects to make a profit.

Rising temperatures throughout the circumboreal zone will undoubtedly affect boreal forests in Russia. Within this dissertation lie insights into the ecological response of forests as well as recommendations for management strategies that may utilize these findings. While warming temperatures will alter the ecological functioning and position of these forests, current trends indicate that it will still be several decades before a complete conversion of these forests to an alternative stable state will occur; however, proper management is imperative to mitigate the consequences of such a conversion.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

LIST OF TABLES

LIST OF TABLES (CONTINUED)

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DISSERTATION PREFACE

This dissertation is divided into six chapters. The Introduction (Chapter 1) introduces the reader to the importance of boreal forests and describes the dissertation rationale. Chapter 2, entitled “Continental Scale Application of a Russian Forest Gap Model” is formatted for submission to Global Change Biology. Chapters 3 through 5 are not formatted for any particular journal, but can be read as stand-alone independent investigations.

Chapter 2 introduces the reader to the FAREAST model, its abilities, and how it functions. From there, the reader is shown two experiments that detail the ability of FAREAST to accurately simulate Russian forests in climate change scenarios and the potential that forest gap models have in understanding ecological responses of forested ecosystems (Chapter 3 and 4). Finally, the reader is given a real-world application of FAREAST in which the direct use of the model serves to help us understand the financial implications of climate change’s influence on forests (Chapter 5). In total, this dissertation moves from methods, to validation, to investigation, and finally to application. The dissertation is summarized in the final chapter (Chapter 6), which recapitulates the findings of the research in each of the chapters.

CHAPTER 1

INTRODUCTION TO THE DISSERTATION

The Global Importance of Boreal Forests

The boreal forests, named for the Greek god Boreas, god of the northern wind and bearer of the winter season, are the second largest terrestrial biome on Earth. Covering 17 percent of the terrestrial surface of the planet (Smith *et al.* 1998), northern boreal forests are located within the July 13° isotherm at their northern edge and the July 18° isotherm to their south (Hame *et al.* 1997). Forests within this range can receive temperatures from 22°C in the height of summer to lows of -70°C in the interior of the Siberian forests in Krasnoyarsk Krai in the dead of winter (Rumney, 1968). Light, soil, and precipitation gradients exist throughout boreal forests, resulting in a variety of different forest types with varying levels of productivity and biodiversity. Forests with biomass levels as different as 280 tons ha^{-1} (Cannell 1982) and 3.3 tons ha^{-1} (Ignatenko *et al.* 1973) have been reported, yet these forests may all be considered boreal forest or taiga. The boreal forests are a broad biome consisting of many different forest types yet in total make up 25% of the world's total forested area (Soja, 2004).

Globally, boreal forests are fundamentally important to the current functioning of the Earth's climate system because of a combination of their scale, properties, and location. Due to their range, boreal forests cover a large portion of the terrestrial surface; therefore, their land cover type and their physical properties influence both regional and synoptic climate. To this effect, boreal forests are the most influential upon global mean temperatures of any terrestrial biome on Earth (Snyder *et al.* 2004). Generally, albedo in the boreal forests is low, with coniferous canopies having low values and deciduous canopies having slightly higher values; this trend is amplified in winter when deciduous canopies senesce and radiation is allowed to reflect off of the snowy surface while coniferous canopies maintain their general albedo values. The albedo of this biome influences the absorption of solar radiation and the energy budget of the region. Additionally, boreal forests range in the magnitude of their sensible and latent heat fluxes, which influence regional energy budgets (Chapin *et al.* 2000). As a result, boreal forests seriously affect the regional climate. Results from modeling studies in which boreal forests are removed caused a general cooling of the region (Bonan, 1992) and added positive feedback to glaciation processes (Meissner *et al.* 2003). In studies where boreal forests are expanded through treeline migration, a warming effect on the region is often the result (MacDonald *et al.* 2008).

The boreal forests contain large stores of carbon, around 200 Pg globally within their vegetation and soils (Bonan, 2008), and serve as a biomass sink of 0.68 ± 0.34 billion tons of carbon per year, nearly 70% of which is in Eurasia (Myneni *et al.* 2001). In addition to storage in live biomass, boreal forests store between 25-35% of the total soil carbon on the planet (Humphreys *et al.* 2006). Fires, logging, and insect outbreaks are common disturbances within the boreal system and often are the sources of large amounts of carbon emissions due to their role in forest death. While land-atmosphere interactions of the boreal forest are, year-to-year, more influential upon the climatic system than forcing from carbon, one large disturbance can tilt the balance towards carbon forcing becoming the more influential characteristic of the system, particularly post-fire disturbance (Bonan, 2008). Thus, boreal systems through their carbon storage, interactions with the atmosphere, and large range, are influential on the world's climate patterns, more so than any other terrestrial biome.

In addition to their biogeochemical importance, boreal forests are home to nearly 20,300 different species identified to science (Ruckstuhl *et al.* 2008), containing large numbers of bird and plant species. Although sparsely populated by humans, the boreal forest is home to a multitude of indigenous populations who depend on the boreal forest for their subsistence and livelihood. Modern societies also depend on boreal forests for many different reasons. The extraction of natural resources, mainly forest products such as lumber, plant extracts, and fur, is common throughout areas of the boreal forest in Russia and Canada and make up a large percentage of the world's total harvest in those products, particularly wood fiber. Therefore, global boreal forests influence not just the Earth's physical processes, but biological, sociological, and economic processes as well.

Boreal Forests in Russia

A majority of the world's boreal forests are located in Russia. Forests spanning the Russian Federation are the largest contiguous terrestrial biome on Earth. Siberia, in particular, is home to a large portion of these forests; nearly half (48%) of Siberia is forested, totaling 605 million hectares (Danilin and Crow 2008). This represents about 25% of the world's forests (Soja, 2004; Bradshaw *et al.* 2009) and about one-half of the world's total coniferous forests (Danilin and Crow, 2008). Russian forests store approximately 42.1 Pg of carbon in live biomass alone (Houghton *et al.* 2007), representing a significant storage of carbon.

Russia relies on its natural resources for an important part of its economy. In 2008, Russian growing stock of forest resources totaled 81.6 billion cubic meters, of which 800,000 hectares are clear-cut annually in Eastern Siberia alone (Danilin and Crow, 2008). The Russian Federation is the largest exporter of industrial round wood in the entire world (Solberg *et al.* 2010), supplying China and the European Union with a large share of its wood fiber. The forestry sector employed 849,000 Russians in 2006 (FAOSTAT, 2006), and its products affect the livelihoods of many more internationally that depend on Russian wood for trade, fiber, and fuel. In addition, Russia's forestlands provide ample other products including plants with medicinal value, agricultural crops, fur, berries, and nuts. Russian forests are a valuable natural resource for their country and for the international community.

Climate Change

Boreal forests are located in areas where large changes in climate have been occurring. Many studies have suggested that warming temperatures could have a large impact on these sensitive forests (Bonan *et al.* 1992; Kaplan *et al.* 2003; Chapin *et al.* 2000; Shugart *et al.* 1992). Projections from many models suggest an increase in annual mean temperature in the circumboreal region of between 1.3 and 6.3°C (Soja *et al.* 2007; ACIA, 2004). Already, several signs of warming temperatures in the boreal regions have been observed. Stocks *et al.* (1998) reported that some areas of Canada and the Soviet

Union have recorded a warming of 2-3°C since the 1970's. Briffa *et al.* (1995) examined dendrochronological samples from Siberia and noted that temperatures have been increasing compared to the past several centuries. The current increase in wildfire frequency is also partially influenced by warmer temperatures in the past decade.

If model projections are accurate, the expected large increase in annual mean temperatures could severely affect the current composition of many of the boreal forests. While this change would likely result in increased productivity in some areas, it may also result in the release in large amounts of carbon from forest turnover, increased fires, and pest outbreaks. Additionally, increased temperatures may allow for conditions conducive for northern treeline advancement. It is critical to understand how boreal forests will respond to changes in climate, such that the implications of climate change may be quantified and proper forest management decisions can be made. Since the boreal forest influences regional and global climate, as well as our economic, biological, and social well-being, it is pertinent that the responses of these forests be examined thoroughly.

Modeling Ecological Change

Computational models are capable of successfully reproducing the vegetation communities present in many different areas around the globe. The boreal forest, due to its relative simplicity and lack of diversity, has been a prime area for vegetation modeling studies. Additionally, the boreal forest has been focused on because of its prime importance in influencing the Earth's climate. The boreal forest gap model FAREAST (Xiaodong and Shugart, 2005) was derived from the NEWCOP model (Shao *et al.* 2001) that simulated forests in northeastern China. Since its creation, it has been reformulated and applied to boreal and temperate forests of the federated territory of Russia. Gap models are named after the fact that they simulate the area of a gap created by the death of a dominant tree crown. While they generally simulate on forest plots that are relatively small in size, gap models can replicate many physical and biogeochemical characteristics of the forest plot not available in large-scale simulators. For instance, FAREAST can model carbon storage as well as nutrient cycling, structural characteristics of forest stands, and species composition.

This dissertation explores the detailed use of the FAREAST simulation model to investigate the response of Russian forests to changes in temperature and the ecological and economic repercussions. First, I expanded the coverage of FAREAST to the entire Federated Territory of Russia by creating a composite of weather, soil, and topographical inputs. Chapter Two examines this procedure and the accuracy of the expansion of FAREAST by comparing the results of its simulations of biomass carbon storage to biomass values obtained from satellite imagery. Next, I examined the behavior of several areas along the Central Siberian Transect, an International Geosphere-Biosphere Programme (IGBP) transect, in response to warming temperatures using the FAREAST model. These results, in Chapter Three, are interpreted with respect to ecological processes and give implications for how the ecology of this region may change with increased temperatures. In particular, the topics of migration and community and geographic response to warming are explored.

In the fourth chapter, I used FAREAST to re-examine the Central Siberian Transect and investigate the resiliency of interior forests of the Transect to warming temperatures, specifically with respect to differences in stand age. This experiment provides pertinent information as to how forests of different stand ages will respond to various temperature changes, a characteristic important in determining the resiliency of the current standing stock of forests to projected climate change. Finally, in the fifth chapter, I combined the output of the FAREAST model to a proven economic timber and carbon forestry model developed by Gutrich and Howarth (2007) and later modified by White and Lutz (in development). I simulated several areas of Russian forests that are currently used by the logging industry and determined their profitability for both timber and carbon projects; additionally, I investigated the effect of warming temperatures upon each project's profitability and make suggestions as to the possible economic effects of a 2 and 4 degree Celsius warming trend in these regions.

In total, this work attempts to discover complex biological responses of Russian forests to warming temperatures by using a forest gap model. These results are interpreted as to their ecological and economic ramifications, since these calculations will help advance the scientific and planning community's understanding of how future decades of warming will affect these forests. Through this work, forest management may find insights into planning decisions that mitigate the impacts caused by warming temperatures; this is the motivation of study.

CHAPTER 2

CONTINENTAL SCALE APPLICATION OF A RUSSIAN FOREST GAP MODEL

Abstract

Boreal and temperate forests in Russia are facing the effects of a warming global climate and can be considered one of the major areas of focus for climate change-related ecological study. While current methods of large-scale forest modeling tend to utilize dynamic global vegetation models (DGVMs) due to their ability to simplify forests into functional types and their ability to interact with climate models, DGVMs lack the specificity and detail that will be integral for precise ecological and biodiversity-related studies. In this paper, the forest gap model FAREAST is modified to simulate over 26,500 locations across the federated territory of Russia; the output of these model runs is compared to biomass data compiled from a combination of forest inventory and remotely sensed ecological data. When mature forest locations were compared directly, FAREAST results related to the derived biomass data with an r^2 of 0.87 ($p < 0.0001$) indicating a close connection between the two data sets. While FAREAST underestimates boreal forest biomass on average by nearly 30%, these estimations are less than one standard deviation from the mean (0.355). These model results can be used in conjunction with DGVM data specifically for regional and continental scale studies, especially those using remote sensing techniques for validation of remotely sensed data sets, and will have important ramifications for model projections of ecosystem response to climate change.

Keywords: boreal forest, remote sensing, model, carbon, biomass, DGVM

Introduction

The Russian boreal forests are the largest contiguous forested biome on Earth and are capable of influencing regional and global climate. Particularly, the rearrangement of boreal forest species in response to anthropogenic disturbance and climate influences may instigate climate change feedbacks through land-atmosphere interactive processes (Chapin *et al.* 2000). The conservative estimate of 42.1 Pg of carbon stored in live biomass in Russia (Houghton *et al.* 2007), around 25% of global terrestrial biomass (Conard *et al.* 2002), dwarfs the entire annual carbon emissions of the United States by nearly 27 times (Blasing *et al.* 2004). The release of this carbon, through both forest fire and degradation following insect outbreak, is significant (Zhang and Alfaro 2003; Shvidenko and Nilsson 2003; Baranchikov *et al.* 2002) and may alter global concentrations of CO_2 and CH_4 (McGuire *et al.* 2007). Understandably, these ecosystems are the focus of many modeling studies in order to investigate their role in global change (e.g. Gustafson *et al.* 2010; Tchebakova *et al.* 2009; Bonan *et al.* 1992, 1995).

Several recent studies document the mounting evidence that Russia's forested ecosystems are subject to fluctuations in climate and disturbance (Soja *et al.* 2007; McGuire *et al.* 2007). The ramifications of this warming and increased disturbance could have serious implications for human societies and future climate fluctuations in the context of global change; changes in disturbance regimes and climate affected by warming temperatures will likely exert influence on the species distribution and land cover change in the boreal forest regions. Air temperature changes can alter soil characteristics, which in turn make localities more or less tolerable for certain boreal forest tree species (Ustin and Xiao 2001). Changes in climate and fire intensity additionally may affect species dynamics, and therefore land cover, in the boreal forest by altering successional dynamics (Soja *et al.* 2004; Amiro *et al.* 2001; Soja *et al.* 2007). These land cover changes will alter regional climate through modifications in surface albedo and land/atmosphere energy fluxes (Bonan *et al.* 1992; Beringer *et al.* 2005; Amiro *et al.* 2001; Chapin *et al.* 2000; Soja *et al.* 2007; Baldocchi *et al.* 2000), as well as alter global climate through carbon sequestration/release patterns (Gaveau *et al.* 2003, Bonan 2008). Essentially, high latitude forests, including Russia's forests, are areas of importance in the field of global change biology.

Currently, the most frequently used computational forest model type for investigating the large expanse of Russian boreal and temperate forests are termed dynamic global vegetation models (DGVMs). DGVMs are technically a combination of equilibrium models and biogeochemical ecosystem process models designed to simulate biosphere dynamics for any system under various climate conditions (Prentice *et al.* 2007); they are commonly nested into general circulation models (GCMs) in order to investigate ecosystem feedback and response to changing climate scenarios. These models, due to their scale and computational expense, generally use a handful of plant functional types (PFT) which represent broad vegetation classifications in their simulations. For example, the CLM 3.0 model's DGVM component uses 10 PFTs (Alo and Wang 2008); in this example, four PFTs would be considered for simulating Russia's forests. Large broad models such as these are the only models that have completely simulated the federated territory of Russia's forested expanse to the authors' knowledge.

While DGVMs are used to investigate the role of forests in global and regional climate processes, they carry specific limitations due to their structure and scale of resolution. Since DGVMs summarize their forests into aggregate plant functional types, they lose the ability to predict how biodiversity will respond to changes in environmental conditions (Purves and Pacala 2008). In direct comparisons between an individual-based model and a DGVM throughout Europe, Smith *et al.* (2001) found that the individual-based model was more capable of predicting forest composition for areas where multiple functional types overlap. This group therefore recommended that individual-based approaches be used for regional to continental-scale studies in order to maximize accuracy. Because PFTs utilized within DGVMs are specific to parameterization, it allows for divergence of results amongst different DGVMs (Sitch *et al.* 2008); by reducing specificity in terms of species response, the output of these models is more variable on the whole. Notable among the DGVM community is the work of Moorcroft *et al.* who included individual stand-level dynamics following the work of Kohyama (2001) as well as Sato *et al.* (2007; 2009).

In addition to losing contrast because of a reliance on PFTs, DGVMs are not fully capable of modeling disturbance events that take place on the scale of individual trees. Particularly absent is the role of forest management and logging, which has yet to be fully implemented in a DGVM scenario. Disturbance from fire has been included in some DGVMs, notably the MC1 DGVM, but output is mostly in terms of total burned area (Lenihan *et al.* 2008; also Sato *et al.* 2007). Since disturbance can have such significant impacts on regional and global change processes, it seems that DGVMs require supplementation in order to address important issues in the field of global ecological change.

Individual-based dynamic gap models typically are those that simulate individual trees, their growth, mortality, and decomposition into litter in a relatively small area, typically the size of a forest gap (Urban and Shugart 1992). Generally, these models often are non-spatial, in that they do not include spatial interactions between each small area that they simulate; yet, these models typically contain ecosystem processes such as nutrient cycling and interaction with the local abiotic environment (Scheller and Mladenoff 2007). Although their size is generally fine scale, they contain large amounts of information at detailed resolution, which is of importance for regional mapping and predictions.

While computational and input constraints have typically hampered efforts to model large areas with these types of models, their detail may prove important with respect to more precise estimates of the intertwined relationship between Russian forests and regional and global climate. Most gap models resolve to use species data for their simulations, thus providing particular information that may be lost using a DGVM. They also can be configured to simulate individual tree stems, such that disturbances such as logging and fire can be simulated. Additionally, the use of this type of forest model may be configured to provide fine-scale information that could be used for forest managers regarding very specific areas within the Russian forests while simultaneously explaining larger scale dynamics. Specifically, stand level and individual-level data can be useful for validation with fine-scale remote sensing systems. Recently, satellite-derived estimates of forest height and structure from LiDAR sensors have been examined; results of these projects indicate that such estimates are accurate (Bergen *et al.* 2009; Lefsky *et al.* 2005; among others). Since DGVM combinations with remotely sensed forest products occur mostly with variables measured at large spatial extents (e.g. Smith *et al.* 2008), running a gap model in tandem with a DGVM may provide data that could be used for satellite validation and coordination.

In this study, we investigate the configuration of a dynamic individual-based gap model (FAREAST) to simulate the forests throughout the country of Russia. FAREAST (Yan and Shugart 2005) has been developed to particularly focus on the silvics of Russia, Northeastern China, and Eastern Europe. Following previously successful tests in China (Yan and Shugart 2005) and Siberia (Shuman and Shugart 2009), we expand the scope of the model to over 26,500 unique site locations, effectively blanketing Russia, to investigate the potential to use this particular model for future studies of global change in the region; specifically, we anticipate using this model to investigate responses of the system to fluctuations in disturbance and climate. By comparing FAREAST biomass output to a dataset of forest biomass derived from a combination of forest inventory data and remotely sensed data, we attempt to make the case that this model is fully capable of demonstrating accurate simulations of the Russian boreal and temperate forests.

The results of this study will address a question of importance in the global change modeling community. Specifically, are DGVMs the only modeling technique that should serve us for large-scale studies? Is an individual-based gap model of forest dynamics capable of effectively modeling forest variables on a continental scale? If so, should we rethink our modeling strategies so as to capture all forest variables using both techniques and allow our modeling methods a way to be tested using remotely sensed data? This paper questions if a forest gap model is able to model forest biomass successfully, examines the results of a continental-wide test of this model, and interprets the significance to the global change community.

Methodology

Site Construction

The FAREAST gap model requires specific input information in order to simulate the forest vegetation of any particular location. These inputs, outlined in Yan and Shugart (2005) include site-specific climate, biogeochemical, topographical, and tree species information. Of greatest importance to the functioning of the model are the input climate parameters. These parameters include monthly mean minimum and maximum air temperatures, monthly mean precipitation in millimeters, and the standard deviations of the temperature and precipitation values (Yan and Shugart 2005). Soil biogeochemical information is also important to the functioning of the model, and specifics such as field capacity and available carbon and nitrogen levels in soil layers are required for FAREAST to accurately simulate forests. Topographical information such as elevation and latitude are also used within model functioning.

Weather information for each site was derived from a 60-year record of conditions at stations located throughout the country (Razuvayev *et al.* 1993). These station data included the necessary temperature and precipitation data that the FAREAST model requires. In order to generate sites where the model could be tested, an interpolation procedure was used to create accurate climate information for the entire study area. Precipitation and temperature data were generated using the interpolation procedure; the results of this procedure were tested with several sites. The FAREAST model was run using both interpolated data and station data removed from the interpolation process. Both model output leaf area index and biomass were not significantly different ($p < 0.05$) suggesting that the interpolated data could be used.

Soil and biogeochemical information was derived from the Land Resources of Russia dataset from the International Institute for Applied Systems Analysis and the Russian Academy of Sciences (Stolbovoi and McCallum 2002). This dataset contained information regarding the particulars needed by FAREAST to function. Elevation and slope information was derived from the Shuttle Radar Topography Mission (SRTM) (Farr *et al.* 2007). These cumulative data were then amalgamated within a GIS-processing program in order to effectively manage the vast number of sites. Each site was constructed as the compiled data from a 484 km^2 square cell. In the case of data that had already been generated in GIS, the input information was re-sampled using a nearest-neighbor sampling methodology to fit the scale of each site. In the case of generated data, information was fit to this particular cell size upon importation into GIS. Figure 2.1 gives a sense of the scale of the coverage of these sites.

Biological Parameters

The FAREAST model requires species specific information in order to simulate forests. These inputs, outlined in Yan and Shugart (2005), focus on the particular abilities of tree species to respond to biotic and abiotic stimuli. Following Shuman and Shugart (2009), ten basic genera of the Russian temperate and boreal forests were used within the simulation, each containing multiple species. An additional assortment of rare deciduous and coniferous species was also included. Updated species parameters and European species increased the total number of tree species used in these model runs to 57 (Shuman 2010)

In addition to biological parameter inputs, detailed information about which species grew at which particular site was considered when running the model. A series of historical range maps were digitized and imported to the GIS framework containing all of the sites. Each site was then restricted to grow only those species that have been observed within their boundaries. This work is documented in Shuman *et al.* (2010) and greatly increases the accuracy of the FAREAST model. Previous simulations without these range maps yields species growing in areas well outside of their observed ranges. This range map inclusion eliminated over 7,000 sites from the original 33,595 since no trees were observed to grow in these areas.

Run-time information

Following site definition, the FAREAST model was initialized over each of the remaining 26,500 sites. For each site, 200 individual plots of a spatial resolution of one-twelfth hectare were simulated. These plots were then averaged in order to remove variability within each individual plot and to serve as a representation of all forests in the area. Each site was simulated for 500 years. Over this time period, the simulated forests were able to enter gap-phase dynamics. The outcomes were not purely a result of stand succesional dynamics; in other words, this time frame allowed for the establishment of a mature-phase forest while the average over 200 plots encapsulated the many different stages that a forest could be in at any one time.

Validation mechanism

Following the simulation of the 26,500 sites throughout Russia, the plot-averaged data were collected at year 500. In order to validate the proper functioning of this model, this information was compared with a dataset containing records of the measured biomass for forests throughout Russia. A biomass product generated from a combination of data from Russian forest enterprise stock volumes, species specific biomass conversion coefficients, and spatial forest boundary and composition information from the GLC2000 dataset (Bartholomé and Belward 2005) was used to validate the outputs of FAREAST for each site.

Since historic disturbance information was not available for every site, we removed all forests from the validation exercise that were not mature. This ensured that the results of the model could be compared to forests of a similar age and successional stage. To remove the younger forests from the validation dataset, we created a mask of sites that consisted of forests with a leaf area index (LAI) of 3.0 or greater. Only biomass information from sites located in areas with a leaf area index of this value were used to compare to the FAREAST output. The LAI mask and biomass datasets were both products of the Center for Ecology and Productivity of Forests, part of the Russian Academy of Sciences, in Moscow. Using the LAI mask, the total number of comparison sites between FAREAST and ground data were 5,698 unique sites. The LAI mask is displayed in Figure 2.2.

Statistical analysis of the two datasets was performed in both Microsoft Excel 2007 and SAS 9.2. A two-tailed student’s t-test was conducted on the results as well as a linear regression procedure to determine the relationship between the modeled data and the observed data. After initial analysis of the data was conducted, outliers were removed and the statistical procedures were performed again. The outliers were defined as plots in which FAREAST simulated forest biomass while the land-cover dataset indicated a lack of forest cover.

Results

A map of the FAREAST results for much of European Russia can be found in Figure 2.3. The results of this validation exercise can be found in Figures 2.4 and 2.5. Figure 2.4 shows the results of the linear regression between the FAREAST model output and the biomass database for areas with an LAI of over 3. The results of this analysis suggest that the FAREAST model related to the biomass database according to the formula:

$$\text{FAREAST biomass (t/ha)} = 0.6696 * \text{Derived Biomass (t/ha)}$$

The two-tailed Student’s t-test for samples with equal variances signified that the two datasets were significantly related ($p < 0.0001$). The r^2-value for the regression line between the two datasets, when forced through zero, was 0.7861. This signified a high success rate of the FAREAST model for simulated biomass dynamics throughout these forests.

Figure 2.5 shows the results of the linear regression between the FAREAST output and biomass database when outliers are removed. The outliers that were removed in this case were data in which the biomass database contained values of zero while the model returned more realistic values. This type of outlier was likely a result of either disturbance occurring on the ground resulting in a value of 0 for the biomass database, or, a misalignment of the LAI mask with the biomass database. When these 518 values were removed, the relationship between derived biomass and FAREAST results remained the same in terms of the slope of their regression; however, the R^2-value for this relationship increased to 0.8721 ($p < 0.0001$) indicating a very close connection between the two data sets.

The FAREAST model generally underestimates biomass for the simulated sites throughout Russia. While the biomass dataset from the CEPF gave estimates of biomass as high as 200 tons per hectare, rarely did the FAREAST output reach that level. Additionally, the FAREAST data were clustered around the 60 tons per hectare level, with the majority of FAREAST output occurring between 60 and 100 tons per hectare for mature forests. The average of the residuals between the dataset and FAREAST values for all 5,698 sites was 15.04 t/ha, suggesting that the model underestimated biomass by that value on average. The FAREAST model underestimated forest biomass across the board, seemingly regardless of forest classification. Comparing the residuals by forest type as classified with SPOT-VGT multispectral data compiled by the CEPF-RAS, the FAREAST model underestimates forest biomass for all forest cover types; only areas classified as marsh and swamplands or croplands saw the FAREAST model overestimate forest biomass.

Discussion/Conclusion

FAREAST simulations underestimate the total biomass of mature Russian forests. The linear regression of these two datasets suggests that FAREAST simulates forest biomass below what is measured in the field by about 30%. Because the average biomass value from the inventory and remote sensing dataset is 91.1 t/ha, on average FAREAST only underestimates forest by less than one standard deviation, or 0.355 standard deviations across the dataset. Thus, although there is around a 30% underestimation of biomass on average, forests throughout this region have relatively low biomass levels overall, so that this error value more often than not is minimal. What is most important about this comparison is less the error than the r^2 which, when outliers are removed, reaches 0.872. So, even though FAREAST underestimates biomass slightly, it does so very consistently, which is important since a detailed investigation for the underestimation could solve the underestimation issue; if the model, however, were inconsistent, the problem would not be as easy to fix, but since it seems to occur across all landscapes in this study, it suggests that revisions may be able to address the issue.

There appeared to be no particular forest type that was more difficult to model accurately. When model results were analyzed with respect to classification, no particular forest type varied in accuracy. All forest types were underestimated by FAREAST consistently. Geographic location also did not seem to affect model function. FAREAST performed equally across all regions of the study area despite there being vastly different climate regimes throughout this range. This suggests that the model is robust enough to model consistently with changes in climate, as was suggested by Zhang *et al.* (2009).

There is likely a degree of error in the comparison dataset due to constraints of spatial scale as well as remote sensing technology. Data for comparison from the CEPF was a combination of data from forest enterprise stock volumes, species characterizations, and remotely sensed data. The spatial scale of this information was compiled and re-sampled in order to generate biomass values per hectare across the range of each study site. While FAREAST used biogeochemical inputs from a similarly sized study site, likely both of these approaches mitigated the highs and lows of each site. However, this type of error is unavoidable when trying to model over such a large territory. Without these generalizations, there would be no way to compare the model over such a large range. Since the validation product and the input values were documented in the scientific literature, we have confidence that their values are accurate and thus are useable within and comparable to FAREAST in the manner described in this paper.

The results of the FAREAST simulations for the Russian boreal forests have several implications. Firstly, in the context of individual-based gap model functioning, these iterations of FAREAST served as highly accurate for predicting biomass over an area around 2.75 million km^2, especially considering the diversity of conditions that cover this area. In comparison to other large-scale gap model projects, FAREAST excels. Pabst *et al.* (2008) examined the ZELIG model, a relative cousin to FAREAST, throughout the Oregon Coast Range. While this study investigated the output parameters basal area and number of trees per plot and not biomass, their results are comparable. For all control plots in one area of the park, ZELIG varied from observed basal area on average by 1.4 standard deviations; throughout another area of the park, the model differed by an average of 5.6 standard deviations (Pabst *et al.* 2008). The results of the FAREAST validation study showed that FAREAST differed, on average across all 5,698 sites by 15.04 t/ha, or just 0.355 standard deviations from the mean.

There have been other gap-model studies that investigated the comparison of a handful of simulation runs to observed stand-level data. Bugmann and Solomon (2000) used the FORCLIM V. 2.9 in areas of the Pacific Northwestern United States, central Europe, and eastern North America. Didion *et al.* (2009) updated FORCLIM and applied it in the Swiss Alps. The ZELIG gap model has been applied to many different areas throughout the world since its creation (Larocque *et al.* 2006). However, rarely are these types of models run over large spatial areas. The FAREAST model, because of its parameterization with a robust dataset and due to the relative ecological simplicity of the area that it simulates, is capable of replicating biomass dynamics for a large area. Simply put, this model application raises the bar for accuracy with respect to replicating forest dynamics by individual-based gap models.

The application of landscape models to large spatial areas is still difficult. Xi *et al.* (2009) note several of the problems that face the expansion of small spatial scale models to a wide expanse of forest. Firstly, running gap models require precise parameterization and significant investments in computer processing (Xi *et al.* 2009). The data for the parameterization of FAREAST was collected from decades of historical Russian forestry stand data archives through extensive collaboration between their developer and the Russian Academy of Sciences; additionally, the boreal and temperate forests of Russia are relatively ecologically simple, and thus lend themselves to be modeled with a limit to the complexity of parameterization that is required in New World temperate or tropical forests. Computer processing power was addressed by linking three SAS RAID Dell PWS t3400 machines each with 2.5 GHz of memory and a total of 2 TB of storage, and simulations were completed over the course of 10 days. The simulation of each 1000 sites required an average of 8 hours to complete. We expect, though, that as average computing processing time reduces according to Moore's Law, the application of gap models such as FAREAST will not be limited by computer processing time.

Xi *et al.* (2009) also contend that landscape modeling efforts, particularly over large spatial scales, face technical challenges with respect to model validations (2009). By using a combination of detailed forest inventory records and remotely sensed data from the CEPF at the Russian Academy of Sciences, there was a significant amount of data with which to validate FAREAST. In fact, future efforts in fine-tuning FAREAST include the comparison of LAI as well as more qualitative aspects of Russian forests to the entire CEPF dataset. But Xi *et al.* (2009), in their explanation, point out, perhaps without intention, exactly why individual-based forest gap models should be considered and applied for large-scale modeling problems: the apparent lack of validation data. Since individual-based gap models such as FAREAST produce the parameters that are also extracted by sensors found on satellites and airborne spacecraft, there is a wealth of comparable datasets with which to validate these types of model results. This study is one of the first to examine the comparison between remotely sensed data and a forest gap model in Russia, and suggests that such a practice should be investigated further.

DGVMs, despite their ability to examine much larger spatial extents as well as determine forest influences on climate, have fewer parameters with which to compare to this remotely sensed type of dataset. A review of DGVM studies suggest that DVGM generated aboveground biomass values are practically non-existent within the literature. It thus seems sensible to suggest that individual-based gap models be either built into DGVMs, or at the least, developed and run alongside DGVMs to generate data that can be verified with satellite sensing systems. This practice will provide output that not only is easily comparable to existing remotely sensed datasets but will also generate fine-scale forest composition details that are essential for understanding many aspects of the ecosystem, especially in the context of global change, that are lost in the spatial scale of DGVMs. By testing the FAREAST model throughout Russia and generating results with a high degree of accuracy, we believe that it is possible to model the fine-scale specifics of forests over a large range of sites throughout a continent in the boreal system successfully. Future tests and applications of FAREAST are currently running in an effort to understand the limitations of the model. The most appropriate future study would be the coupling of FAREAST with a DGVM, or at least the mutual simulation of a similar area in order to investigate the differences between these two model types. Although DGVMs and individual-based gap models differ in their output and approach, perhaps together they may provide the scientific community with the full range of outputs necessary to fully take on the most difficult global change problems.

Figure 2.1: A map showing the scale of plot sizes in European Russia. Over 26,500 of these 484 km^2 cells were used to model the forests of the federated territory of Russia. The red box indicates the relative size of one unique site modeled by the FAREAST model. The study sites were not limited to European Russia, stretched from border to border across the country, and were confined to range maps based on historical observation of species ranges.

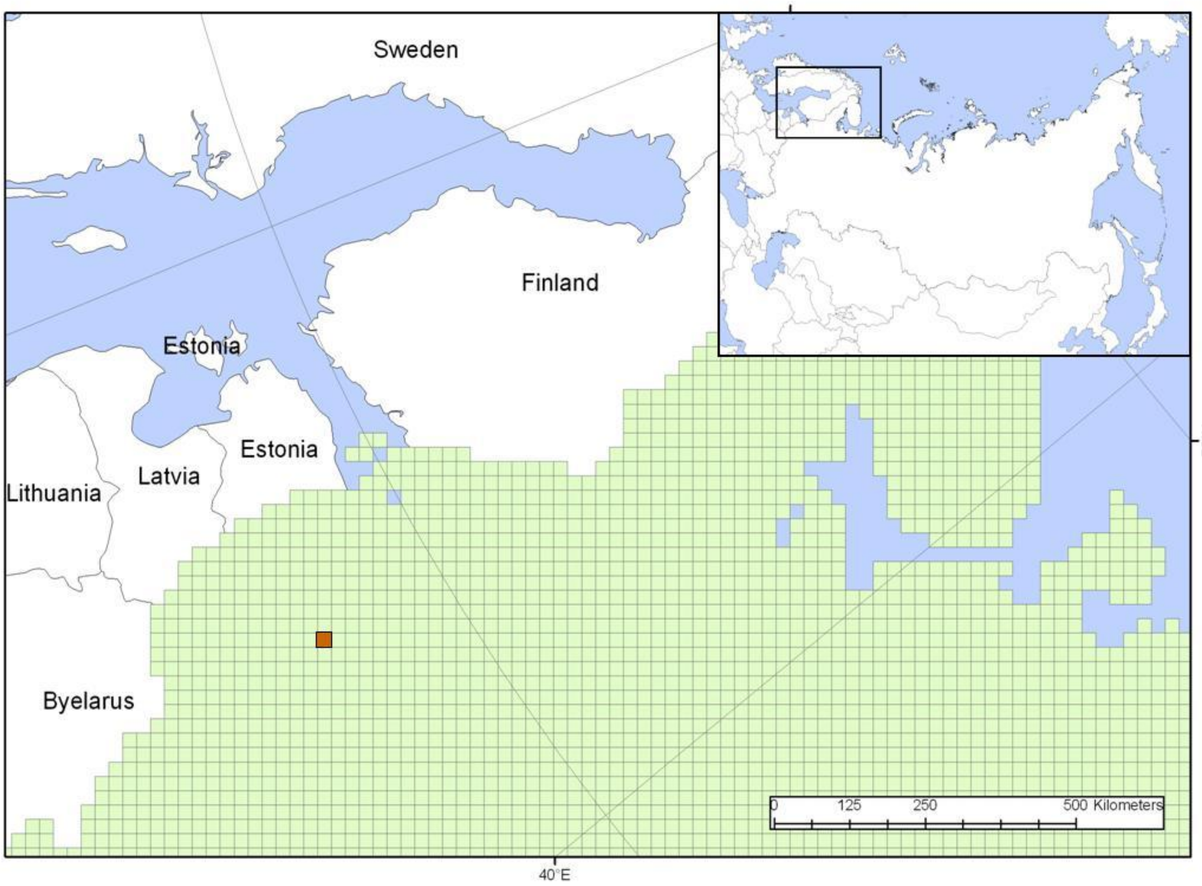


Figure 2.2: The Leaf Area Index mask used to separate out mature forests. Shaded areas represent forests with a leaf area index greater than 3. Leaf area index was derived from the MODIS LAI product and was processed by the CEPF-RAS. Notice the areas of mature forests in a central latitudinal belt across the country, particularly in Central Siberia.

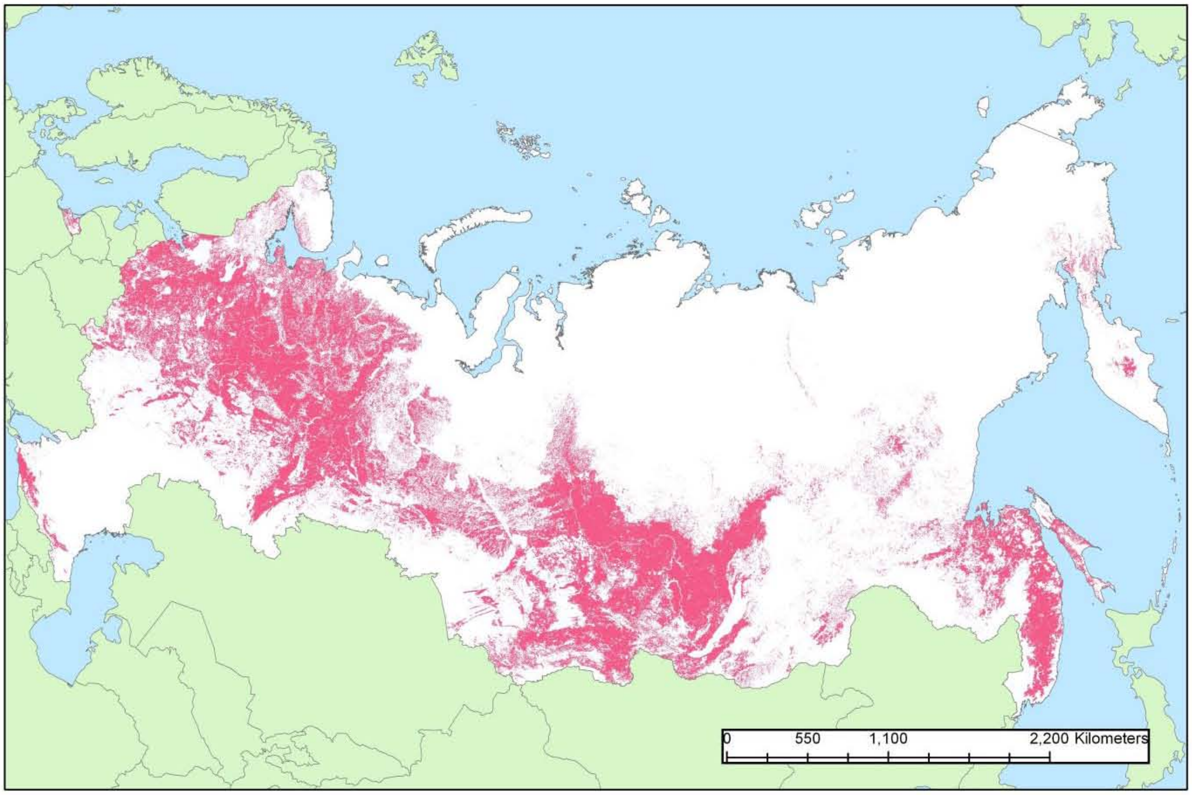


Figure 2.3: FAREAST model results for Western Russia for areas masked by the LAI mask. Each circle represents a site, with darker values representing forests with larger quantities of biomass. These results were compared with the forestry enterprise and remote sensing database. Note the lack of sites in Southwestern Russia, an area markedly used for agricultural production.

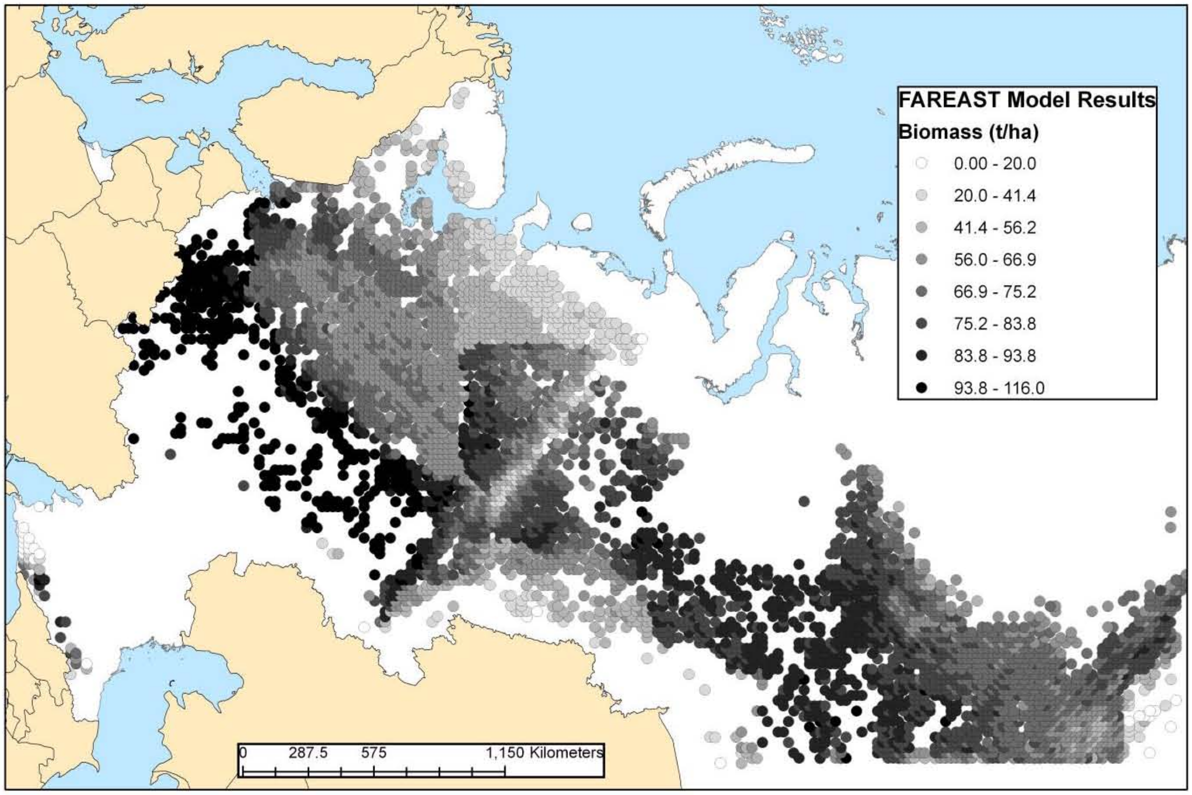


Figure 2.4: Comparison between forest inventory and remote sensing dataset and FAREAST results of site biomass in tons per hectare. The slope of the linear regression between the two variables is 0.6696 and the r^2 of the regression line is 0.7862. This chart contains over 5,000 data points, many of which are not visible but are centralized around the linear trendline.

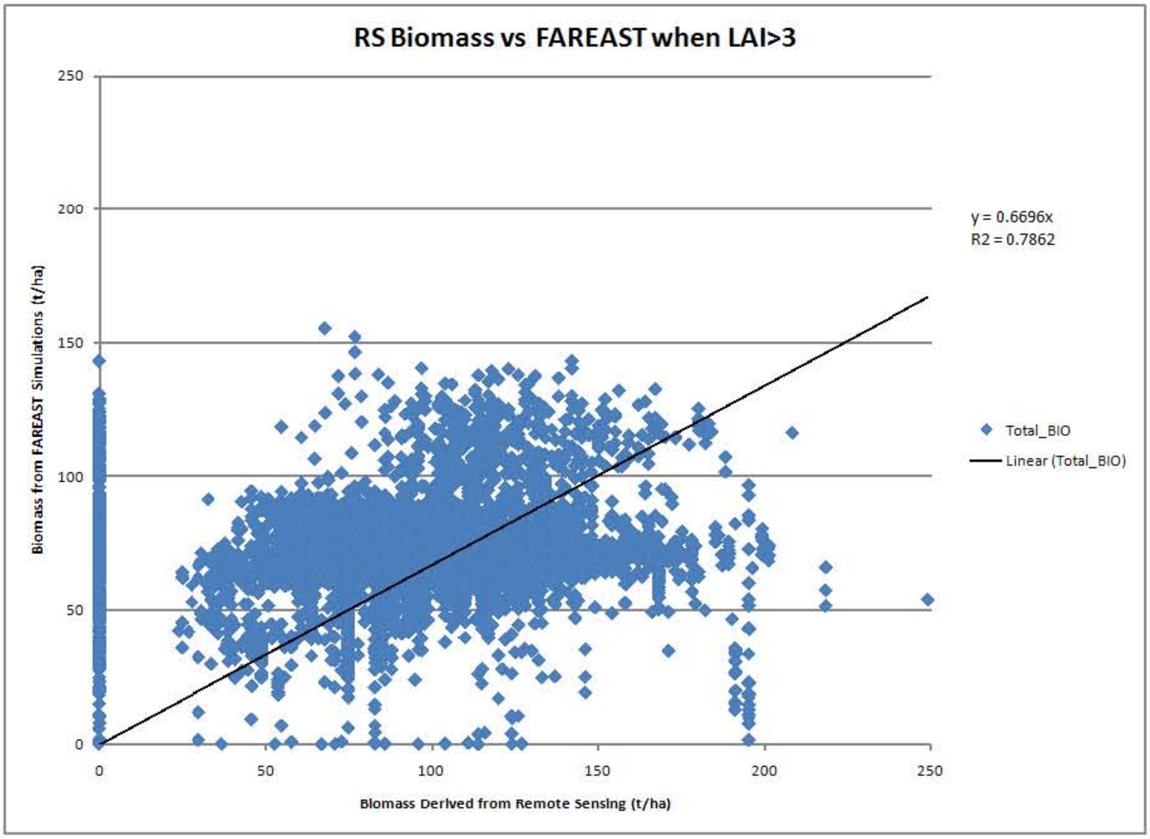
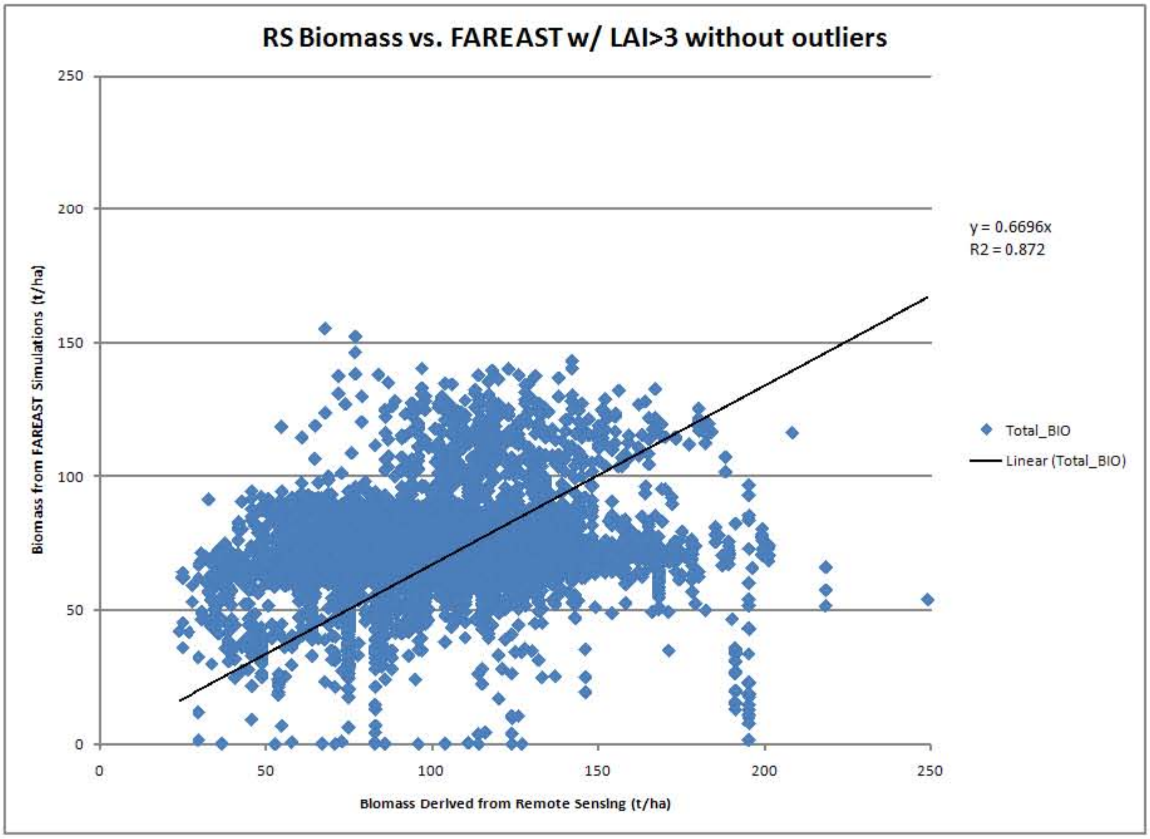


Figure 2.5: Comparison between forest inventory and remote sensing dataset and FAREAST results of site biomass in tons per hectare. The removal of outliers increases the r^2 value for this regression to 0.872. Note the heavy density of forests between 50 and 150 tons per hectare, indicating the relative average carbon storage of mature forests in this biome.



Chapter 3

CLIMATE CHANGE SCENARIOS, LEADING AND TRAILING EDGES, AND DISCRIMINANT ANALYSIS IN RUSSIAN FORESTS

Abstract

Understanding how forested ecosystems respond to changes in climate is important for biodiversity and conservation management, natural resource management, and for accurate future global climate projections. This project simulates the International Geosphere Biosphere Programme (IGBP) Central Siberian Transect with the forest gap model FAREAST under different levels of warming. Results from discriminant function analyses suggest that the leading edge of Russian boreal forests are resilient to composition change and instead change physiologically for individual trees. Interior forests are more likely to show the ramifications of warming particularly by changes in plant productivity and carbon storage. Without disturbance, community composition changes do not occur in the interior forests until more than 100 years after the beginning of warming temperatures affect the area; this result is likely conservative as there is a minimum of disturbance simulated within the model. Most importantly, this study suggests that it will be difficult to discriminate and discern whether forests are changing due to temperature until at least 50 years after the warming begins. These results may affect how change detection projects are structured and may help forest managers elect proper scenarios for these areas.

Keywords: forest ecology, model, biomass, climate change, discriminant analysis

Introduction

As the scientific community focuses on the ecological ramifications caused by changes in global climate, a significant amount of interest has been placed on the response of forested ecosystems to warming temperatures (Foley *et al.* 2000; Xu *et al.* 2007; Luo, 2007; Bonan, 2008; Millar *et al.*, 2007). With the advent of sophisticated computer modeling techniques and long term field studies, researchers have been making small steps toward discerning how changes in temperature will affect vegetated communities, from physiological response (Rennenberg, *et al.* 2006, Dunn *et al.*, 2007) to community level shifts in composition (Kellomäki, *et al.* 2008). Modeling studies by scientists are also beginning to decipher how changes in the location and composition of vegetated communities, particularly forests, affect regional and global climate (Bonan, 2008; Bonan *et al.*, 1992; Starfield and Chapin, 1996). With recent estimates showing global mean temperatures in the past decade being the warmest in the past millennium (IPCC, 2007), and with projections estimating a rise in land surface temperatures throughout the 21st century in the boreal region (ACIA, 2005), understanding how forested communities will respond to changes in climate patterns is essential for biodiversity and conservation management (Heller and Zavaleta, 2008), natural resource management (Nitschke and Innes, 2008), and is critical for more precise and accurate global climate projections.

In this paper, we focus on the boreal forests of Russia. These forests, generally located between 13° C July isotherm and the 18° C July isotherm from north to south (Larsen, 1980; Soja *et al.* 2007), are the largest contiguous terrestrial biome on Earth. Due to the enormous amount of carbon they store, 42.1 Pg in live biomass alone

(Houghton *et al.* 2007), these forests are important in the global carbon cycle. Additionally, Russian boreal and temperate forests lie in regions that are expected to receive the most severe warming trends in the upcoming decades (Hansen, *et al.* 1996), with continental Siberia being particularly pronounced (Serreze *et al.* 2000). Several biogeographical models predict the movement of these boreal forests northward by an estimated 500 km or more (Kirilenko and Sedjo, 2007; Cramer *et al.*, 2001; Foley *et al.*, 1998). Many signs point to significant changes occurring in these areas, and it seems logical to investigate how forests will respond.

Boreal Forests at the Forefront

The global boreal forests are of particular importance with respect to how changes in global climate affect the ecology of the Earth's surface. There are multiple reasons why these ecosystems are so significant. First, these biomes make up an important part of the climate system (Chapin *et al.*, 2000; Bonan *et al.*, 1992; Bonan *et al.*, 1995). The responses of these ecosystems have consequences for regional and global climate, the former through land-surface energy exchange in the form of heat, water vapor, and momentum fluxes from the ground to the atmosphere (Beringer *et al.*, 2005; Amiro, 2001; Kharuk *et al.*, 2005; Snyder *et al.*, 2004) and the latter through carbon release into the atmosphere and storage in biomass (McGuire *et al.*, 2007). Understanding how this system will change under a variety of climate scenarios seems prudent and critical to mitigate further climatic effects. Second, these regions occur in areas where we have already seen some of the most significant warming trends and are also likely, according to modeling studies, to receive even more changes in climate in the near future (Soja, *et al.* 2007; Bonan *et al.*, 1992, Chapin *et al.* 2000, Snyder, Delire and Foley, 2004, Kaplan *et al.* 2003, Bonan, 2008). Finally, the forested parts of these regions have significant economic impacts since the extraction of forest products there affects the livelihoods of thousands of individuals around the world.

As a result, there have been a vast number of scientific projects focusing on how these systems have responded to warming temperatures. Several methodologies are common, including ground-based field studies, computational ecological models, and the analysis of remotely sensed images from space. In a sense, these regions serve as forecasters for how other forested ecosystems will respond to warming temperatures since they are located in areas undergoing significant climate change. Therefore, understanding the particulars of how the terrestrial ecological components of these regions will respond to a warming climate is essential for our ability to mitigate and adapt our management of these territories in the future.

Unfortunately for our ability to make simple forecasts, biotic responses to changes in climatic conditions are not immediate, particularly for long-living organisms such as trees. Animal species respond much more quickly to climate changes than do plants, with community-level responses in forests often delayed for decades (Davis, 1986, Davis, 1989). Early forest models indicate that forest communities may take as long as several centuries to change the dominant species type (Davis and Botkin, 1985). Although bioclimatic models suggest much quicker migration rates, for example 30-500 km per century given the right conditions (Kirilenko and Solomon, 1998), field studies using remotely sensed data do not show this type of immediate response (Masek, 2001). This slow lag time makes adaptation and mitigation strategies to climate change difficult to implement, since it is unclear exactly how a particular forest community will respond and what steps should be taken.

How are forest managers and natural resource planners expected to know how to adjust their strategies under changes in local and regional climate without an understanding of these lag times, or better yet, without a clear understanding of what to look for? Similarly, to echo Chapin *et al.* (2004), as forests migrate in response to warming temperatures, how do they do so? Does the entire forest move in a large swath, or are there regions of relative stability that are isolated from the change? These questions require the examination of an area of forested ecosystem that has been subjected to a variety of changes in climate. This study used the power of a validated and proven computational forest model to examine the ramifications of warming temperature on forests in Central Siberia.

A Matter of Scale

In order to understand how changes in forested communities take place and how forests respond to changes in climate, it is important to take into consideration several applications of scale. Ecological processes must be observed at the scale at which they emerge in order to properly understand them (Mitchell *et al.*, 2001; Levin, 1992; May, 1994). This applies not only to physiological scales (individual tree level response versus community response), but also to temporal (single year versus century time scales) as well as geospatial scales (leading edge, trailing edge, global observations). One issue in observing how forests respond to climate change is the inability to properly identify which of these three scales (physiological, temporal, or geospatial) investigations should focus on. As Mitchell *et al.* (2001) observed, by examining an ecological phenomenon at the incorrect scale, one can draw incorrect conclusions about how processes will change 2001. While Mitchell *et al.* (2001) were talking about the investigation of animal communities, the same holds true for forest communities.

Physiologically, trees in the boreal forest respond to warming temperatures by initially increasing production if they have the appropriate hydrogeological circumstances and conditions and are not water-limited (Pastor and Post, 1988), although this is not always true as there are many factors necessary for plant growth. Whole-tree chamber experiments have shown increases in productivity, diameter, and needle area for *Picea abies* when observed under increased temperature and CO_2 (Medhurst, *et al.* 2006). Boreal and temperate trees strongly respond to changes in temperature on a climatic gradient (Aitken, *et al.* 2008), but forest communities as a whole may shift in response to changes in climate by changing their species composition. This has been documented with the analysis of pollen held within lake sediments (McLachlan *et al.*, 2005; Pearson, 2006) and has also been suggested by numerous studies (Soja, *et al.* 2007; Goetz *et al.*, 2007; Rehfeldt,*et al.* 2003). In order to address how a forest is responding to increases in temperature, therefore, one must understand whether the response variable will be at a physiological, individual, or community scale.

Temporally, forests change in response to different environmental conditions based on their life histories and their individual species tolerances as well as biotic interactions. Short-term response of forests to warming temperatures may include increased net primary production (Hyvönen *et al.*, 2007; Devi *et al.* 2008) and carbon uptake by the existing vegetation. However, longer-term responses to warming temperatures include a shift in species composition due to the changing climatic envelope and the tolerances of different species to the growing conditions on the ground. Boreal forests are particularly sensitive to changes in temperature (Dullinger *et al.*, 2004; Hansen *et al.* 2001). In particular, many studies have suggested that the boreal forests may radically change their composition, from mostly deciduous species (e.g. *Larix siberica*) to coniferous evergreens (e.g. *Pinus siberica*) (MacDonald, *et al.* 2008; Chapin III *et al.* 2004; Kharuk, *et al.* 2005). Thus, depending on the time scale at which climate change has occurred, an observer may find a variety of responses. It is important then, in order to plan accordingly, that we understand the timeline of forest responses to warming temperatures in the boreal forest, since different types of changes may be observed depending upon the frequency of observation.

Finally, since boreal forests exist over a large territory throughout Russia, there are many different forest responses depending on the geographical location of the forests in question. There is a significant number of studies investigating the northern Russian and boreal treeline (Esper & Schweingruber, 2004; Kharuk *et al.*, 2006; Masek, *et al.* 2001) with varying results. Treeline has been constantly referred to as an important area to investigate for the first indication of ecological response to changes in climate (Guisan *et al.*, 1995; Dullinger *et al.* 2004; Næsset and Nelson, 2007; Thuiller *et al.*, 2008) due to basic principles of ecological theories on range expansion and colonization; yet recent attention has been placed on various other elements of the boreal forest. The trailing edge is an important area in terms of serving as a stronghold of species diversity (Thuiller *et* *al.* 2008; Hampe and Petit, 2005) but is critically understudied in the boreal forest. Additionally, the interior of the boreal forests has been suggested to be a location of initial resiliency followed by rapid and massive community transition given a steady increase in temperature (Chapin, 2004).

This study thus investigates many different scales of boreal forest response to changes in temperature. We use the boreal forest gap model FAREAST (Yan and Shugart, 2005) to simulate an area representing 1,000,000 square kilometers within the International Geosphere Biosphere Programme – Global Change and Terrestrial Ecosystems (IGBP-GCTE) Western Siberia Transect (Steffen and Shvidenko, 1996; McGuire *et al.* 2002). Over 1800 individual sites within this area were modeled under current climate conditions as well as with a steady ramp-up of temperature to a maximum increase of 4°C. Using canonical and discriminant analyses, we investigated multiple physiological, temporal, and geospatial scale responses of Siberian forests. The large study area was divided into several latitudinal transects in order to discern various geospatial responses (leading edge vs. trailing edge). Through this analysis, we attempt to discern the various forecasted responses by forests to increasing temperature in Siberia at different scales (physiological, community, geospatial); this type of analysis can then be used for mitigation and further study depending on the scale of interest.

Methodology

The FAREAST model is an ecological forest gap model created to simulate the dynamics of Eurasian forests (Yan and Shugart, 2005). Originally developed to focus on north-eastern China and the easternmost areas of Russia, it has been expanded and developed to model a variety of forests in the Russian boreal zone (Shuman and Shugart, 2009; Chapter 2) as well as investigate climate change scenarios (Zhang *et al.*, 2009; Huo *et al.*, 2009; Shuman and Shugart, 2009). 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 Shugart (1984) and Yan and Shugart (2005). Essentially, FAREAST simulates boreal forest stands with species-level discretion, but also reports biophysical parameters of forest trees as well as biogeochemical conditions of the stand.

A total of 1872 sites were created within the IGBP-GCTE Central Siberia Transect (CST) (Steffen and Shvidenko, 1996). This transect spans the latitudes between 59° and 69° N in the federal department of Krasnoyarsk Krai, Russia (McGuire, *et al.* 2002). Each site was generated by accumulating the environmental conditions in a 400 square-kilometer rectangular area. These sites were evenly spaced amongst the CST so as to capture variability that can arise due to slight topographical and geochemical conditions as well as to investigate leading and trailing edge conditions. Most soil values for these sites were derived from the Land Resources of Russia IIASA database (Stolbovoi and McCallum, 2002), while several were kept constant throughout all sites due to their limiting influence on model results. A list of soil variables used in FAREAST can be found in Yan and Shugart (2005). Elevation and slope information was consolidated from the Shuttle Radar Topography Mission (SRTM) dataset (van Zyl, 2001).

Climate information for each site was derived from a 60-year record of conditions at weather stations across Russia (Razuvayev, V. N. *et al.* 1993). Point station data was interpolated to create accurate climate information for the entire study area. Tests performed on sites created by the interpolation procedure and control points not included in the procedure indicated that model output of leaf area index and biomass were not significantly different between datasets (p<0.05) indicating that the interpolation could be used appropriately. For the increased temperature regime, a linear increase in temperature was applied each year-step totaling 4°C over a period of 300 years. No changes in precipitation were made in addition to the increased temperature.

For each site, the model was run for 200 replications with each replicate plot running for 500 years total. The averages of all 200 plots for each site were used as model output data for statistical analysis. At each site, 200 replications were run for 500 years for both the 60-year climate record conditions as well as the increased temperature conditions. These two conditions were given the labels ‘current climate’ and ‘climate change.’ In the ‘current climate’ conditions, the 60-year climate record was used to generate monthly climate parameters by the model for the full 500 years. In the ‘climate change’ set, the 60-year data set was used as the initial conditions, with temperature increasing each year by 0.013°C until year 300 and then holding steady until year 500. All model runs began with bare ground conditions; there was no ‘spin-up’ procedure. A series of range maps was used to restrict species ranges according to current distributions akin to Shuman and Shugart (2009); although this process restricts most migration, it does allow for naturally occurring species transitions within the transect.

Year steps 25, 50, 100, and 300 for all sites were investigated and analyzed. The total stem count, maximum tree height, maximum tree diameter, stand leaf area index (LAI), stand basal area,total stand biomass, and two coniferous to deciduous ratios for each site were then compared between the two treatments using the DISCRIM and CANDISC procedures in SAS 9.2 (©2008 SAS Institute). The two ratios used were coniferous species to deciduous species LAI and coniferous to deciduous species biomass. Canonical analysis was included in order to derive standardized coefficients for each variable in order to determine the most significant forest variable signaling change between the two groups (current climate and climate change). All 1872 sites were divided into three 'zones' which were split by latitude (Figure 3.1). These zones served to represent the leading edge, interior, and trailing edge of the CST; these partitions were labeled part 1, part 2, and part 3 respectively. Comparison of the discriminant analysis findings occurred at years 25, 50, 100, and 300 as well as at these years between each of the three zones in order to investigate how different physiological, temporal, and geospatial factors affected boreal forest function when temperature was increased incrementally over several decades and centuries.

Results

Table 3.1 shows the canonical correlations of the DISCRIM procedure for each part of the CST transect. Also included are the eigenvalues of the product of the model matrix for each analysis. All p-values were $p < 0.001$ indicating that each test was statistically significant. Table 3.2 displays the standardized coefficients for each part and each year of analysis. Finally, Table 3.3 shows the classification error rate of subsequent classification procedures based on the discriminant function equation generated in the DISCRIM procedure.

Short-term responses of temperature increases in year 25 and 50 suggest that discriminant analysis was only partially able to mathematically discern between forests subjected to warmer climate and 'normal' climate conditions. After 25 years, the canonical correlation for the discriminant procedure returned values between 0.215 and 0.425 with all results being $p < 0.001$. Classification using the discriminant function resulted in error hovering between 0.4228 and 0.304. After 50 years, the canonical correlations improved, but were still low, between 0.434 and 0.550 with all results being $p < 0.001$. Classification error for year 50 was notably lower, between 0.221 and 0.263. In year 25, the same standardized coefficients were important throughout each partition of the transect. Stand basal area, stand LAI, and total stand biomass (in tC/ha) were the most significant coefficient for all parts, except for the northern-most part, part 1, in which stand maximum tree height replaced total stand biomass as the third most significant standardized coefficient.

After 50 years, the standardized coefficients differ between different parts of the transect. In the northern most part, maximum height, total stand biomass, and the stand LAI were the most important coefficients to the discriminant function in that order. In the central part of the transect, part 2, the order was slightly different, with stand biomass, stand basal area, and maximum tree height being the most important coefficients. However, these standardized coefficients were only slightly larger than other variables including maximum height, maximum diameter, and the coniferous to deciduous ratio of stand biomass. In the trailing edge, part 3, the most important standardized coefficients were purely stand-related; stand LAI, stand basal area, and both biomass variables were the strongest of the coefficients.

Longer-term responses of temperature increases yielded much higher canonical correlations for the discriminant procedure between groups. After 100 years of temperature increase, or a total of 1.33°C, canonical correlations for the transect ranged between 0.633 and 0.760 with all results being $p < 0.001$. Classification error using the discriminant function resulted in low error, between 0.104 and 0.115. After 300 years, and a total of 4°C, the canonical correlations were extremely high, with values ranging between 0.867 and 0.923 and all results being $p < 0.001$. Classification error for this year was almost negligible, ranging from 0.02 to 0.009. Unlike the short-term responses, standardized coefficients began to differ between leading edge and the interior and trailing edge partitions. At 100 years, the stand biomass, basal area, maximum height, and LAI were the strongest coefficients for the northern leading edge while parts 2 and 3 showed coniferous to deciduous ratios being the stronger coefficients. For both of these parts, the LAI ratio and the biomass ratio were the most important coefficients, followed by stand biomass.

After the full temperature increase all three partitions were strongly influenced by the coniferous to deciduous biomass ratio and other stand-level variables, yet their strength varied by location. In the northern edge stand variables such as the biomass ratio and basal area were strong, and diameter and height were also important coefficients. In the interior of the transect, stand basal area and the biomass ratio were strong coefficients, while the trailing edge found LAI and stand biomass to be the most important coefficients. Table 3.2 shows the results of long-term response at 100 and 300 years. In addition to the three partitioned parts, discriminant analysis was performed on the transect as a whole. The canonical correlations for the whole transect were always lower than any one part on its own; this trend was also mirrored by classification error rate. Similarly, the eigenvalues reflect a stronger and larger correlation away from the northern-most edge.

Discussion

Physiology versus Community Response

Table 3.2 displays the results of the standardized coefficients for each partition of the CST at years 25, 50, 100, and 300. The variables can be best summarized as referring to individual physiological properties of the trees in the stand (max dbh, max height), total stand properties (stem count, stand LAI, stand basal area, and stand biomass), and community composition (the coniferous to deciduous ratios). It should be mentioned that the stand properties, such as stand basal area, also have implications as to the physiological properties of individual trees since these properties are, by definition, inherently related.

Examining the results of the discriminant procedures gives us several insights into responses of boreal forest communities to increasing temperatures. First, stem count does not appear to be the most important variable in any of the discriminant procedures, for any partition of the transect or time period throughout the analysis. While range restrictions used in the FAREAST model runs limits migration to an extent, natural migration rates would not extend farther than 2 sites northward, and such, minimizes the effect on this variable. This result stands in contrast to investigations examining the treeline for increased tree presence (e.g. Næsset and Nelson 2007, Olthof and Pouliot 2009 among others) as a response to climate change. Historical remotely sensed images stretch back no more than 60 years, with the exception of aerial photography, and analysis at years 25 and 50 suggest that stem count is not a critically important variable for detecting change. Hence, it seems appropriate that remotely sensed imagery not be clearly able to discriminate and identify a stem count increase at treeline. This resonates with the study by Masek (2001) that suggests minimal treeline advancement and relative stability on the leading edge based on remotely sensed imagery. It also corroborates with studies drawing attention to the difficulty in boreal forest migration into arctic tundra (Starfield and Chapin, 1996; Chapin and Starfield, 1997; Lloyd *et al.* 2003; Chapin *et al.* 2004; Pearson, 2005), and with modeling studies of treeline (Dullinger, *et al.* 2004).

In central and northeastern Russia, there has been a negligible movement in species ranges at treeline (MacDonald *et al.* 2008), suggesting that FAREAST analysis corresponds to natural conditions. However, the decrease in importance of stem count stands in contrast to reports of increase in tree recruitment in the twentieth century (Esper and Schweingruber, 2004). With this in mind, it is important to realize that a decrease in the magnitude of the stem count standardized coefficient in the discriminant function does not reflect the absence of change in that variable; instead, it indicates that this particular variable is not the most highly correlated with determining change between two groups. Therefore, while stem count and recruitment may be significantly increasing, investigating it for signs of change may be less meaningful than other predictors when tracking ecological changes in the boreal zones.

Individual tree physiological variables such as maximum diameter and maximum height seem to also be relatively unimportant in the discriminant function. Only in the northern-most partition, part 1, do these variables carry significant weight. There, height and maximum DBH measured in each stand are important variables for distinguishing between the two groups at treeline. While measuring *Pinus siberica* in the Sayan Mountains, Kharuk *et al.* (2008) found the initial responses of these trees at a physiological level, with radial and apical increases in response to a warming climate, which validates treeline findings in this study. While Kharuk *et al.* also found that these trees transform from prostrate to erect, thus increasing their height, this physiological mechanism was not built into FAREAST, and therefore we must conclude that increases in height and diameter in the model are all results primarily from increased growth. Tree-ring analysis of *Larix sibirica* throughout the CST shows that in the twentieth century, radial growth has increased, albeit at the expense of similar changes in physiological state as Kharuk *et al.* 2008 (Devi *et al.* 2008). However, ring widths in trees with single stems increased in correlation to increasing temperatures indicating that diameter also shows significance in situ (Devi *et al.* 2008). Generally, these physiological variables are also most important in the first 50 years, as trees respond individually to warming temperatures before successional changes take place. Thus, it seems reasonable to conclude that physiological properties of existing trees at treeline are more indicative of change than recruitment and stem count, suggesting that treeline advancement studies may not be as reliable as in situ tree height and diameter at breast height measurements.

With advances in Lidar and radar remote sensing methods, however, these variables may be captured and measured accurately with little field work. The results of Devi *et al.* (2008) suggest a substantial increase in forest biomass at treeline with the increase in radial growth, and results of this study suggest significant storage of carbon, particularly in sparsely populated *Larix sibirica* communities.

Community level variables that indicate composition change within the boreal forest were the coniferous to deciduous ratios. Were composition to begin to change, these ratios would change in their magnitude. These variables were important in the interior section of the CST throughout all time periods. In the northern leading edge, these ratios were not important until the 300 year analysis, signifying a slow transition of the community composition. Compositional variables were not important in the southern edge until year 50, and became increasingly important in years 100 and 300. These analyses suggest that compositional change in this area of Russia will be slowest at the edges of the forest and less indicative of change, yet more rapid and more descriptive of change in the interior areas. Many studies have suggested that changes in composition of the boreal forest will be significant and have ramifications for regional climate feedbacks (Chapin et al, 2004; Amiro, 2001; McGuire *et al.* 2002). While that may be the case, results from this analysis suggest that given natural disturbance without the inclusion of fire or logging, composition change will be marked mainly in the interior of the CST. This idea is supported by Chapin *et al.* (2004) who suggest rapid community transitions in the interiors of forests may take place. Since shrub and smaller plant types are not present in FAREAST, the analysis can only be limited to the response of tree species; thus, while LAI and albedo may increase on the leading edge due to other community transitions, it is unlikely that tree species composition will be the major driver of this phenomenon. This is understandable, since many sites in the leading edge partition only contained one or two different tree species.

Overall, we see that individual physiological variables will be the most significant in the first 50 years of stand lifetime, resulting in general increasing productivity throughout the stand. While many studies focus on the presence and indication that trees will migrate poleward, our study suggests that the strongest change will occur within the existing stands themselves, that they will become more productive resulting in a larger basal area and greater biomass storage, as well as increase their stand leaf area. With more significant warming and disturbance, however, it is the community composition variables that will signify change. After 100 years, the quantity of species of *Betula*, *Pinus*, and *Populus* noticeably increased, in some cases existing where they were not present before; this explains the increase in importance in coniferous to deciduous ratio standardized coefficients. By 300 years of warming, up to a maximum of 4°C on top of current climate conditions, boreal forests in this region were statistically different and readily distinguishable from their previous state. At this point, massive increases of *Betula*, *Pinus*, *Picea*, and *Abies* take place in the FAREAST model runs. The implications for regional climate at this point due to forest response may be marked.

Temporal Response

As temperature rose within the FAREAST simulations, the discriminant function procedure was better able to discern between climate change and ‘normal’ climate groups. This occurred for every year and for every partition of the CST, as well as throughout the entire CST as a whole. Canonical correlations for the discriminant procedure show an increase from an average of 0.326 at year 25 to an average of 0.896 at year 300. Classification errors using the function derived from the discriminant procedure decreased with time as well, from an average of 0.3507 at year 25 to 0.017 at year 300. Generally, although the standardized coefficients that carried the most weight changed both in scale and in space, forest stands became more and more recognizably different with increasing temperatures.

The initial responses of all three partitions of the transect were to increase the basal area of forest stands. High-latitude forests, such as those investigated in the CST, are generally restricted from productivity due to the shortened growing season caused by low temperatures (Bonan and Shugart, 1989; Kaplan *et al.* 2003, MacDonald *et al.* 2008). With an annual increase in temperature, growing season length within the model runs increased, giving trees the ability increase their productivity. Within the first 25 years, stand basal area was the most important standardized coefficient, signifying that it changed the most and indicating that productivity markedly increased. Composition changes did not occur, due to the relatively small increase in temperatures which were enough to influence individual productivity, but not enough to influence species range shifts. In the interior of the transect, however, the coniferous to deciduous ratios were not negligible; compositional change was minimal though.

After 100 years, and into 300 years, the ratio standardized coefficients are of the highest magnitude and indicate a modification of forest structure and composition. Examination of individual site runs show an increase in previously outcompeted genera such as *Betula* and *Pinus* yet without a subsequent decrease in *Larix*. At this point in the time period of the stand, temperature has increased so as to allow for a shift in composition, and significant stand replacement processes have occurred so as to allow for gaps to create opportunities for understory species to reach the canopy. Results of this process in FAREAST modeling are slower than may occur naturally, due to the lack of a significant disturbance mechanism within the model (such as fire, logging, or insect outbreak).

After examining the results at 500 years (which were not investigated with discriminant analysis), significant composition change takes place. We can see this year in model runs as what may happen with increased disturbance and a 'reset' of the community as stand breakup would occur by this time and allow for gaps to form which allow for composition shift. These results echo Chapin *et al.* 2004 who indicate that on a landscape scale the change in composition may be 'gradual', but with a large disturbance event, the change may take place rapidly. The northern half of the CST has minimal fire activity and we suggest that the process of change will take place slowly and gradually. However, with significantly warmed average monthly temperatures, disturbance may allow understory and secondary species to be released and change the composition of a stand. Other modeling studies have suggested that disturbance events, particularly logging, can be important drivers in community composition shifts (Gustafson *et al.*, 2010). Additional studies with a disturbance regime within FAREAST are needed to shed insights into this discussion.

Geographic Trends in Response

The leading edge of boreal forests in the Arctic are commonly studied areas because of their significance in indicating ecological response to warming climate. Migrations and changes in land cover bring about changes in albedo and physical heat fluxes, which alter small-scale climatic land-surface interactions (Bonan *et al.* 1995, Foley *et al.* 2003). Additionally, monitoring the edges of these communities has practical advantages particularly with the ease of detecting change using remotely sensed data series (Ranson, Sun 2004). Our results indicate that the leading edge of the CST will mainly change with respect to the productivity of the forest stand and will not undergo significant community composition realignment. Stem count is a poor predictor of change in our results, suggesting that recruitment is also less indicative of substantial change compared to other variables such as stand basal area, stand LAI, and the maximum stand height. Most importantly, results from the 25 and 50 year analyses still contain significant error. Not until year 100 is the leading edge effectively capable of being differentiated between a warm climate scenario and a current climate scenario. Essentially, this suggests that the response time for the leading edge is slower than records of fossil pollen data for other forests (Huntley and Birks, 1983; Davis, 1981). The leading edge also lags behind the interior and trailing edge in both canonical correlation from the discriminant procedure as well as classification error (Table 3.1 and 3.3), signifying that it is the most resilient to warming scenarios. This radically suggests that the most appropriate areas to look for ecological responses of boreal forests lies in the interior.

The interior and trailing edge partition of the CST have noticeably higher canonical correlations for the discriminant procedure for every time period. Classification error is lower at year 25, but is negligible from year 50 onwards. While these two parts change much like the leading edge with respect to which coefficient is largest in magnitude initially, at year 100 and 300, the interior changes compositionally while the trailing edge changes with respect to stand properties such as basal area and leaf area index. The suggestion here is that most compositional changes will take place in the interior of the CST. At year 300, this effect is magnified and noticeable within the individual site data. Based on the strength of the standardized coefficients, we can estimate that the period of transition within the community noticeably occurs at the 100 year time step or with 1.34°C or more warming.

In addition to each of the three partitions of the transect, data from the entire transect was analyzed using the discriminant procedure. Results of the entire transect, compared to individual parts, were much weaker with respect to the ability to discriminate it under climate change conditions. This result suggests that large regional and continental analyses of change will be less informative than detailed and smaller-sized studies. When looking for change, this study indicates that regional and sub-regional analysis is more appropriate, especially in the initial decades under which climate warms since ecological response will be mainly physiological and site specific.

Conclusions

From this modeling study we can draw several conclusions for the CST and central Siberian boreal forests. First, the leading edge of the forest shows relative resilience to composition change and is instead marked by physiological changes to individual trees and stand properties. Particularly, the increasing temperatures allow for increased production resulting in larger and taller trees and increased stand basal area. While many studies have investigated this area for forest migration as a descriptor of change, better indicators in this region of ecological change are physiological variables such as height, stem diameter, and stand basal area. In a similar vein, the interior portion of the CST is more responsive to warming temperatures than the leading edge. Here, stand properties, particularly those centered around plant production, are the best indicators that change is occurring. This contrasts with examinations of treeline plant growth and suggests that interior plots be constructed to examine if there is a rapid increase in growth as noted by dendrochronology. If so, this result suggests that the CST should serve as a large carbon sink, at least in the next 100 years. These results follow previous model work with FAREAST throughout Siberia (Shuman and Shugart, 2009).

Community shifts in species composition do not appear to occur significantly until at least 100 years in the interior and trailing edge partitions of the transect. This coordinates with a large increase in mean temperature as well as the beginning of stand break-up events which give way to previously suppressed individuals. By 300 years, community composition is well on its way towards a shift from evergreen deciduous to evergreen conifer with some broadleaf deciduous species. This trajectory has been suggested by previous studies (MacDonald *et al.* 2008; ACIA, 2004) and this type of forest community was present in warmer periods in the Earth’s past as evidenced by fossil collection (MacDonald, 2006; MacDonald *et al.* 2008). Since FAREAST does not include additional forms of disturbance other than naturally occurring gaps, we view this estimate to be conservative, since fire, bug infestation, or anthropogenic disturbance will likely reset the community and allow the stand to continue on an alternate trajectory (Chapin *et al.* 2004). Future work with FAREAST will determine if increased disturbance will speed the community shift time frame.

Finally, this work presents evidence that ecological responses to climate change occur on a variety of temporal, physiological, and geospatial scales. Initial results after 25 and 50 years of our model suggest that it is at that point still relatively difficult to discern between forests growing under ‘normal’ climate and those growing under a warming climate. Given the increases in temperature in the area of the CST, however, it seems likely that this ecosystem can be represented by model results farther along the change timeline. As such, it seems that we are still decades away from complete community composition shift, but there is likely the beginning of a change in the understory. This study also suggests that the interior of the CST is the most likely place to find concrete statistical differences and changes occurring to forest stands when compared to the leading edge.

As with all ecological modeling results, the work with FAREAST on this project should not be taken to represent reality, rather an insight into general trends of forest development. There are significant mechanisms lacking in FAREAST currently: the absence of anthropogenic, fire, or insect disturbance; the beginning of plots from bare ground; limited migration between plots. Yet despite these disadvantages, FAREAST is a robust and proven forest gap model, and its results should hold scientific weight and give sound guidance. To expand on the concepts discussed here, Chapter 4 investigates how stands of different ages respond to a similar increase in temperature.

Figure 3.1: The Central Siberian Transect in context to the Federated Territory of Russia. The FAREAST model was run at 20km increments throughout the Central Siberian Transect. Three partitions, part 1, part 2, and part 3 are displayed from North to South, respectively. These partitions represent the leading edge of treeline, deep interior, and relative trailing edge respectively.

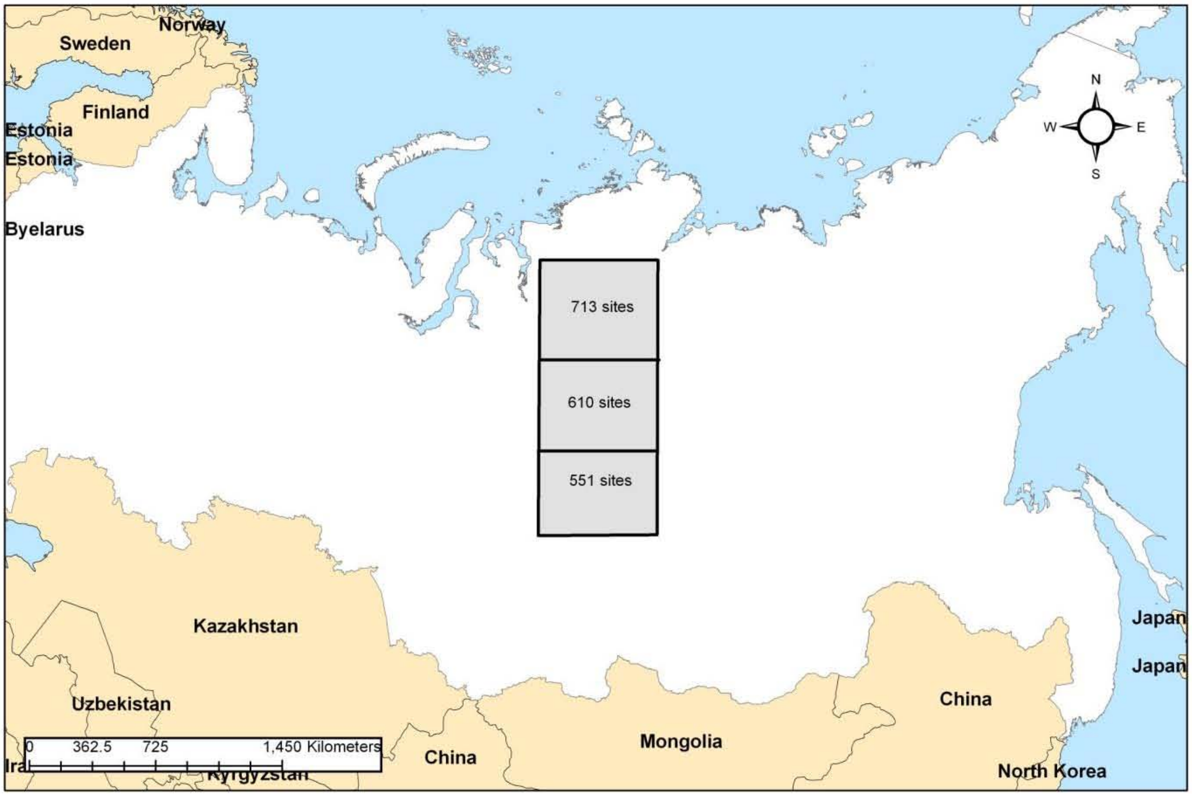


Figure 3.2: The Central Siberian Transect in context with FAREAST model output. The top section of the transect contains sites with very little amounts of vegetation. The southerly end of the transect represents the transition from Larch forests to coniferous and deciduous forests. In this way, the transect encapsulates the natural range of these forests and investigates many different ecological areas.

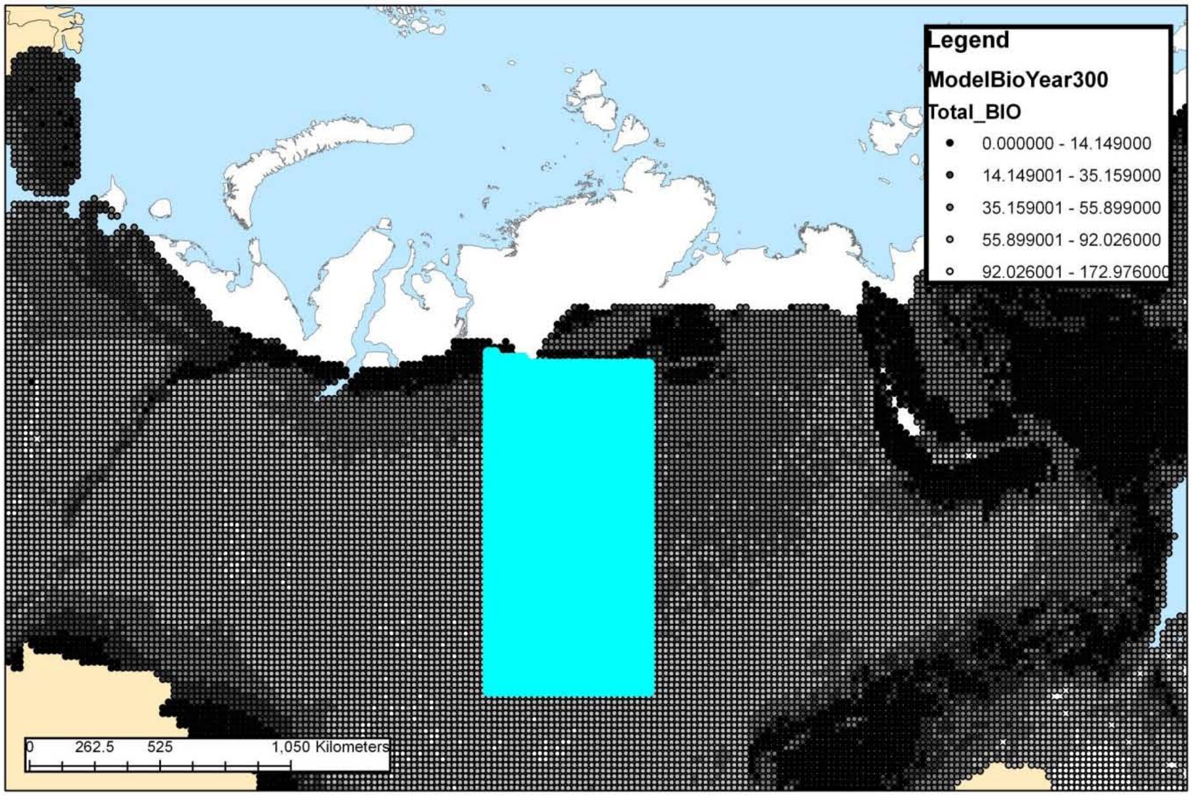


Table 3.1: Canonical Correlations, Eigenvalues, and P-values for discriminant function analysis for each partition of the Central Siberian Transect at four different time steps. The discriminant procedure analyzed two different series of FAREAST model runs: current climate conditions and increased temperature conditions with a 4 degree Celsius increase to mean monthly temperatures.

Year 25			**Year 50**		
Part 1	Canonical Correlation	0.215	**Part 1**	Canonical Correlation	0.434
	Eigenvalue	0.048		Eigenvalue	0.233
	Pr > F	0.0001		Pr > F	0.0001
Part 2	Canonical Correlation	0.425	**Part 2**	Canonical Correlation	0.478
	Eigenvalue	0.221		Eigenvalue	0.5
	Pr > F	0.0001		Pr > F	0.0001
Part 3	Canonical Correlation	0.338	**Part 3**	Canonical Correlation	0.551
	Eigenvalue	0.129		Eigenvalue	0.435
	Pr > F	0.0001		Pr > F	0.0001
All CST	Canonical Correlation	0.175	**All CST**	Canonical Correlation	0.388
	Eigenvalue	0.032		Eigenvalue	0.177
	Pr > F	0.0001		Pr > F	0.0001
	Year 100			**Year 300**	
Part 1	Canonical Correlation	0.633	**Part 1**	Canonical Correlation	0.867
	Eigenvalue	0.67		Eigenvalue	3.022
	Pr > F	0.0001		Pr > F	0.0001
Part 2	Canonical Correlation	0.738	**Part 2**	Canonical Correlation	0.923
	Eigenvalue	1.193		Eigenvalue	5.74
	Pr > F	0.0001		Pr > F	0.0001
Part 3	Canonical Correlation	0.76	**Part 3**	Canonical Correlation	0.899
	Eigenvalue	1.372		Eigenvalue	4.221
	Pr > F	0.0001		Pr > F	0.0001
All CST	Canonical Correlation	0.513	**All CST**	Canonical Correlation	0.788
	Eigenvalue	0.358		Eigenvalue	1.639
	Pr > F	0.0001		Pr > F	0.0001

Table 3.2: Standardized coefficients for each variable in the DISCRIM procedure from SAS. The absolute value of the magnitude of the standardized coefficient corresponds to the strength of the coefficient within the discriminant procedure, indicating its relative importance.

Standardized Coefficients		Year 25	Year 50	Year 100	Year 300
Part 1	Stem Count	1.5799	0.8921	1.1144	0.1156
	Max DBH	2.5140	1.9304	0.4852	-1.7428
	Max Height	-3.3786	-3.0492	-2.5499	-0.9052
	C/D LAI Ratio	-0.5145	-0.1465	-0.1749	0.0863
	Stand LAI	3.6358	1.1592	2.5773	0.7858
	Stand Basal Area	-5.6447	-0.6195	-2.2859	1.1411
	Stand Biomass	2.8383	1.2839	2.9967	-0.1623
	C/D Biomass Ratio	0.2314	0.0321	0.0268	2.3261
Part 2	Stem Count	-0.2894	0.2549	0.4964	-0.1226
	Max DBH	0.1737	1.1543	0.0451	-0.2913
	Max Height	-0.1812	-1.1871	-0.2741	0.0317
	C/D LAI Ratio	-1.3282	-1.0416	-2.7241	-0.2690
	Stand LAI	6.8622	-0.1669	0.2847	2.8530
	Stand Basal Area	-9.3362	1.2300	0.2672	-3.2400
	Stand Biomass	3.2827	1.6444	1.4764	0.3633
	C/D Biomass Ratio	1.8402	1.1243	2.5775	2.9285
Part 3	Stem Count	0.0102	0.0881	0.5962	0.1140
	Max DBH	0.4031	1.0871	0.2972	-0.3718
	Max Height	0.3274	-0.1908	-0.3728	0.2699
	C/D LAI Ratio	-0.3098	-0.5487	-2.7616	-1.1552
	Stand LAI	7.8630	5.5648	0.3857	1.8015
	Stand Basal Area	-10.4417	-3.3388	0.1272	-0.8685
	Stand Biomass	2.9881	1.2560	1.6749	1.2501
	C/D Biomass Ratio	0.4487	-1.2228	2.5092	0.2898
All	Stem Count	1.1896	0.7698	1.0424	0.0607
	Max DBH	3.4506	2.8829	0.3237	-2.2229
	Max Height	-4.2991	-4.4444	-2.2368	0.0481
	C/D LAI Ratio	-0.5492	-0.1938	-0.2593	-0.6267
	Stand LAI	6.5993	0.9101	1.1195	2.0093
	Stand Basal Area	-10.7434	-0.3354	-1.2446	-2.2608
	Stand Biomass	5.1636	1.9157	3.0778	0.7147
	C/D Biomass Ratio	0.3387	0.0293	0.0316	3.1921

Table 3.3: Classification error for each partition of the Central Siberian Transect. This error was the result of a classification procedure based on the discriminant function derived from the DISCRIM procedure. Lower classification error indicates a better prediction capability of the discriminant function derived by the DISCRIM procedure.

Class Error	Year 25	Year 50	Year 100	Year 300
Part 1	0.4228	0.2633	0.1152	0.0239
Part 2	0.3038	0.2452	0.1092	0.0090
Part 3	0.3203	0.2214	0.1044	0.0191
All	0.4375	0.3126	0.2898	0.0497

CHAPTER 4

RESILIENCY OF BOREAL FORESTS TO INCREASING TEMPERATURES

Abstract

Recent observations of forest die-back have been attributed to changes in regional climate. Particularly, warming temperatures are thought to be responsible for significant diebacks in the Russian boreal forests. In this study, the FAREAST gap model was used to investigate the resiliency of interior forests along the Central Siberian Transect to changes in temperature. A discriminant function analysis procedure was used to determine which stand ages were more or less resilient to warming temperatures. Forests at the peak of their growth were more resilient to warming temperatures and resisted community composition shifts compared to bare ground, early successional forests, and forests over 200 years old. These results follow Holling's (1986) conceptual adaptive cycle framework. Forests in this partition of the Central Siberian Transect mainly responded with increases in productivity rather than community composition shift; however, similar analyses should be performed on more southerly sites to investigate the effects of temperature increase on forests at the warmer end of their range of habitability. These results have implications for management strategies of boreal forests, mainly, that middle-aged forests will be less vulnerable to warming temperatures and that recently disturbed sites and ancient forests will be the harbingers of forest response.

Keywords: gap model, forest ecology, climate change, stand age, resiliency, Siberia

Introduction

Climatic change and its resultant effects, warmer temperatures, increased drought, and higher fire risk, threaten the current stability of many of the world's forested ecosystems (Allen *et al.* 2010, IPCC, 2007). The boreal forests of Russia have experienced gradually warmer temperatures over the past century as evidenced by dendrochronological studies (Jacoby *et al.* 2000; Briffa *et al.* 1995). Projections for changes in seasonal mean temperature in Russia range from 2-6° C (ACIA, 2005), well outside the climatic envelope of many of the tree species that currently exist in the boreal forests. Many forest diebacks have been documented in the scientific literature in recent decades and have been linked to climatic processes (Solberg, 2004; Krotov, 2007). Recent warming trends throughout Russia that trigger forest fires signify a serious danger to forested ecosystems in this region (Soja *et al.* 2007). The Russian Federal government, in response to what it views as potential risk to its forests, has categorized 76 million hectares of forests as 'high threat' areas to be monitored for other diebacks (Kobelkov, 2008). Integrated climate and land cover Dynamic Global Vegetation Model (DGVM) simulations have suggested a notable dieback and recession of the boreal forests of Russia in response to climate change (Lucht *et al.* 2006).

The scientific literature is awash with investigations into the response of forested ecosystems in the boreal zone to climate change. Several studies focus on the positive implications of small levels of warming and of those, most are associated with increased forest growth from longer growing seasons, more efficient water-use, and conditions optimized for metabolic functioning (Allen *et al.* 2010). However, many more studies have examined the negative consequences of climatic change to these forests (Scholze *et al.* 2006; Lloyd and Bunn, 2007). Increased temperatures can result in several conditions that can lead towards mortality for individual trees. Firstly, drought caused by increased temperatures can affect xylem tissue within the trees themselves through cavitation (Rennenberg *et al.* 2006; Zweifel and Zeugin, 2008; Allen *et al.* 2010). Water stress from the droughts caused by increased temperatures can also result in inefficiencies of metabolic processes and results in an energy deficit in the plant (McDowell *et al.* 2008; Allen *et al.* 2010), leaving the tree vulnerable to invasion by pests. This tendency has been summed up and termed 'Manion's cascade' in which the inability to produce energy through carbon fixation leaves trees limited in the production of resins which normally help prevent insect attack (Manion, 1991). Increased summer high temperatures may also lead to increased heat stress, amplifying mortality in vulnerable individual trees (Lucht *et al.* 2006) As well, increased temperatures can influence fire probability, intensity, and other related abiotic factors, all which can result in forest dieback.

Given that projections of climate change throughout Russia's boreal forest range from 2-6° Celsius, forests may respond in a variety of ways; however, it is likely that they will adapt by drastically shifting their community composition, as species with a preference for a warmer climate will gradually take the place of heat-intolerant species. Chapter 3 documents the trend of composition shifts given large enough changes in mean temperature and disturbance in the form of stand break up. Russian boreal forests, along with Amazonian rainforests, are critical components in the Earth's climate system, meaning that their modification and alteration may lead to dramatic results, shifting them to an alternative state, and causing consequences that may have lasting impacts upon society at large (Lenton *et al.* 2008). According to ecological modeling studies, boreal forests may decline in their general area by 19% (Krankina and Dixon, 1997) and may significantly change the way they look and function (Zhang *et al.* 2008); the ramifications of this change may be serious.

The consequences of boreal forest modification are many. As one of the largest stores of terrestrial carbon, Russian boreal forests, when altered significantly, may affect the global carbon cycle by decreasing carbon storage in woody biomass through alternative stable states and releasing stored carbon through decomposition following large-scale mortality events. The result is an increase in the carbon flux to the atmosphere. Boreal forests also affect the Earth's climate through physical interactions related to energy transfer, particularly albedo (Bonan 2008) and surface and latent heat and energy fluxes (Amiro *et al.* 2001). Thus, changes in the current state of boreal forest cover may alter regional climate significantly (Chapin *et al.* 2008; Bonan 2008). Ecologically, the shift of boreal forests to alternative states due to diebacks and community modification will affect other species that depend on forests for cover, shelter, and nourishment, and subsequently may affect large numbers of boreal species. Additionally, boreal forests in Russia constitute a major part of the country's economy; warming temperatures may affect the ability of forest timber projects to maintain profitability as stock volume decreases and thereby alter many regions' economies, a subject investigated in Chapter 5. Not least is the role that these natural systems have in traditional communities and societies that depend on them for food, fuel, and income.

Ultimately, society must determine the proper management strategy for naturally forested ecosystems in response to climate change. However, understanding the response of forests to different aspects of climate change is necessary to determine which forests face the greatest threat and which forests are likely to maintain their current structure in the impeding face of a warmer climate in Russia. Many scientists have called for studies to increase our understanding of effective forest management decisions with regards to this issue (Allen *et al.* 2010; Noss 2001) and to develop forest management strategies that optimize and anticipate changes to forests such that they function effectively in the future for many different needs (Seppala *et al.* 2009; Ogden and Innes, 2007). Particularly, modeling studies and studies that investigate species and stand specific responses to changes in climate will be helpful in determining what species and what stand structures are more and less resistant to warming temperatures (Bolte *et al.* 2009). In order to make this determination, we must address the concept of resiliency and stability in forested ecosystems and find suitable criteria with which to gauge Russian boreal forest response.

Background

Stability and Resiliency

The terms stability and resiliency are commonly used throughout the ecological literature when examining how ecosystems will respond to disturbances. There are several reviews of the use of these terms (Bodin and Wiman, 2007; Drever *et al.* 2006; Grimm and Wissel, 1997) so this paper will not delve too deeply in the debate regarding the proper usage of each of them. In this study, I define resilience as the capacity of a natural system to absorb a disturbance or alternative conditions without changing into an alternative steady-state (Holling, 1978; Holling, 1986; Drever *et al.* 2006). Particularly, I attempt to shed light on patterns of resilience of the boreal forest to warming temperatures. However, with respect to the use of the stability of the system, I follow Grimm and Wissel (1997) in identifying a suitable definition of stability in order to remain consistent with their recommendations.

Firstly, according to Grimm and Wissel, we must identify the properties being addressed as stand level properties of boreal forests in Russia. Particularly, I focus and am interested in large-scale properties that can be detected from remotely sensed data sets in the boreal forest. This interest is calculated such that future monitoring efforts will be able to examine these properties from space via remotely sensed data sets from satellites. Aboveground live biomass, stand leaf area index (LAI), canopy height, and to some extent the breakdown of coniferous and deciduous species in a stand can all be discerned from current remote sensing methodologies in the boreal forest (Lutz *et al.*, 2008). Therefore it is these properties of boreal forests that are focused on to determine if the system will remain stable in the face of warming temperatures.

Second, we must describe in detail the ecological situation with which we define the boreal system as being stable. In this case, I identify the current state of boreal forests as being ‘stable’, as their current distribution is relatively remnant of the past several centuries of climatic conditions. This study examines boreal forests in a relatively remote location, with major influences being fire and insect outbreak. The major constraints to the system are climatic, with little input from forest management and land cover and land use change. I therefore classify the current distribution and stand properties of the boreal forests within the Central Siberian Transect as stable and compare all future simulations of stand state to these values. Finally, we must address Grimm and Wissel’s (1997) concern with generalizations about stability by pointing out that the key variables that I address, major and commonly examined parameters of forest stands such as stand biomass and LAI, are among the most important and descriptive variables in defining and classifying forest stands that are consistently used throughout the scientific literature; therefore, in examining these descriptive variables, this study covers many fields of interest and investigates many properties of these forests (not just one particular property) since many different disciplines' use of these variables indicate importance to their interests.

General resilience theory of forests suggests certain pathways for boreal forests in the face of warming temperatures. The conceptual adaptive cycle described by Holling (1986) essentially predicts resiliency in forests during their period of heavy growth, while forests in their conservation phase, their limit of mature growth, will be more vulnerable to shifting towards an alternative stable state. Following this train of thought, stand age and the distribution of tree ages are important elements that contribute to a forested community's stability (Harper, 1977). Observations of forest dieback have found that large and older trees are less resistant to drought-induced mortality (Mueller *et al.* 2005). This dieback of long-lived trees may also result in quicker changes than natural forest stand replacement (Allen *et al.* 2010). Investigating the response of different aged stands to warming temperatures in the boreal forest therefore seems like an important place to look in order to determine how this ecosystem will respond. By determining the ability of different aged stands to resist moving to alternative stable states, it may be possible to suggest forest management policies that can utilize tree age information to identify areas of particular vulnerability.

Modeling Forest Response

Understanding the potential for climate-induced tree dieback is an important research priority for ecologists (Allen *et al.* 2010). Using modeling approaches to examine the resiliency of species and stands to climate change is a powerful tool in that model observations can examine all stand ages as well as simulate a variety of various conditions unlike field-based studies (Bolte *et al.* 2009). Mechanistic process models, such as those that simulate the biological processes within individual trees and stands, may be helpful to determine which forest management strategies are best suited for future disturbances (Bodin and Wiman, 2007). Models have been one of the primary ways for scientists to simulate the effects of ecological systems by disturbance.

There have been many studies investigating the boreal forest in order to determine how it will respond to changes in climate. These studies include forest succession models (FORSKA, in Prentice *et al.* 1993), frame based models particularly interested in ecosystem change (Starfield and Chapin III, 1996), models of biogeography and vegetation distribution (Kirilenko *et al.* 2000), and forest gap models (Xiaodong and Shugart, 2005; Shuman and Shugart, 2009; Zhang *et al.* 2009; Gustafson *et al.* 2010). As this study focuses on stand-based variables, the use of an individual-based forest gap model seems most appropriate. The FAREAST model is an individual forest-gap model originally designed to replicate and simulate forests in northern China and the far-eastern forests of Russia. Significant testing has shown that it dutifully replicates stand structure in China (Xiaodong and Shugart, 2005) and throughout many locations in Siberia

(Shuman and Shugart, 2009) as well as forest biomass (Chapter 2). In this study we use FAREAST as an ecological model to investigate boreal forest response to changes in climate much as was completed in Chapter 3.

Previous work with FAREAST has been completed to investigate the effect of climate on boreal forests in slightly different locations and conditions. Zhang *et al.* (2009) used FAREAST to simulate Eastern Eurasian forests under IPCC warming scenarios. They found a significant shift in community composition for many forests under most climate scenarios; only under a very small climate range do eastern forests maintain their current distribution (Zhang *et al.* 2009). However, in this study, forests were simulated for 1000 years under current climatic conditions, so only mature-phase forests were examined as to their response. Similarly, Shuman and Shugart (2009) use FAREAST to investigate how increasing temperatures of 2 degrees C and precipitation affect forests in Siberia. However, this analysis also begins climate change ramp-up at bare ground with no simulation spin up. Essentially, all studies used with FAREAST have investigated how bare ground conditions will respond to warming temperatures and an altered climate. In this study, we delve further into the potential of FAREAST by utilizing forest spin up to determine differences in how stand ages respond to climate change.

In order to investigate the potential stability of different stand ages in boreal forests in Siberia, I focus on one segment of the IGBP-GCTE Central Siberian transect (CST) that dissects Siberian boreal forests. Specifically, I isolate the interior forests of the CST as dictated by our previous investigation of this area (Chapter 3). In order to determine the effect of climate change on the resiliency and stability of differing stand ages of boreal forest, I simulated several different repetitions of the CST, each with an increasing climate beginning at different times within the forest's life cycle. I use a 4° C increase over 100 years and begin the climate change at 5 different stand ages and then compare these results with a 'current climate' run. To investigate whether the magnitude of climate change additionally affects this relationship, I use a 2°C and a 6°C increase over 100 years as well. Therefore, this study isolates and identifies how different aged stands will respond in their own way to an amplification of annual mean temperature in the heart of Russian boreal forests. Based on the findings, I make suggestions for effective adaptive forest management solutions that take into consideration the variation among response of different stand ages, as this has not been a major subject of discussion in the literature, yet remains an important point to consider.

Methodology

The FAREAST model uses four different modules to simulate the growth and dynamics of a forest stand. A complete description of these modules and the specific equations used within each module can be found in Shugart (1984) and Xiaodong and Shugart (2005). Essentially, FAREAST simulates boreal forest stands with species-level discretion, but also reports biophysical parameters of forest trees as well as biogeochemical conditions of the stand. FAREAST only investigates an area the size of a large tree gap in a forest, and in the current version of the model, simulates a forest the size of a third of an acre; this size is consistent with other gap models in the scientific literature and simulates a large enough size region to consider essential elements of forest ecosystems.

A total of 609 sites were created within the IGBP-GCTE Central Siberia Transect (CST) (Steffen and Shvidenko, 1996). These sites were identified as ‘Part 2’ of the discriminant analysis performed in Chapter 3. Each site was generated by accumulating the environmental conditions in a 400 square-kilometer rectangular area as detailed in Chapters 2 and 3. Figure 4.1 shows the location of the sites used in this analysis. In total, over 240,000 square kilometers of area were summarized into the sites simulated here. Most soil values for these sites, as in Chapters 2 and 3, were derived from the Land Resources of Russia IIASA database (Stolbovoi and McCallum, 2002), while several were kept constant throughout all sites due to their limiting influence on model results. A list of soil variables used in FAREAST can be found in Yan and Shugart (2005). Elevation and slope information was consolidated from the Shuttle Radar Topography Mission (SRTM) dataset (van Zyl, 2001). This information is all similar to information on site creation as discussed in Chapters 2 and 3.

Climate information for each site was derived from a 60-year record of conditions at weather stations across Russia (Razuvayev, V. N. *et al.* 1993). Point station data were interpolated to create accurate climate information for the entire study area. Tests performed on sites created by the interpolation procedure and control points not included in the procedure indicated that model output of leaf area index and biomass were not significantly different between data sets ($p<0.05$) indicating that the interpolation could be used appropriately. Each of these sites was run with ‘current climate’ for 200 replications, with each replicate plot running for a total of 300 years. The average of all

200 plots for each site was used as a baseline for comparison with climate change simulations. In reference to the earlier discussion of stability, I define these runs and their stand properties as a stable system.

In addition to these baseline runs, each site was run under several other climate and spin-up conditions. For each climate change scenario, temperature was increased incrementally and linearly to total the desired warming magnitude over a period of 100 years. For example, for a total climate change of 2 degrees Celsius, each year the monthly average minimum and maximum temperatures were increased by .02 degrees C. Several variations of model spin-up were created so as to bring forest stands at each site to a prescribed stand age before implementing the change in climate. Stands of ages 0, 25, 50, 100, and 200 years were spun-up under current climate conditions. Next, these spun up forests were run for linear temperature increases to a maximum of 2, 4, and 6 degree Celsius warming over a 100 year period. This methodology insured that many different stand ages were subjected to a sudden increase in temperature. No changes to precipitation or any other site variables were made in addition to the increased temperature. A series of range maps was used to restrict species ranges according to current distributions akin to Shuman and Shugart, 2009; although this process restricts most migration, it does allow for species transitions in most areas and therefore is capable of detecting natural transition into alternative stable states by definition, a key insight into the system's resiliency.

The results of these simulations were investigated and analyzed statistically. The total stem count, maximum DBH of the stand, stand LAI, total stand aboveground biomass, and the ratio of coniferous to deciduous biomass for each site under all climate change and spin-up variations was compared to the neutral climate run of the same age. This ensured that stands would be compared at the exact same age so as not to introduce variability inherent in successional processes not related to climate. As is common with discriminant analysis, all variables were subjected to correlation matrices to determine their correlation to each other. All variables had low correlations with only one pair of variables above 0.65. This signifies that the variables used could be properly analyzed with a discriminant analysis.

Linear discriminant analysis was used to examine the differences between the climate and spin-up simulations and neutral runs in SAS 9.2 (©2008 SAS Institute). Canonical analysis was used to derive a linear function through the two groups of data and determine standardized coefficients of each variable; these coefficients represent the relative importance in discriminating between the two groups. Furthermore, a canonical correlation was calculated; this statistic displays the ability of a discriminant function to separate the two groups. Higher canonical correlations result from populations with statistical differences among the five variables examined and reflect a difference in the stands' properties. Error values were also propogated when using the discriminant function in order to examine the accuracy of the classification procedure.

Results

The canonical correlations, eigenvalues, and error values for each stand age and climate scenario can be found in Tables 4.1,4.2, and 4.3. For each table of values, the spin-up time and stand age is listed beginning from 0 and proceeding to 200 by row. Each column holds the value of the canonical correlation, eigenvalue, or error value for discriminant analyses performed during years 25, 50, and 100 after the climate change has been implemented. In this fashion, one can observe the change in canonical correlations for the area studied under a particular climate scenario for various stand ages, and among these various stand ages, at different points since temperatures have begun to increase.

Canonical correlations in the 4 degree Celsius climate scenario show an increase in the ability of the discriminant function to discriminate between the two stands both as a function of time since climate change begins, as well as a function of stand age. As the time since the implementation of a linear rise in temperature increases, so does the ability of the linear discriminant analysis to differentiate between the two groups; the relationship appears logarithmic in that it approaches a limit of 1 in which the two groups are easily separable with no error. This follows logically as the time since implementation of climate change relates to the time that the stand has had to change its properties. As stand age increases, however, the canonical correlation does not respond logarithmically. Instead, young stand ages and particularly old stand ages are more prone to high canonical correlations. These results signify a lack of resiliency in old and over-mature stands as well as in bare ground and very young stands.

These results are replicated in the other climate scenarios as well. However, in these cases, a larger magnitude of temperature increase increases the initial canonical correlation in the year 25 comparison. At 2 degrees C, the correlations are nearly half that of the same comparison at 4 degrees C, and nearly one third what they are at 6 degrees C, indicating the resiliency of stand age to be dependent on the magnitude of climate change occurring. Classification errors, also found in these tables for each climate scenario, support the results of the canonical correlations in that as the time from initialization of the climate change increases, the error rate of the discriminant function to differentiate between the two stands decreases. Error rate decreases with stand age until a minimum of between 100 and 200 years, whereby it increases again with stand age to similar values as bare ground stands. This trend is consistent with all magnitude of temperature increase as well.

Tables 4.4, 4.5, and 4.6 show the magnitude of standardized coefficients of the discriminant function for each variable. Across all analyzed scenarios, the most important variable is the ratio of coniferous to deciduous biomass, indicating that these values are quite different between the two stands consistently among all the combinations of simulations when compared to neutral runs. These results mimic those found in Chapter 3 in which interior forests change compositionally. The second most important variable is stand LAI, which is consistently greater than 1. In stand ages of 200 years, the stand leaf area index is as or more important than the coniferous to deciduous ratio; this trend is pronounced after 100 years of climate change in stand ages of 200 years. The stem count and DBH variables add very little to the discriminant function’s ability to discriminate between groups. This signifies that these variables do not change particularly much between the different scenarios. While stand biomass standardized coefficients indicate some relationship between climate change and neutral stands, it is not clear that it is significant when compared to both the coniferous to deciduous ratio and stand LAI.

Discussion

Resiliency of Stand Age

Data from these simulations give support to the theoretical assumptions made by Holling in his conceptual adaptive cycle framework (1986). With these data, we see differences between stands of young, medium, and mature state respond differently to changes in increasing temperature. Particularly, stands at the peak of their growth period, from 100 years until about 150 years, show less change in the five measured variables than stands of very young or very old ages. The primary rationale to explain this behavior is the climatic envelope and tolerances set for each species in the input model parameters; these values were collected from historical stand data and also were based on latitudinal range limits. While FAREAST does not simulate the three major types of tree death in response to high temperatures as described by Allen *et al.* (2010), the temperature sensitivity variables calculated from each species inherently capture these vulnerabilities, as these types of tree deaths likely occurred in the stands used to derive temperature sensitivities. In other words, although FAREAST does not actually simulate xylem cavitation, it triggers individual tree death at temperatures that would cause xylem cavitation in reality, since this affliction likely claimed forests in areas of unsuitable climate, and thus, this feature was encapsulated in temperature tolerance variable data.

At a warming level of two degrees for a period of one hundred years, the discriminant analysis was able to differentiate between neutral stands and climate change stands with effectiveness by the end of the 100 years of climate ramp-up. However, with only 25 years of a climate increase, canonical correlations signify that the forest stands are not easily differentiated. Even at 50 years of warming, stands that are 50 years in age have canonical correlations of just 0.366. If the trends in the 4 degree warming scenarios are consistent, it is likely that stands 100 years in age under a 2 degree warming will have even lower canonical correlations after 50 years. Thus, despite regional warming in the area of the Central Siberian Transect, it may be difficult if not impossible to quantitatively differentiate changes in forest characteristics in many stands in the area, particularly those whose stand age was near 100 years at the beginning of recent climate warming. Yet this does not imply that there is no difference at all, since only 5 variables were examined. More specific investigations particularly those dealing with more qualitative aspects of the forests may be more sensitive to changes in temperature; however, these types of variables would be inherently difficult to investigate using the techniques in this study as discriminant analysis is particularly susceptible to error if the variables used are not thoroughly numerical.

Standardized coefficients generated by the discriminant analysis suggest that the coniferous to deciduous ratio was the most significant variable in differentiating between neutral and climate change stands. This is a good indication that stand stability, as we defined in the introduction, may be altered; a varying coniferous to deciduous biomass ratio indicates community composition change. Yet this standardized coefficient strength must also be taken into consideration with respect to the magnitude of the canonical correlation. For instance, consider the scenario at 4 degrees change with zero spin-up at 25 years into the simulation. Here, the standardized coefficients signify the coniferous species to deciduous species biomass to be a very strong indicator of change. Yet, the canonical correlation is only 0.57 with a classification error of 27.5%. This may signify sensitivity to the ratio change, but may not necessarily indicate a complete composition change. Comparing the results side by side of FAREAST simulations, conversely, show changes in the size of genus biomass, but the dominant species stay entrenched. Particularly, Larch forests maintain the dominant species in the area studied. This result is important, in that it shows us that the discriminant function can magnify slight differences in stand characteristics while visibly, the stand may be characterized in the same fashion. This result suggests that only in extreme cases of temperature change will forests in this area noticeably be different with respect to their stability; it is important to note, however, that this area represents one of the northern areas of larch range. A more southern study similar to this one may suggest a more noticeable change in complete community structure, particularly at the warmer ends of the species ranges.

Implications for Management Strategies

The major implications from this study are that there is notable stand resiliency to warmer temperatures among forest stands of young yet mature trees in Siberian forests. When warmer temperatures occur when a stand is at bare ground following disturbance, or at post-mature age (200 years old or longer), these stands are more likely to change with respect to their structural characteristics than stands near their period of heavy growth (between 75 years and 150 years). These results are significant in that forest fires have markedly increased in the past 10 years in Siberia (Soja *et al.* 2004) and that forest fires are essentially mechanisms to wipe the ecological slate clean in order to bring the current vegetation community ‘in line’ with current climate conditions (Shugart *et al.*

2000). Since bare ground states are less resilient to changes in climate than are more mature stands, fires will likely be the final act for many current stands in Siberia before they shift to an alternative stable state. Without fire, forests appear to be markedly resilient to even 6 degrees of climate change, except for very old-growth forests, which are as resilient to some extent, as bare ground is.

In this area of Russia, we do see shifts towards alternative stable states in the bare ground scenarios. However, most results do not implicate a complete transformation of forest type. This echoes work by Nemani *et al.* (2003) who found that climate change could positively influence the growth of forests in areas where low temperatures are inhibitory factors to stand productivity. While subtle shifts in composition, particularly among the understory, are notable in the most resilient stands, productivity flourishes in nearly every plot in the study site. The study area does not appear to be in particular danger of forest die-off as was discussed in the introduction and it is particularly unlikely that these forests may need adaptive stand management to prevent them from catastrophic collapse. In fact, it seems more likely that these forests could benefit nearby economies due to their increased productivity. Examining areas along the CST may be a future application of the methods proposed in Chapter 3. Also to note is that the discriminant function took the whole of the 609 sites and treated it as a single entity. Therefore, refuges of alternate stands that completely changed during these simulations may have been mitigated by the constancy of larch forests, which did not change composition considerably.

As with all modeling studies, there were many limitations to effectively representing reality with the FAREAST model that should be taken into consideration.

Firstly, only the effect of temperature was considered. A decrease in precipitation was not added to these simulations although this condition is commonly predicted by climate models for the future of Russian forests. Details into the effect of this variable are thoroughly discussed in Shuman and Shugart (2009). Second, no fire or disturbance other than stand replacement through large crown death was simulated in the FAREAST model. Thus, this study serves as a ‘pristine’ simulation that sheds light on underlying ecological processes. As fire is a critical part of the boreal forest system, it is important to mention that it is not simulated here and that fire will likely affect the resiliency of these forests by either weakening them or causing large scale die back. A secondary result of fire is that it pushes the landscape to a more vulnerable state for change. As land with minimal biomass is less resilient to change, as demonstrated by this study, forest fires will force areas into more vulnerable states. Finally, in contrast to Chapter 3, this study only allowed for 100 years of simulation with climate change; thus, the results are likely more conservative, and there was likely less stand composition change than in the previous chapter.

Conclusions

This experiment examined 609 unique sites in the Central Siberian Transect and inspected their response to climate change under different warming scenarios. The FAREAST forest gap model (Xiaodong and Shugart, 2005) was used to simulate forest response under different warming increments as well as determine the ability of different stand ages for resilience to warmer temperatures. Input data to the model were taken primarily from data calculated by the CEPF-RAS in Moscow as well as from the IIASA soils database (Stolbovoi and McCallum, 2002). As FAREAST has been extensively validated throughout areas of Russian boreal and temperate forest (Xiaodong and Shugart, 2005; Shuman and Shugart, 2009; Chapter 1), we see these simulations as having credence towards investigations of climate change effects on Russia's forested areas.

Discriminant analyses of simulated stands when compared to neutral stands run under current climate conditions indicate that forests of stand ages 75 through 150 are more resilient to warmer temperatures with respect to the five variables measured: stem count, maximum stem DBH, stand LAI, stand biomass, and a ratio of coniferous to deciduous biomass. Bare ground plots are more likely to change with respect to these variables than fast growing mature stands, as are old-growth forests greater than 200 years of age. The standardized coefficients from these discriminant analyses also suggest that the most important variable indicating change in these forests stands is a variable comparing the ratio of coniferous to deciduous biomass. This is important in that of the variables studied, it is most indicative of a change in our definition of stability of the stand to an alternative stable state.

Two important aspects of this study to consider are that significant increases in temperature seem to moderate the effect that stand age has on resiliency. In other words, at a certain increase in mean temperatures, stand age is not an effective variable in resisting transition to an alternative stable state, since all individuals are to some degree vulnerable with large increases in warm temperatures. While the area studied showed particular resilience in terms of complete stand replacement by an alternative stable state, other areas closer to the southern edge of Siberian larch forests may show stronger results signifying community transition. As well, there were indications of understory transition similar to Chapter 3. Future studies using this same methodology in different parts of the Russian boreal forest may identify more vulnerable forests to increased temperatures and help suggest areas that may benefit from adaptive forest management.

Figure 4.1: The Central Siberian Transect in relation to the Federated Territory of Russia. The sites simulated by FAREAST for this chapter are the central 610 sites. These sites are generally made up of Larch-dominated stands, yet contain several understory elements.

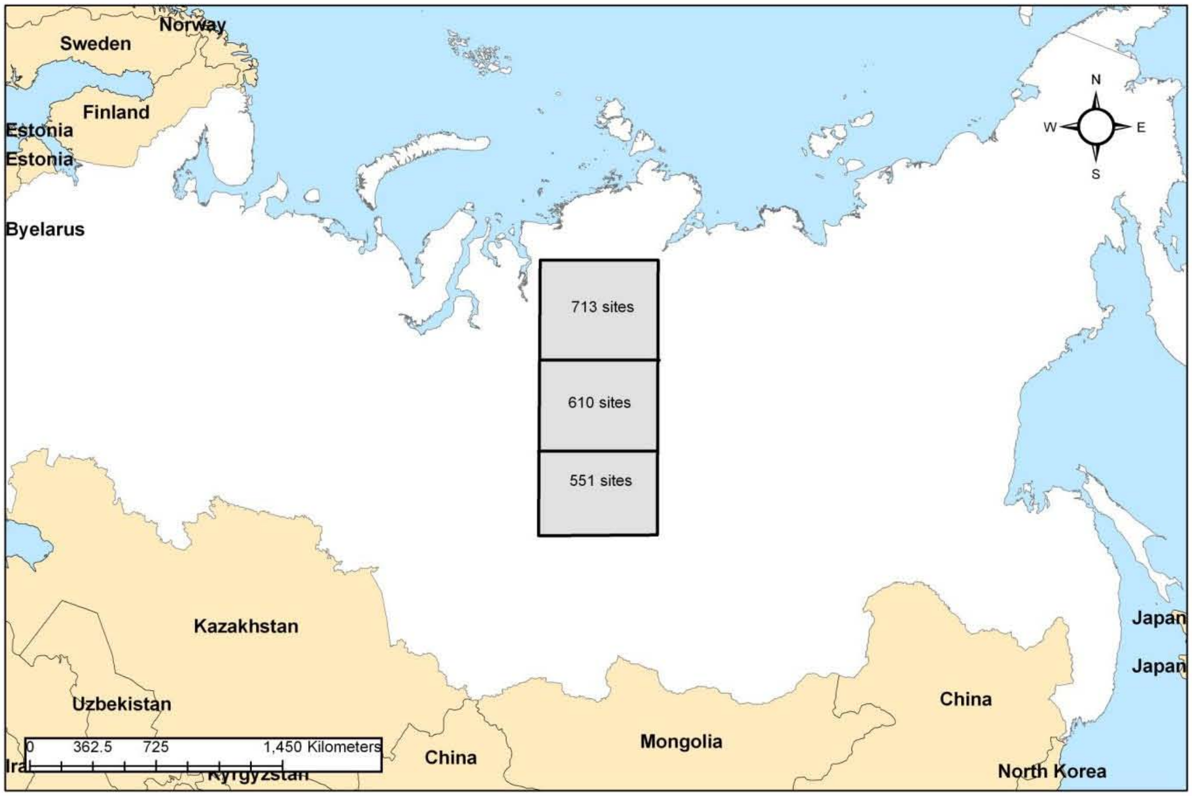


Table 4.1 Canonical Correlations for 2, 4, and 6 degree increases in temperature for the study area when compared to the base case. In all cases Year 100 of the simulation had larger canonical correlations indicating a greater degree of change compared to the base case. Notice the relatively low values for forests between 50 and 100 years, indicating their resiliency to temperature increases.

2 Degree Increase			
stand age	year 25	year 50	year 100
0 yrs	0.345	0.535	0.711
50 yrs	0.188	0.366	0.636
200 yrs	0.334	0.524	0.73
4 Degree Increase			
stand age	year 25	year 50	year 100
0 yrs	0.57	0.771	0.904
25 yrs	0.467	0.797	0.893
50 yrs	0.381	0.621	0.822
100 yrs	0.244	0.782	0.853
200 yrs	0.546	0.746	0.896
6 Degree Increase			
stand age	year 25	year 50	year 100
0 yrs	0.715	0.874	0.93
50 yrs	0.518	0.771	0.886
200 yrs	0.664	0.852	0.9

Table 4.2: Eigenvalues of the product of the discriminant model matrix and the inverse of the error matrix for 2, 4, and 6 degree increases in temperature for the study area when compared to the base case with a discriminant function analysis. These values are another methodology used to indicate the ability of the first discriminant function to separate between the two groups. Larger eigenvalues generally indicate lower p-values.

2 Degree Increase			
stand age	year 25	year 50	year 100
0 yrs	0.135	0.401	1.023
50 yrs	0.037	0.154	0.68
200 yrs	0.125	0.379	1.144
4 Degree Increase			
stand age	year 25	year 50	year 100
0 yrs	0.471	1.469	4.486
25 yrs	0.279	1.743	3.961
50 yrs	0.17	0.627	2.084
100 yrs	0.063	1.575	2.675
200 yrs	0.426	1.25	4.053
6 Degree Increase			
stand age	year 25	year 50	year 100
0 yrs	1.045	3.237	6.443
50 yrs	0.366	1.465	3.647
200 yrs	0.79	2.655	4.274

Table 4.3: Error values for the discriminant analysis for 2, 4, and 6 degree increases in temperature for the study area when compared to the base case with a discriminant function analysis. This classification error displays the ability of the calculated function to discriminate between groups and is an indication as to the difference between the two groups, current climate forests and climate-change forests.

2 Degree Increase			
stand age	year 25	year 50	year 100
0 yrs	0.375	0.287	0.156
50 yrs	0.442	0.349	0.2
200 yrs	0.356	0.273	0.126
4 Degree Increase			
stand age	year 25	year 50	year 100
0 yrs	0.275	0.119	0.009
25 yrs	0.3177	0.0731	0.0115
50 yrs	0.348	0.218	0.054
100 yrs	0.406	0.076	0.059
200 yrs	0.267	0.139	0.037
6 Degree Increase			
stand age	year 25	year 50	year 100
0 yrs	0.169	0.021	0.004
50 yrs	0.277	0.107	0.03
200 yrs	0.19	0.055	0.043

Table 4.4: Standardized Coefficients for the 2 degree Celsius increase scenario. The five variables listed are those used in the discriminant analysis procedure and are: the sum of all stems within the plot, the maximum diameter at breast height of any tree within the plot, the sum of the leaf area index of the stand, the sum of the biomass in tons of carbon per hectare for the stand, and a ratio of the coniferous to deciduous biomass for these species within the stand.

0 Years of Spinup			
Variable	**Year 25**	**Year 50**	**Year 100**
Sum Stem	-0.001	0.001	0.002
Max DBH	-0.138	0.034	-0.008
SUM LAI	-1.548	1.265	0.279
SUM BIO	0.73	0.152	0.229
C/D Bio	25.325	-9.685	2.313
50 Years of Spinup			
Variable	**Year 25**	**Year 50**	**Year 100**
Sum Stem	0.001	0.001	0.002
Max DBH	-0.028	-0.004	-0.009
SUM LAI	1.146	0.572	-0.986
SUM BIO	0.134	0.099	0.128
C/D Bio	1.653	2.075	1.344
200 Years of Spinup			
Variable	**Year 25**	**Year 50**	**Year 100**
Sum Stem	0.001	-0.001	0
Max DBH	0.077	-0.124	-0.088
SUM LAI	-8.676	6.305	1.187
SUM BIO	0.201	-0.096	0.121
C/D Bio	7.084	-3.43	0.077

Table 4.5: Standardized Coefficients for the 4 degree Celsius increase scenario. The five variables listed are those used in the discriminant analysis procedure and are: the sum of all stems within the plot, the maximum diameter at breast height of any tree within the plot, the sum of the leaf area index of the stand, the sum of the biomass in tons of carbon per hectare for the stand, and a ratio of the coniferous to deciduous biomass for these species within the stand.

0 Years of Spinup				25 Years of Spinup			
Variable	**Year 25**	**Year 50**	**Year 100**	**Variable**	**Year 25**	**Year 50**	**Year 100**
Sum Stem	-0.001	0.001	0.001	Sum Stem	0.001	0.001	0.001
Max DBH	-0.097	0.029	-0.004	Max DBH	0.015	-0.021	0.003
SUM LAI	-1.881	1.198	0.421	SUM LAI	1.291	0.951	0.097
SUM BIO	0.732	0.164	0.094	SUM BIO	0.16	0.102	0.083
C/D Bio	21.571	-10.196	5.388	C/D Bio	-5.456	6.715	3.968
50 Years of Spinup				**100 Years of Spinup**			
Variable	**Year 25**	**Year 50**	**Year 100**	**Variable**	**Year 25**	**Year 50**	**Year 100**
Sum Stem	0.002	0.001	0	Sum Stem	0.002	0.001	0
Max DBH	-0.035	-0.002	0.019	Max DBH	-0.048	0.003	-0.001
SUM LAI	1.25	0.698	-0.279	SUM LAI	-0.259	-0.084	4.383
SUM BIO	0.134	0.097	0.096	SUM BIO	0.125	0.049	-0.066
C/D Bio	0.356	0.673	4.343	C/D Bio	4.326	1.32	-5.723
200 Years of Spinup							
Variable	**Year 25**	**Year 50**	**Year 100**				
Sum Stem	0.001	0.001	0				
Max DBH	0.071	0.115	-0.091				
SUM LAI	-8.441	5.982	1.471				
SUM BIO	0.195	-0.088	0.116				
C/D Bio	7.228	-3.36	0.01				

Table 4.6: Standardized Coefficients for the 6 degree Celsius increase scenario. The five variables listed are those used in the discriminant analysis procedure and are: the sum of all stems within the plot, the maximum diameter at breast height of any tree within the plot, the sum of the leaf area index of the stand, the sum of the biomass in tons of carbon per hectare for the stand, and a ratio of the coniferous to deciduous biomass for these species within the stand.

0 Years of Spinup			
Variable	**Year 25**	**Year 50**	**Year 100**
Sum Stem	-0.001	0.001	0.001
Max DBH	-0.065	0.023	-0.003
SUM LAI	-2.7	1.174	-0.047
SUM BIO	0.799	0.174	0.121
C/D Bio	32.39	-9.538	4.379
50 Years of Spinup			
Variable	**Year 25**	**Year 50**	**Year 100**
Sum Stem	0.002	0.002	0.001
Max DBH	-0.034	-0.008	0.027
SUM LAI	1.233	0.773	0.438
SUM BIO	0.135	0.1	0.04
C/D Bio	1.067	0.927	-0.066
200 Years of Spinup			
Variable	**Year 25**	**Year 50**	**Year 100**
Sum Stem	0.001	-0.001	0
Max DBH	0.07	-0.116	-0.061
SUM LAI	-8.083	6.092	2.473
SUM BIO	0.183	-0.092	0.036
C/D Bio	7.034	-3.512	-0.755

CHAPTER 5

MODELING RUSSIAN FOREST MANAGEMENT: CARBON, TIMBER, AND CLIMATE CHANGE

Abstract

Russia has become the world's largest exporter of industrial round wood and supplies many countries, including China, Finland, and Japan, with a large share of their coniferous wood fiber. However, warming temperatures are likely to have ecological impacts on the productivity of Russian forest stands. This study investigates the effect of warming temperatures on the profitability of several forest timber projects within Russia. The forest gap model FAREAST is used to drive biological growth parameters of several forest types while a modification of Gutrich and Howarth's timber and carbon model (2007) investigates the economic aspects of each timber project. As well, the economic model is used to analyze the future of forestry carbon projects in Russia. Warming temperatures initially allow for an increase in production and profitability to several timber projects, however, a 4 degree Celsius increase of monthly mean temperatures caused all forest timber and carbon projects to become less profitable than when run under current climate conditions. Only stands in the Northwestern part of the country stocked with *Pinus sylvestris*, a fast growing heat tolerant species, were more profitable under warming temperature scenarios. Stands with higher diversity showed a financial resiliency to warming temperatures; in particular, forest stands with several deciduous species fared better than monoculture plantations due to the ability of different species to adapt to a warmer climate. These results suggest that diverse stands of heat-tolerant species will likely be the future of the Russian forest industry if temperatures continue to increase in the region. Carbon projects, intended to serve as mitigation projects for climate change, will become rendered economically ineffective by the same process they were designed to assuage.

Keywords: forest management, climate change, boreal forest, economic model, gap model, ecological resiliency

Introduction

The forestry industry is a key intercept between the boundaries of the fields of ecology, economics, politics, and climate change. Russia's forests make up nearly one-quarter of all forests on Earth (Bradshaw *et al.*, 2009) and the consequences of forest management decisions within the country has strikingly important consequences for all four disciplines. There has been an intensification of ecological, economic, climatological, and political issues affecting Russian forest management in the past decade. The result has been that a large industry, which affects a majority of the boreal forests of Earth, faces several pressing questions for a sustainable future. This study attempts to make headway into different management options for Russian foresters.

The Russian logging industry is enormous. The Russian federation is the largest exporter of industrial round wood in the entire world (Solberg *et al.*, 2010) with the majority of exports going to China and the European Union. In 2002, timber exports to China from Russia totaled $1.32 billion (Lankin, 2005) and since that time, exports have nearly doubled (Solberg *et al.*, 2010). Considering that nearly 30% of Russian logging is estimated to be illegal (Bosello *et al.*, 2010), calculations of total contributions to the economy are likely conservative since there are likely hidden costs and expenditures. The forestry sector employed 849,000 Russians in 2006 (FAOSTAT, 2006) contributing over $6 Billion to the Russian Gross Domestic Product, a staggering amount considering Russia's harvest only makes up 3% of the world's total (FAOSTAT, 2009; Solberg *et al.*, 2010). The consistent increase in exports suggests that the Russian forestry sector will grow as exports increase and Russia attempts to revitalize its economy by utilizing its vast stores of natural resources.

Yet, despite its potential, the forest industry in Russia faces many hurdles. Firstly, although blessed with an enormous quantity of forested land, about 20% of global wood resources (Moiseyev, Uusivuori, and Burdin, 1999), Russia only utilizes a fraction (40%) of its potential harvest each year (Karvinen *et al.* 2006). Statistics from the Russian Interior department project an even lower number, at 29.4%. The combination of a lack of forest roads (Karvinen *et al.* 2006) and outdated machinery (Kotilainen *et al.* 2008) prevents foresters from achieving maximum utilization in accordance with planned extraction limits. It also prevents Russian companies from exporting value-added finished wood products and increases its own export of raw logs to other countries, leaving only a fraction of potential earnings locally. The recent implementation of a tariff on round wood exports was an attempt to incentivize the development of the Russian forestry sector, yet more investment is still needed. The result of this climate is that Russia cannot develop manufactured wood products. Along with increasing demands from Finland and China, who have decimated their forests to the point that logging is severely restricted, Russian forest managers find themselves turning to the direct export of lumber over the border. In 2006, Russian exports of round wood totaled nearly 1/3 of its total harvest (Solberg *et al.* 2010). Due to the current system of stumpage fee creation and illegal logging undercutting the process, Russian prices for lumber are currently lower than products developed elsewhere (Mayer, *et al.* 2005). In 2003, the total profitability of wood harvesting in Russia was below -5%, indicating a difficulty in maintaining timber operations that are economically viable (Karvinen *et al.* 2006).

Infrastructural and systematic problems aside, Russia faces a much bigger hurdle in its forest management future. Both the Arctic Climate Impact Assessment and the IPCC's findings suggest that the circumboreal region will experience temperatures nearly 40% above the global mean (Soja *et al.* 2006), and this area contains nearly all of Russia's boreal forests. Among the many studies investigating warmer temperatures throughout Russia, the results of Briffa *et al.*'s (1995) study using dendrochronological methodologies showing that temperatures in northern Siberia are the warmest in over 1000 years and Hansen *et al.* (1999) detailing the analysis of global weather station data showing severe temperature anomalies in Russia suggest that Russia has already been experiencing warmer temperatures. Modeling exercises have shown that underlying forest compositions will change in response to predicted changes in temperature (Parfenova and Tchebakova, 2000; Zhang *et al.*, 2009; Cramer *et al.*, 2001; Chapter 3 and 4). To properly capitalize on these shifts, forest managers may have to cultivate species that traditionally were not planted in the areas that they manage or look for alternative sources of income from their forests. At the minimum, forest managers should be aware of how changes in climate will affect their yield and at what point to change to different growing stocks.

Carbon sequestration platforms that encourage forestry plantations as a methodology to mitigate greenhouse gas levels in the atmosphere may provide additional strategies for forest management. For example, the Kyoto Protocol's Clean Development Mechanism includes afforestation and reforestation; by managing their forests to maximize carbon sequestration and selling credits on regulated and/or unregulated markets, Russian forest managers have another option for the direction of their policies.

A detailed study of how much income these alternative sources of revenue could bring to Russian forest managers has not been completed however, so it is unlikely that many forest managers will move in this direction.

How should Russian foresters proceed given the challenges facing them in the near future? For the difficulties related to ecological change, modeling strategies may provide some insight. The robustness of economic and ecological modeling has advanced in the past decade and recently several models have been developed that incorporate carbon and timber harvest for forest management strategy (Liu and Han, 2009; Raymer *et al.*, 2009; Gutrich and Howard, 2007). Additionally, ecological models have been designed to simulate the ecology and development of Russian forests even when timber harvest (Gustafson *et al.*, 2010) and climate change (Yan and Shugart, 2005; Zhang *et al.*, 2009) are considered. There is not, however, an integration of these two models such that a clear variety of options and potential outcomes for forest management in Russia and Siberia can be discerned. This is significant, particularly given the challenges facing the industry detailed above. This study integrates the biological and ecological abilities of a forest gap model FAREAST (Yan and Shugart; 2005; Chapter 1) with a modification of an economic forestry model (Gutrich and Howarth, 2007; White and Lutz, in preparation) to address several pressing questions currently facing Russian forestry management.

Background

In this study, we examine the boreal and temperate forests of Russia. The total area covered by forest in Russia is nearly 776 million hectares, and nearly 96.0 percent of these forests fall under the control of the Ministry of Natural Resources with the remaining 3.0 percent under the direction of regional governments (Karvinen *et al.* 2006). Within these 776 million hectares lie 81.6 billion cubic meters of growing stock (Danilin and Crow, 2008).Forested lands are not able to be privately owned in Russia as dictated by the Forest Code of Russian Federation. The Ministry of Natural Resources manages the composition of the forests that are under its control. In 2003, the most common forest type was dominated by Larch (*Larix spp*.) which made up over 30 percent of all forests. Pine (*Pinus spp*.), Spruce (*Abies spp*.), and Birch (*Betula spp*.) make up the other three major forest types. Coniferous species make up the majority of harvest, primarily because of their dominance in Russian forests, but also for their use in many commercial applications.

Russian forests, particularly those in Siberia, are currently under-developed. Low productivity rates and unassisted regeneration after clear-cut practices leave open the ability to manage many forests more appropriately for carbon sequestration. Estimates suggest that nearly 50-80 million hectares of currently unforested land could be reforested, yielding a 2.5 t C $ha^{-1}yr^{-1}$ carbon sink (Danlin and Crow, 2008). From 1993 to 2002, the amount of fallow agricultural land has nearly doubled, suggesting open areas available for further carbon farming. Many forested lands in Russia are unavailable for harvest due to limited accessibility; these areas may be left for carbon sequestration projects at minimal expense. Additionally, current logging practices allow for regeneration rates of significant length, typically 120-140 years as dictated by the biology of the stand, and not the economic yield (Karvinen *et al.*, 2006). Gutrich and Howarth (2007) constructed a forest model that determined the net present value of forests in New

Hampshire from both carbon and timber perspectives. This model could be applied, given the appropriate growth and timber price data, to Russian forests to determine similar net present value data.

Here I attempt to utilize the ability of the Gutrich and Howarth model to determine several conclusions about Russian forest management potentials. First, I adapt the GH model to Russian forests by incorporating growth rates, maximum timber and carbon storage, and soil carbon data generated from ecological forest gap model runs; FAREAST, the forest model used, has been thoroughly validated across Russia and Siberia in a variety of climates (Shuman and Shugart, 2009; Chapter 1) and generates reliable growth information. Given the appropriate prices for different types of timber and carbon, I determine the net present value of the most common commercial forest types in some of the most heavily utilized locations within Russia. Second, I use Monte Carlo simulation methods with this model to determine the price points whereby the decision to grow forests for carbon outweigh the decision for traditional management for timber and forest products, particularly when forests are remote and access is limited and expensive. Using this same methodology I find the break-even price points for timber and carbon of each forest type and location.

Third, I consider the effects of a warming climate upon these forested areas and determine the most appropriate financial decision for forest managers to make in areas where species shift is likely. Using simulated output data from the FAREAST forest gap model (Yan and Shugart, 2005; Lutz *et al.* 2010) given a 2-degree Celsius and 4-degree Celsius warming over the life of the stand, we explore the NPV of all sites and forest types given current prices. Finally, I use a simulation analysis tool in the program Crystal

Ball, to generate the revenue for each forest type and location under different carbon prices and under different climate regimes. This information suggests which forest types succeed and fail economically as carbon sequestration projects continue under a warming climate.

Russian forests are underutilized compared to the forests of other developed nations. There are many options available for Russian forest managers to select for future management strategy. The motivation of this study is to provide scientifically and economically driven analyses that answer questions facing Russian boreal and temperate forests. Finally, I examine the results of these analyses and determine the climatological implications of these decisions. While sequestering carbon may be best financial decision for forest management, there may be climatic interactions that counteract the good intentions of the decision.

Methodology

Model information

Gutrich and Howarth (2007) first explored the interplay between economic forest management models with carbon sequestration returns in a study analyzing New Hampshire timber stands. Their model calculates total timber stock as a function of time since the previous clear-cut harvest. Therefore, although it simulates forest growth, it does not take into consideration environmental, ecological, or disturbance effects upon the stand. Timber growth and the amount of harvestable timber is determined by the derivation of a multitude of parameters, focused around four central equations, and 3 groups of slightly less important but contributing parameter sets.

Gutrich and Howarth calculate the total current timber volume of their stands by estimating the maximum timber volume (m^3/ha), the timber growth efficient (%/yr), and the minimum stand age with timber volume (years) from forest yield tables from the U.S. Department of Energy in 2004 using the equation:

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

in which the maximum timber volume is α_0, the timber growth coefficient is α_1, and the minimum stand age with a positive timber volume is α_2. The timber is then divided into share coefficients for sawtimber, as the total tree volume is not utilized completely for sawnwood once it is felled and processed, with values derived from data from the Forest Inventory and Assessment (FIA) of the U.S. Forest Service. A proportion of the harvest allocated to different timber products is calculated in order to determine the total output of the stand once it is processed. Finally, saw timber and pole timber/pulpwood prices are utilized so as to obtain the NPV of the forest stand. Forest stands may be adjusted by harvest rotation age and percent harvest, although Lutz and White (in preparation), noticed irregularities with the percent harvest function and so it is not used here.

For the calculations of total carbon content for the stand, Gutrich and Howarth utilize a series of equations that focus on live and dead carbon. For live carbon, the equation:

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

is utilized 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:

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

was used in which δ_0 represents the decay rate of dead and downed wood in percent per year, 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.

The other major equation examines the proportion of sawtimber as a function of total timber volume. In this equation, the proportion of sawtimber for the whole stand is curvilinear in relation to stand age and eventually achieves a maximum value of one. In practice, however, this value rarely reaches more than 80% according to Gutrich and Howarth. In addition to these main equations, the other significant coefficients are $h_{1,2,3,4}$ which take into account the percent harvest that is allocated to pulp wood or saw logs. All parameters and their description can be found in the original Gutrich and Howarth paper (2007). As well, White and Lutz (in preparation) readjusted the original model to account for the costs of timber felling and shipping and carbon project development costs. These values were derived from the forest science literature as well as from papers published by the U.S. Forest Service.

Parameter and Price Calculation for Russia

In order to properly investigate Russian forestry, the Gutrich and Howarth model needed to be readjusted to reflect conditions in Russia. This adjustment required the modification of many of the parameters with analogs taken from literature specific to Russian forests. Parameters directly related to the growth of forests and ecological processes were able to be derived from results of the FAREAST model. The FAREAST model, documented in Xiaodong and Shugart (2005) and Shuman and Shugart (2009) was modified to be able to model much of the federated territory of Russia (as discussed in Chapter 2). Several locations were chosen to represent several different focal points of the Russian timber industry. These generally fell into the category of East, Central, and western Russia, and site selection was guided by annual logging extraction values provided by the Center for Ecological Productivity of Forests at the Russian Academy of Sciences (CEPF-RAS), Moscow. In Eastern Russia, the principal area of study was nearby Amursk, a city in Kabarovsk Krai, one of the dominant producers of lumber in Russia. In Central Siberia, two locations were used in Irkustk Oblast. This region houses a large portion of the Siberian timber trade. The Western sites were selected in the Republic of Karelia, a federal subject of Russia that borders Finland and houses a large timber industry that caters to European demand. Each site chosen was validated previously by comparison to remotely sensed imagery (see Chapter 2).

At each site, the FAREAST model was run for a total of 200 repetitions of 1/12th hectare plots, each for 90 years of run time. In order to replicate the conditions of a forestry plantation, each forest type of interest was isolated such that only that selection of species was allowed to grow, thereby maximizing the growth of the species of interest. This required the site to be conducive to the species of interest; in this regard, site locations were based on areas of known locations of dense stands of the species of interest. This process was also guided by forest maps provided by the CEPF-RAS. Table 5.1 details each site and its location and the forest types investigated there.

For each forest type, several of the parameters needed to be modified to reflect the different conditions and species from Gutrich and Howarth's study. The alpha value of maximum timber volume, the maximum carbon storage in live biomass, and biomass and timber growth coefficient were derived from plot data from FAREAST simulations. Their corresponding coefficients (alpha 1 and alpha 2) were calculated by using the Solver Excel add-in which charted the best fit for equation 1 given the value of alpha 0 determined by FAREAST. In this sense, the equations most directly related to forest growth were taken from the FAREAST model to most accurately derive the proper parameters for each location. These values were recalculated for forest simulations undergoing a total of 2 and 4° Celsius increase in monthly mean temperature over the 90 year simulation period.

Many other parameters necessary to run the economic model were taken from previous estimates of similar forest types as estimated by Gutrich and Howarth (2007) and White and Lutz (in preparation). The delta values representing coefficients for dead and downed wood and the beta values representing sawtimber share coefficients were taken from forest type analogs in the United States. Only the coefficients for Larch, with no direct analog, were calculated from U.S.F.S Evalidator data by using information from stands of Western Larch. Carbon content of pulpwood and sawwood, the decay rate of wood products, and carbon percentage in timber products, were all kept constant as was done in both Gutrich and Howarth (2007) and White and Lutz (in preparation). The percentage of harvest was modified for each forest type to reflect the actual percentages of harvest that go to pulpwood and saw products; these estimates were derived from Gerasimov *et al.* (2005). The small percentage of harvest going to hardwood saw products reflects the relative lack of proper infrastructure for processing this resource. Soil carbon values were taken from site information from the FAREAST model.

Pricing information for each forest type was amalgamated from several sources. The majority of prices were taken from annual averages as reported by Wood Resources International (personal comm., 2010). Other prices were found in World Timber Price Quarterly (2007). Larch prices, unavailable elsewhere, were determined and calculated from market reports from Northeastern China, the location of a majority of the import of Siberian Larch products. All of these values were transformed into 2009 USD using the Producer Price Index. Cost information for timber production was taken primarily from Gerasimov and Karjalainen (2009) which details the cost of hauling and loading wood products (Gerasimov *et al.* 2005, and Gerasimov and Karjalainen, 2007). All data was converted to USD and transformed into 2009 USD through the Producer Price Index. Table 5.2 contains the pertinent parameter information for each site and forest type, while Table 5.3 contains pricing and financial parameters used in the simulations.

Results

Table 5.4 contains the net present value information for each site location and forest type over the course of 90 years for a stand of one hectare in size. These results utilize current pole and saw timber prices, and the carbon price is set to the current market price of $1.00 per ton of carbon. The western sites yield larger revenues for both spruce/fir forests and pine forests. Specifically, the eastern plot containing spruce/fir forests failed to be profitable given the current conditions. The most profitable forests were the pine and spruce/fir forests of North-Western Russia, with returns from one hectare of forest of over $500 for the 90-year lifespan. Centrally located forests yielded a lesser return, likely due to increased transportation costs associated with their remote location. At the current market price of $1.00 per ton, no sites yielded a positive NPV over the life of the plot for a carbon sequestration project.

In order to determine the price point at which carbon sequestration projects finally become profitable, Monte Carlo analysis was used to find break even points for NPV of each forest type and location. Table 5.5 shows the price points at which a carbon sequestration project will become slightly profitable. Most projects become profitable at a carbon price of just over $6.00 per ton, yet the Pine East project becomes profitable very quickly, and the Larch project becomes profitable at $2.00. Table 5.6 charts the price point for carbon whereby a carbon sequestration project will become more profitable than a timber project of equal size. These data are an important indicator for the viability of carbon sequestration projects in the future. Most forest types and locations require a carbon price of $10.00 or more to achieve better returns than a timber project. However, the eastern Pine and Central Spruce/Fir forests require only a modest increase in the current carbon market price to become an economically viable option at $4.67 and $5.85 respectively.

To determine the effect of a warming temperature upon the economic sustainability of these forest types, simulations of the models were performed with a 2°

and 4°C rise throughout the life of the forest project. This information is displayed in Tables 5.7 and 5.8 which show the NPV of forest plots for timber and carbon projects with different warming scenarios. Table 5.7 gives the NPV of timber projects for each forest type and location given current prices of timber. Projects either increase their revenue with a slight (2°C) rise in temperature or decrease slightly, but nearly all projects are less rewarding at an increase of 4°C compared to the initial conditions. Only one project, central spruce/fir, is not profitable regardless of the degree of warming.

The profitability of carbon sequestration projects in forests given warming scenarios is documented in Table 5.8. While carbon projects follow the same pattern as timber projects under a modest warming (2°C), under a more intense warming scenario (4°C), carbon projects become not only less profitable, but economically unviable. This has profound implications for the future of forest sequestration projects and their economic utility as will be discussed later. Only one project, pine west, returns a higher NPV under a four degree warming scenario than under the initial conditions. The degree to which warming compromises revenue for forestry carbon projects is illustrated in Figures 5.1, 5.2, and 5.3. These figures show NPV lines for all 9 projects and how the profitability of each project changes with increases in the carbon market price ($/ton). For five of the nine studies, a 2° C warming scenario increases the NPV of the carbon project significantly. Yet, the more intense warming scenario decreases the NPV of the plot for 8 out of 9 projects. The marked changes in slopes of the NPV lines in Figure 5.3 compared to Figure 5.2 illustrate this trend nicely.

Discussion

Initial Prices and Model Functioning

Model output for the net present value of forests under current prices give us an idea of the current breakdown of Russia as it is utilized for timber production. In the Northwest, Pine is the most profitable species per hectare with Spruce/Fir only slightly over $100 per hectare less profitable. Pine is the most dominant genus utilized in the Republic of Karelia, the location of the study, comprising 56% of the composition of leased forest stands in the region (Gerasimov *et al.* 2005). It is likely that this higher profit margin serves as an incentive for forest managers to lease Pine stands although that is likely not the only reason for the dominance of Pine as the major leased forest type in the region. Deciduous stands are much less profitable than coniferous wood, likely due to the inability of the region to have the proper production mills in place to handle Deciduous sawn wood (Gerasimov et al 2005). Therefore, a majority of what would be valuable sawn wood is instead used for less valuable round wood. This is reflected in the low values for the parameters h_1, h_2, h_3, and h_4. Since the price of deciduous sawn wood is 7$ per cubic meter higher than pulp wood, a change in this percentage could make these forests more profitable. Birch pulpwood is the major export of Russian wood to Finland, mainly due to the decimation of Birch stands in Finland from its own logging industry (Mutanen and Toppinen, 2007). Even a modest boost in the production capability of nearby sawmills would likely allow this forest type to become the most profitable in the region due to the high demand for its products.

In the Russian Far east and Siberia, Pine is the most profitable species to grow. There is a large market for Pine in China, as documented by the dominance of this genus in imports to several Chinese markets, Larch, however, is not nearly as profitable as it could be with its high market price. Yet the geographic range of *Larix sibirica*, Siberian larch, is constrained to Central Siberia, where transport costs are high due to the geographic location of sawmills and the major markets for its products (China and Japan). Siberian larch is a fast-growing tree species that peaks in growth rates between ages 20 and 40 years (Trees and Shrubs of the USSR, 1956). It also has the ability to withstand changes in climate and growing conditions (Kikolov and Helmisaari, 1992) as is evidenced by its historical range in paleodata (Dylis 1981). Since it is able to successfully grow on many types of soils in plantations (Dylis, 1981), it may be a possible candidate for a transplant species closer to larger markets.

Spruce/Fir was not profitable in Central Siberia. The likely reason for this forest type's low profitability comes from its alpha parameter (α_2) referencing the time until there is harvestable timber. According to the input parameters, in this site, it takes over 19 years to get a stand age where there is positive timber growth. This seems unlikely and may be a site-specific issue, yet is more likely a function of the physiological characteristics of the tree species present. *Abies siberica*, Siberian Fir, is a shade-tolerant species that commonly is found with *Picea obovata*, Siberian Spruce. These two trees make up the Central spruce/fir plots studied. However, *A. siberica* takes quite a long time to grow, nearly 15-25 years to reach one meter in height (Nikolov and Helmisaari, 1992). As *A. siberica* makes up more than 50% of stand biomass in the Siberian site, and while the other two Spruce/Fir plots do not contain this species, it is likely that its presence and slow growth patterns contributed to the lack of profitability. In 30 years, the harvest return period used in this model, one of these individuals would not be tall enough to render much valuable timber, and therefore, it would not be useful for short-rotation stand projects, as evidenced by its constant negative NPV. As this is a physiological growth issue, a warm climate will not help this stand be profitable, which matches the consistent negative NPV for the site even under warmer temperatures. In general, the reasonable values that this model calculates for each forest type give confidence in the model's ability to simulate Russian forest project dynamics.

Initially, Carbon forest sequestration projects throughout Russia seem unlikely to be profitable. At the current market price of $1.00 per ton of C, no project comes even close to approaching the realm of making a profit. While many forests obtain a neutral NPV at a carbon price around $6.00 a ton, they still fail to overtake the amount of revenue gained by managing the same forest for timber. Only when prices reach the mid-teens do most forest types become more profitable if managed primarily as carbon sequestration projects even with a thirty year harvest rotation period. If these forests were managed exclusively as carbon sequestration projects, with zero harvest, the price points necessary to overtake timber revenues would be lower; however, the joint timber and carbon project management scenario combines two sources of revenue and is the most economic form of management until the price of carbon becomes much larger. While it is unlikely for forest managers to completely forgo their forestry practice immediately and focus on zero-harvest carbon projects, since they depend on forest product revenue to repay loans for machinery and capital costs and carbon prices are currently at a bottom, these data suggests that a modest increase in the price of carbon on international markets may allow Russian forests to become viable sequestration projects. At a carbon price of $6.00 per ton, three different forest types will return equal revenue from a carbon project as a timber operation; investing in the capacity to design forest carbon projects in these areas, therefore, seems a wise decision financially.

The influence of climate on forestry timber projects

Warming temperatures influence the projected NPV for forestry projects of all of the forest sites studied. There are several general trends which I will expound upon here. All results imply the importance that forest management be cognizant to temperature trends in the next several decades. Two forest types, Pine in the Northwest and Larch in Siberia, only obtain a higher NPV with both 2 degree and 4 degree warming. There is a more than doubling of NPV with both of these forests when temperature ramps up to 2 degrees; however, this value essentially remains flat when temperature is increased an additional 2 degrees for a net of 4 degrees. The likely explanation for this trend is that these two forest types contain species that are currently constrained by the initial temperature conditions and will respond to warming with increased productivity and timber production. Siberian Larch, the main species in the Central Larch forest type, is known to have the largest potential distribution area of all Russian boreal species (Polikarpov, Tchebakova, and Nazimova, 1986), reflecting its tolerance to warm climates. *Pinus sylvestris,* the species present in the Karelia Western Pine site, has the largest range of any Pine tree in the world and is present in many climates, signifying its tolerance to a range in climate. However, a large (+3-5° C) temperature increase will ultimately lead to the inability of these forests to maintain their current structure as is shown by their absence from FAREAST output at the end of 90 years at the 4° C warming scenario.

Countering the trend of Pine and Larch forest types, some forest plots show nothing but a general decline in economic return as temperature increases. Deciduous mixed forests in the Northwest and Eastern Pine forests decline considerably to nearly half of their current NPV when temperature increases 4°C in the next 90 years. This suggests that these forests are currently at optimal climatic conditions and that a warming temperature will not necessarily help their profitability in timber management. Both of these forests are among the top three most profitable forests under current climate conditions, indicating that they currently produce timber stock at a higher rate than other forests; it thus follows that increases in temperature will lead to environmental stress on the stands and decrease their productivity. The Deciduous forest type in the Northwest is made up largely of *Populus tremula* and *Betula pendula*. Eurasian Aspen, *P. tremula*, is known to be sensitive to high temperatures (Hempel and Wilhelm, 1897) and could likely affect the productivity of the stand in warmer than current temperatures. Korean Pine, *Pinus koraiensis*, makes up the majority of biomass in the Eastern Pine site, and is clearly not capable of tolerating the 4°C increase as evidenced by output of FAREAST simulations with this climate. The economic implications from these results are significant and suggest that profitability in these forest types may be on the decline with warming temperatures.

Other forest types in this analysis gave mixed responses to an increase in temperature. Spruce/Fir forest in the East and Pine forests in Siberia initially increased in NPV with a slight increase in temperature, but became economically less valuable when the temperature was increased to 4 degrees. These forests represent communities that currently are somewhat inhibited by temperature, but soon reach their climatic threshold and begin to decline in productivity and storage capacity by a full 4 degree warming. Managing these forests in the future may become more risky, as the degree of warming may either make the returns higher, or lower, depending on the extent of warming temperatures.

Deciduous forests respond to warming temperatures with in an initial decrease in NPV at 2°C, yet rebound when a 4°C increase occurs. These forests' response in increased production with warmer temperatures is due to their diversity and complexity. While the other forested stands were constructed to be primarily composed of one or two species, the deciduous mix grown in this project consisted of several species of hardwoods that were local to the sites. Upon examining FAREAST model run output, these forests have enough diversity such that while 2 degrees is detrimental to the current standing stock of the forests, 4 degrees benefits those species that were otherwise suppressed by the dominant species. When climate is allowed to shift and the dominant species cannot tolerate the environmental conditions, more tolerant species are allowed to prosper, and their increased productivity makes up for the decline of the other species.

For instance, at current temperatures, the Western deciduous site was dominated by *B. pendula* and *P.* tremula. However, at a 4°C warming, other species are visible throughout the stand, including *Acer platinoides*, *Ulmus glabra*, and *Alnus incana*; these species add biomass to the plot when *B. pendula* declines. Also, under current conditions *Populus tremula* is a significant part of the composition of the Eastern Deciduous plot; with a four degree increase, *Populus tremula* declines to near nonexistent levels, but the

Birch species *Betula platyphyll* , which was previously absent from the forest plots, appears at levels above *Populus tremula*; thus, one species masks out the loss of another previously dominant species. In this case, increasing diversity within a forest plot mitigates the likelihood of financial loss given changing environmental conditions, since a change might be detrimental to one species yet beneficial to another. These results echo several other forest management studies suggesting the creation of plantations with high diversity to mitigate losses due to climate change (Bolte *et al.* 2009; Bodin *et al.* 2008; Drever *et al.* 2006; Ravidranath and Sukumar 1998).

In contrast, for mainly homogenous stands, while their standing stock may be resilient because of their age (an idea investigated in Chapter 4), long term simulations of a four degree change does not bode well for production of these species for time periods over 100 years. Thus, while climate may increase productivity in the short-term, the long-term repercussions due to the need for a complete species shift may be troublesome. Because forest projects managed in this study were only 90-years long, we can only suggest what would happen with projects begun at the current date; the fate of projects begun under an already warmed climate is not investigated here, although Chapters 3 and 4 give some inclination about the influence of temperature upon Russian forest ecology.

The influence of climate on forestry carbon projects

Forestry carbon projects do not fare as well as forestry timber projects when temperatures increase. Only one project has a net increase in NPV with a four degree increase in temperature (Pine West). Generally, all projects suffer a significant decrease in value when the temperature is increased to four degrees, many becoming economically unprofitable. Even the Pine project in Eastern Russia, which is the most economically promising area for carbon exploration, becomes a financial liability at four degrees. This trend can be seen on Table 5.8 and in Figures 5.1, 5.2, and 5.3. Most visibly, the breakeven point for carbon projects shifts markedly higher upon an increase from 2 degrees to 4 degrees; this is evident in the decrease in magnitude of the slopes of the NPV lines in Figures 5.2 and 5.3.

These results signal that carbon forestry projects become less effective when current species are used and temperature increases. Ironically, projects designed to mitigate climate change by sequestering carbon become economically unviable when exposed to the conditions they were designed to ameliorate. The current species that exist in these locations throughout Russia are not likely to be financially viable carbon projects if planted in monoculture stands, suggesting two alternatives. First, forest managers must plant a diversity of species in order to allow the stand to be productive with a changing climate; or, secondly, forest managers must plan accordingly to warming temperatures and plant species and seedlings that will reach their climatic optimum under several decades of climate change. As the second option is more financially risky, hedging against climate change by planting a heterogenous and diverse plantation for a forestry project may allow for a project with a positive NPV. As values for this project were considered using natural regeneration, planting and seeding costs would need to be added to this model to see if these different projects would remain financially viable. Another alternative would be to restrict investment into only those forest stands that show only positive responses to large degrees of warming: amongst our studied areas, only Pine forests in the Northwest of Russia are good candidates.

Conclusions

This project, which combined a scientifically tested forest gap model and an economic timber carbon model, and applied the result to Russia, yielded results that suggest general trends in the economic stability of Russian forest management in years to come. First and foremost, the projects with initial profitability come from forest types with fast growth, tolerance to climate variation, and the ability to tolerate high light conditions. When the rotation age of a stand is 30 years, trees must grow quickly in order to obtain enough length and mass to become viable for saw timber, which yields a higher price than pole timber. For some species and forest types, this is not possible, meaning that short rotation times are not economically successful. This logic may explain the rationale for long rotation times in forest types such as Spruce/Fir in the Russian Fareast and Siberia; a shorter rotation time provides lumber that is not properly aged to provide high quality timber and is therefore not profitable to harvest. Pine species in the northwest and east are fast growing and are subsequently the most profitable as determined by the economic models in this exercise.

In the near future and at current market prices, carbon forestry projects in the forests studied are not a viable option. All projects had negative NPV even with a 1% annual growth rate in the price of carbon. However, once carbon approaches $5/ton, many of these forests become an equal source of revenue as timber. Particularly, the fast growing species of Pine are possible areas for exploration for future forestry projects in Russia. When prices reach $15 per ton, many forest types, under current conditions, are more profitable as carbon forestry projects than as timber projects. This suggests that carbon forestry projects in Russia are likely more feasible than similar forestry projects in the Northeastern United States because they are less economically viable as timber projects and therefore require a small increase in market price in order to incentivize forest managers to maintain them as zero-harvest carbon projects. These results should suggest that forestry carbon projects in particular forest types may be worth investigation for future carbon projects. In areas with high levels of illegal logging and high conservation priority, this option may be a short-term (90 year) strategy.

Climate change and warming temperatures should significantly affect the profitability of forest projects in Russia and the strategy of forest managers. If temperature increases quickly and at a large magnitude, nearly all of the forest types studied in this project lose profitability. Only one project, Pine forests in the northwestern area of Russia, becomes more profitable under a 4°C warming scenario. At this level of warming over such a short time period, most species that are planted at year 0 cannot survive to year 90, a period of three harvest rotations. At more modest changes in temperature (2°C over 90 years), many forests are capable of becoming more profitable and are also able of working as timber or carbon projects, as long as carbon prices are higher than they are currently.

The results of these modeling scenarios suggest several strategies for forest managers. Firstly, given the speed at which climate may affect Russian forests, and the relative instability of several species to warming temperatures, many projects that rely on long-lived stands with long rotation periods may become unprofitable as these forests will change their growth patterns and possibly perish under the unfavorable climatic conditions. It is likely then that the drastic step of immediate harvest of some of these types of projects, particularly Spruce/Fir stands in Siberia, may be necessary to at least return some profitability to the forest owner. At this point, forest managers can replant with more tolerant species that will not be as severely affected by warm weather. Secondly, fast growing species that are capable of climate shifts, may be more profitable if transplanted in areas closer to current markets. Finally, given an increase in market prices for carbon in forestry projects, many forest managers should investigate the feasibility of setting up a carbon forestry project, as revenue from these projects will quickly overtake those returned by forestry practices with only a modest increase in the price of carbon (Table 5.6).

This study would not be complete without a comment on the ecological and climatological implications of change in forest management. With a small increase in the price of carbon, many areas in the Russian boreal forest may be strategic candidates for a carbon forestry project. However, as discussed in the Introduction to the dissertation, vegetated canopies provide relative warming to the regional climate, particularly in northern latitudes when the difference in albedo between snow covered ground and coniferous cover is severe. It is not completely known how carbon sequestration benefits balance with albedo and heat forcings for all areas of the boreal forest, however, before carbon sequestration projects are begun, this topic should be analyzed in detail to ensure that the growth of forests does not result in the opposite of its intentions with respect to warming.

Table 5.1: Table documenting the geographic locations and species used for each study site.

Site Name	Latitude	Longitude	Species Included	Notes
Central Larch	57.78	100.65	Larix sibirica	200 km from Bratsk Irkutskaya Oblast
Pine West	61.63	38.23	Pinus sylvestris	40 km from Kargopol Republic of Karelia
Pine Central	57.78	100.65	Pinus sylvestris Pinus sibirica	200 km from Bratsk Irkutskaya Oblast
Pine East	50.51	137.53	Pinus koraiensis Pinus pumila	30 km from Amursk Khabarovsky Krai
Spruce Fir West	61.63	38.23	Picea obovata Picea abies	40 km from Kargopol Republic of Karelia
Spruce Fir Central	55.99	106.22	Abies sibirica Picea obovata	200 km from Severobaykalsk Irkutskaya Oblast
Spruce Fir East	50.51	137.53	Abies holophylla Abies nephrolepis Picea ajanensis Picea koraiensis	30 km from Amursk Khabarovsky Krai
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
Deciduous Mix East	56.72	96.83	Populus tremula Betula pendula Betula pubescens Betula platyphyll	30 km from Amursk Khabarovsky Krai

Table 5.2: Table of model parameters for each study site investigated with the timber/carbon model.

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 (m3/ha)	209.00	402.79	207.46	742.19	137.10	65.31	145.46	160.41	163.78
alpha1	Timber growth coefficient (%/yr)	0.0071	0.0184	0.0195	0.0074	0.1426	0.0946	0.0199	0.0262	0.0262
alpha2	Minimum stand age w/ positive timber volume (yrs)	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 (%/yr)	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 (%/yr)	0.0320	0.0400	0.0400	0.0400	0.0480	0.0480	0.0480	0.0650	0.0650
delta1	Formation coefficent 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 coefficent 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	Sawtimber share coefficient (%)	6.3600	6.3700	6.3700	6.3700	7.2700	7.2700	7.2700	1.3800	1.3800
beta1	Sawtimber share coefficient (years)	2.7000	2.7000	2.7000	2.7000	1.4700	1.4700	1.4700	20.0200	20.0200
beta2	Sawtimber 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/m3)	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234
epsilon3	Carbon content of hardwood(t/m3)	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

Table 5.3: Financial Parameters used for model simulations.

		Larch	Pine West	Pine Central	Pine East	SpruceFir West	SpruceFir Central	SpruceFir East	Dmix West	Dmix East
Ppole	Poletimber price ($/m3)	$52.46	$65.90	$52.46	$52.46	$65.90	$52.46	$52.46	$53.02	$59.26
Psaw	Sawtimber price($/m3)	$118.97	$67.78	$75.78	$75.78	$67.78	$75.78	$75.78	$60.76	$120.47

Timber Costs	
One-Time Costs	
$77.50	Site Preparation (per ha)
$50.00	Inventory Costs (per ha)
$8.70	Management Plan (per ha)
$136.20	Total
Infrastructure Costs	
$1.24	infrastructure maintenance ($/m3)
Harvesting Costs	
$ 4.18	$/m3 harvest
$ 0.15	Hauling Costs ($/m3/km)

Carbon Costs	
One-Time Costs	
$73.00	Site Prep Costs-Carbon ($/ha)
$50.00	Inventory
$37.50	Management Plan
$28.00	Carbon project development
$6.25	Pre-Project Analyses
$2.40	Establish Inventory Baseline
$0.87	Growth Modeling
$1.50	Calculation of LLWP Carbon
$0.33	Monitoring Sampling
$199.85	Total
Ongoing Costs	
$6.25	Site Maintenance
$0.42	Measurement and Monitoring
$0.18	Annual Verification
$0.02	Annual Growth Modeling
$0.01	Calculation of LLWP Carbon
$6.87	Total

Financial Parameters		
25 km	Distance	*Distance from mill (km)*
2.39%	StumpagePriceGrowth	*Stumpage price growth rate (%/year)*
5.00%	DiscountRate	*Discount rate (%/yr)*
$1.00	CarbonPrice0	*Initial carbon price ($/t)*
1.00%	CarbonPriceGrowth	*Carbon price growth rate (%/yr)*

Table 5.4: Net Present Value of timber and carbon projects for all sites examined in this project. Parentheses around values indicate a negative NPV and that the project is financially unstable over a 90-year period.

	West		Central		East	
Forest Type	Timber	Carbon	Timber	Carbon	Timber	Carbon
Spruce/Fir	$568	($303)	($31)	($306)	$53	($342)
Pine	$682	($312)	$204	($325)	$524	($172)
Deciduous	$191	($305)	-	-	$425	($304)
Larch	-	-	$116	($359)	-	-

Table 5.5: Table showing values for carbon ($/ton) at which each forestry project becomes profitable over a 90-year period.

Forest Type	West	Central	East
Spruce/Fir	$6.11	$6.39	$17.34
Pine	$4.50	$9.60	$1.91
Deciduous	$6.36	-	$6.22
Larch	-	$114.25	-

Table 5.6: Price points for carbon ($/ton) at which point a carbon forestry project is more profitable than a traditional timber forestry project for each study site.

Forest Type	West	Central	East
Spruce/Fir	$15.66	$5.85	$19.89
Pine	$17.20	$15.00	$4.67
Deciduous	$9.71	-	$13.50
Larch	-	$150.80	-

Table 5.7: Net present value ($) for forestry projects given current climate, a 2 degree Celsius, and 4 degree Celsius increase in monthly mean temperature over a 90-year period. Timber prices are based on cited literature and industry sources.

	West			Central			East		
Forest Type	0° C	2°C	4°C	0° C	2°C	4°C	0° C	2°C	4°C
Spruce/Fir	$568	$476	$362	($31)	($105)	($84)	$53	$71	($24)
Pine	$682	$1,296	$1,301	$204	$224	$158	$524	$437	$259
Deciduous	$191	$41	$63	-	-	-	$425	$219	$380
Larch	-	-	-	$116	$338	$342	-	-	-

Table 5.8: Net present value ($) for carbon projects given a 4 degree Celsius increase in monthly mean temperature over a 90-year period. Carbon was priced at 10$/ton.

	West			Central			East		
Forest Type	0° C	2°C	4°C	0° C	2°C	4°C	0° C	2°C	4°C
Spruce/Fir	$232	$201	($154)	$206	$563	($326)	($153)	($136)	($210)
Pine	$417	$727	$765	$16	$68	($16)	$1,541	$750	($244)
Deciduous	$209	($7)	($78)	-	-	-	$221	$308	$124
Larch	-	-	-	$431	($44)	($19)	-	-	-

Figure 5.1: NPV of carbon forestry projects for a 90-year lifetime as a function of increasing carbon prices under current climatic conditions. Pine plantations are the most profitable projects to consider pursuing given the current climate.

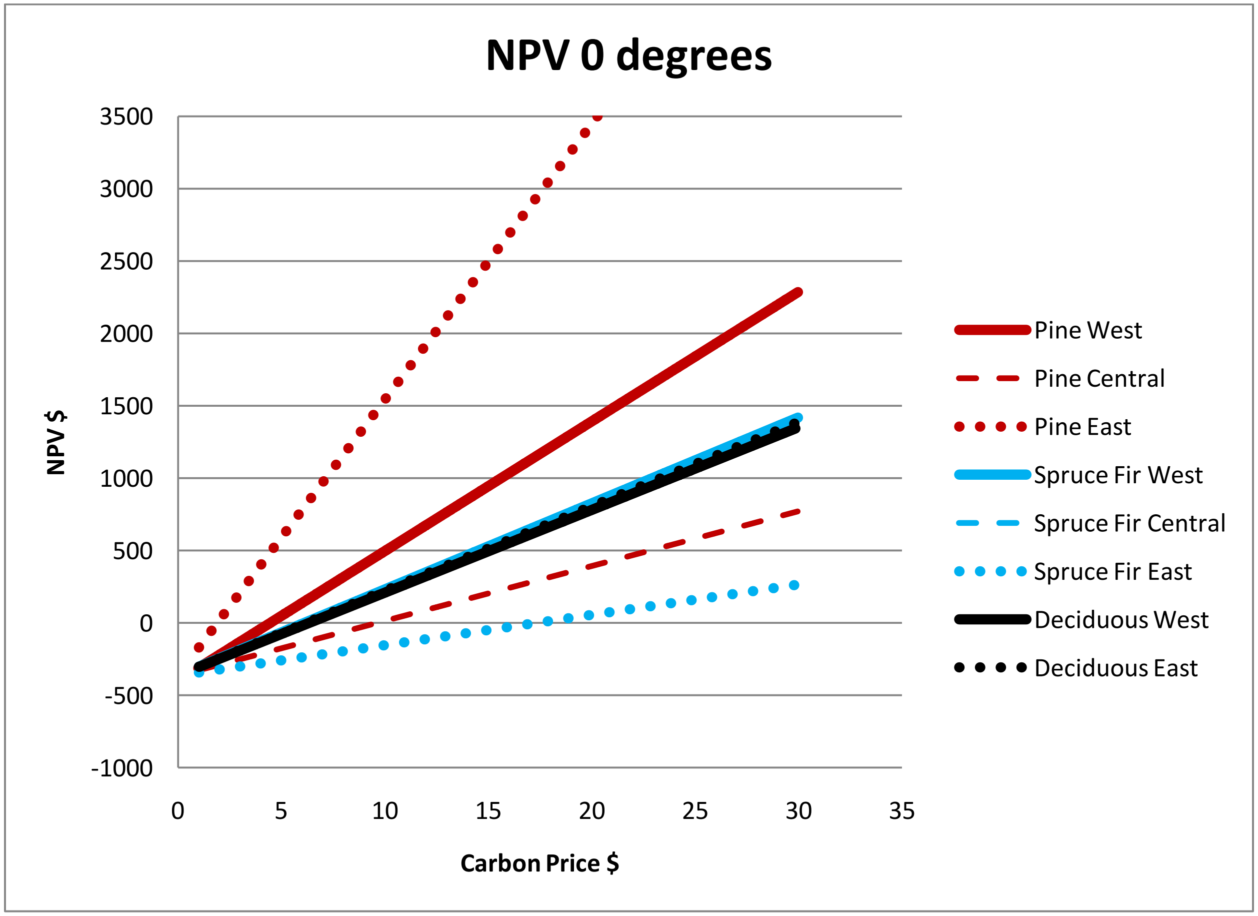


Figure 5.2: NPV of carbon forestry projects for a 90-year lifetime as a function of increasing carbon prices with a 2 degree Celsius increase to monthly mean temperatures. Pine plantations are the most profitable projects to consider pursuing. Projects in Siberia and Deciduous projects in the East are also relatively profitable.

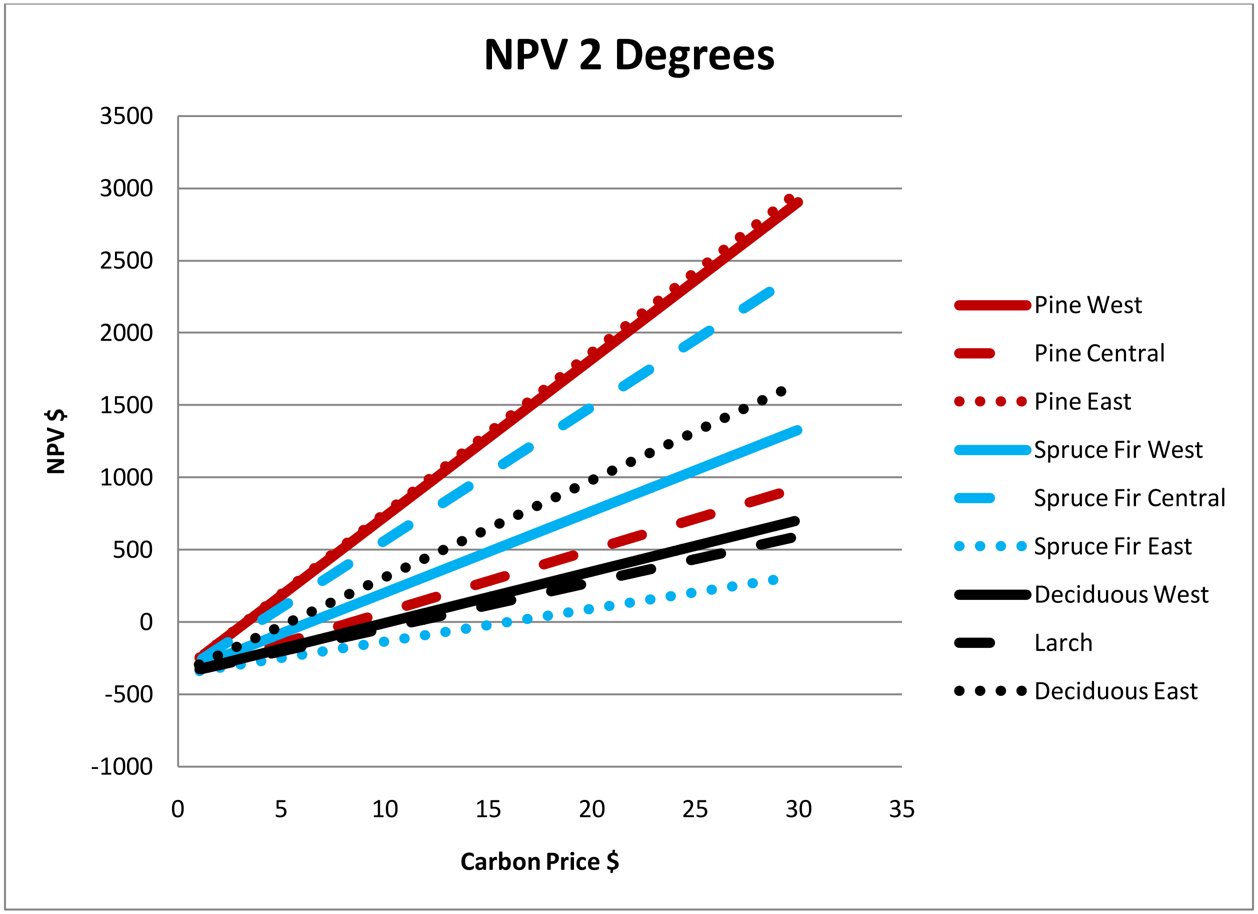
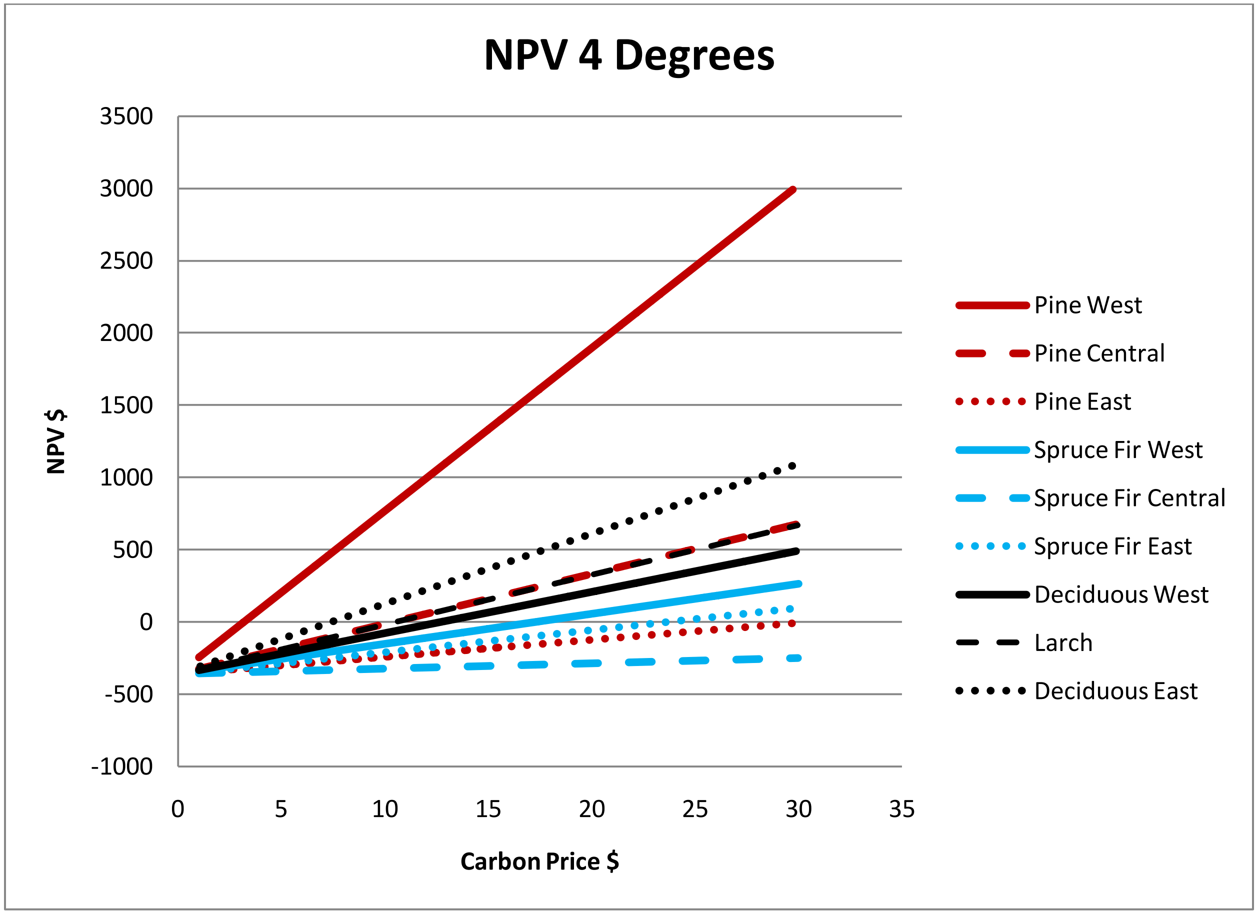


Figure 5.3: NPV of carbon forestry projects for a 90-year lifetime as a function of increasing carbon prices with a 4 degree Celsius increase to monthly mean temperatures. With this increase in temperature, virtually all projects become less profitable than with current conditions, except for Pine plantations in the Republic of Karelia due to the fast growing nature and temperature resiliency of *Pinus sylvestris*.



CHAPTER 6

CONCLUSIONS TO THE DISSERTATION

This dissertation utilizes a proven forest gap model to investigate the consequences of rising temperatures upon Russian boreal and temperate forests. Boreal forests are an important ecosystem, not only because of their ability to store carbon, but also for their influence upon regional and global climate, their importance in the Russian and global economy, and the resources that they provide local communities and biodiversity. Under these pretenses, I have investigated how temperature affects the ecological and economic realities of highlighted areas of Russian forests. Here, I document the many conclusions that can be taken away from this dissertation.

The second chapter of this dissertation details the process by which the FAREAST gap model was expanded to simulate the totality of Russian forests. Upon comparison with a dataset generated by the Center for Ecology and Productivity of Forests, a division of the Russian Academy of Sciences, FAREAST biomass simulations for over 5,000 unique sites compared well to observed data. When only mature forests were used and outliers removed, the coefficient of determination for a linear regression between FAREAST output and remotely sensed biomass data was $r^2 = 0.872$. FAREAST data varied on average just 0.355 standard deviations from the mean with an average difference of 15.04 tons per hectare. This is considerably better than many large-scale simulation attempts by forest gap models documented in the literature. This procedure documents how long-standing problems of parameterization of gap models and computational difficulties were met. In general, the ability of FAREAST to successfully model biomass dynamics throughout the continental Eurasian boreal forest suggests that forest gap models may be effective cross-validation mechanisms for Dynamic Global Vegetation Models and may enhance model findings if run simultaneously with DGVMs.

Chapter three utilizes the detailed stand property output of FAREAST to examine the ecological consequences of warming temperatures on forests in Siberia. Instead of solely biomass, this chapter analyzes seven physiological, structural, and compositional characteristics of Siberian forests and uses a discriminant function analysis technique to determine how temperature change affects forest stands. Analysis of the results suggest that stand physiological properties are the largest indicators of change in the leading edge. As well, the areas where the most change was detected was towards the interior of the forest, where disturbance and stand replacement processes were able to alter the properties of the stand. These results indicate that change detection studies may be more suitable for interior stand observation than treeline advancement in northern Siberia. Additionally, this chapter suggests that interior Siberian forests are many decades away from complete compositional shift, although, with increased disturbance, the shift may occur more quickly.

The fourth chapter of the dissertation investigates the influence of temperature on ecological stability and resiliency in Siberian forests. Utilizing a similar methodology as chapter three, this section focuses on the influence of stand age upon resiliency to rising temperatures. Data analysis using a discriminant function analysis suggest that forests of stand age 75 to 150 years are significantly more resilient than areas of bare ground, very young stands, and very old stands of 200 years of age. The most important variable in these investigations was a ratio of coniferous to deciduous biomass, an indication of composition change. These results follow the theoretical work of Holling who predicts forest resiliency in mature stands at the peak of their growth period; in this study, Siberian boreal forests show no exception to this theory. This resiliency, however, is dependent on the magnitude of temperature shift. At a six degree Celsius warming over 100 years, even mature and fast growing stands were not able to maintain resiliency. Forest management implications suggest that the majority of Central Siberian Transect will be resilient to complete composition shift for several decades, particularly in mature stands; however, a more southerly application of this methodology may not yield the same results, particularly at the southern end of forest ranges.

The final chapter of this dissertation centers around the economic implications of warming temperatures in Russia's forests. The Russian forestry industry has several ingrained production issues that minimize its ability to realize full economic benefits from the vast natural resources within the country. Currently, carbon sequestration projects in Russian forests are unprofitable, mainly from the low growth rates of these forests, but also because of the extremely low price of carbon on international markets. A two degree increase in annual monthly temperatures has both positive and negative effects upon timber projects in Russia. Depending on the properties of the species harvested, some forests see a boost in profitability, as much as double their net present value for a ninety year project. A four degree increase in temperature, however, has radical impacts upon forestry and carbon projects in these forests. Of nine projects, only one project returns an increase in NPV; the rest all lose value compared to current climate conditions or become completely unprofitable. Carbon sequestration projects are an option for Russian forests given modest increases in the price of carbon; the results of this study suggest that investments into carbon forest project development may be beneficial. Finally, this final chapter finds that forests of increased diversity are better able to handle increases in temperature due to the balancing effects of having a multitude of species responses. This suggestion has been made before, but this study is the first to find that it also yields economic benefits to forest management.

This dissertation scratches the surface of many important topics in the field of forest ecology. The methods described here can be utilized on all Russian forests; detailed and thorough analysis may help the international community learn where the most vulnerable boreal forests lie, and what management decisions may be the most effective in preparing them for changes in climate. Future studies in forest ecology must incorporate economic realities in order to provide proper guidance for policy makers; this study, particularly chapter 5, makes strong headway into interdisciplinary approaches to the issue of warming temperatures in Russian forests. The past several decades have advanced the field of computational ecological modeling to where we can now thoroughly analyze and apply these instruments towards real-world issues with great accuracy. It is pertinent that we as a scientific community begin to employ our instruments to help forestry management in the urgent issues involved with regional and global climate change. I believe that this dissertation opens the door for many future studies on Russian forests and hope that its conclusions can be utilized by forest managers so as to ensure that we can maintain forests in ways that benefit society and the planet, economically, ecologically, and biologically.

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