GLOBAL CLIMATE CHANGE ADAPTATION: EXAMPLES FROM RUSSIAN BOREAL FORESTS

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Abstract. The Russian Federation contains approximately 20% of the world's timber resources and more than half of all boreal forests. These forests play a prominent role in environmental protection and economic development at global, national, and local levels, as well as, provide commodities for indigenous people and habitat for a variety of plant and animal species. The response and feedbacks of Russian boreal forests to projected global climate change are expected to be profound. Large shifts in the distribution (up to 19% area reduction) and productivity of boreal forests are implied by scenarios of General Circulation Models (GCMs). Uncertainty regarding the potential distribution and productivity of future boreal forests complicates the development of adaptation strategies for forest establishment, management, harvesting and wood processing. Although a low potential exists for rapid natural adaptation of long-lived, complex boreal forests, recent analyses suggest Russian forest management and utilization strategies should be field tested to assess their potential to assist boreal forests in adaptation to a changing global environment. Current understanding of the vulnerability of Russian forest resources to projected climate change is discussed and examples of possible adaptation measures for Russian forests are presented, including: (1) artificial forestation techniques that can be applied with the advent of failed natural regeneration and to facilitate forest migration northward; (2) silvicultural measures that can influence the species mix to maintain productivity under future climates; (3) identifying forests at risk and developing special management adaptation measures for them; (4) alternative processing and uses of wood and non-wood products from future forests; and (5) potential future infrastructure and transport systems that can be employed as boreal forests shift northward into melting permafrost zones. Current infrastructure and technology can be employed to help Russian boreal forests adapt to projected global environmental change, however many current forest management practices may have to be modified. Application of this technical knowledge can help policymakers identify priorities for climate change adaptation.

1. Introduction

The accumulation of greenhouse gases (e.g., CO_2, CH_4) in the atmosphere due to fossil fuel combustion, deforestation, and other human activities may have already begun to change the global climate (Victor and Salt, 1995; IPCC, 1990). The response and feedbacks of boreal forests to projected global change are expected to be profound (Smith et al., 1991; Smith and Tirpak, 1989). Large shifts in the

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distribution and productivity of vegetation, especially boreal forest systems, are implied by the climate change scenarios of GCMs such as those of the Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald, 1987) and United Kingdom Meteorological Office (UKMO) (Mitchell et al., 1989). Tropical and temperate forests may expand by up to 20%, whereas boreal forest could decrease by up to 50%. Grassland/shrublands may significantly increase in extent, whereas the tundra zone may decrease by up to 50%. Uncertainty regarding the potential redistribution of vegetation in response to global climate change complicates the development of strategies to adapt to a changing global environment (King, 1993). Even if the GCMs are only partially correct, the productivity of boreal forest systems will inevitably change, and the proportion of lands with marginal productivity will increase (Neilson et al., 1995; Smith et al., 1991).

Shifts in atmospheric CO_2, precipitation quantity and timing, wind patterns, and ambient temperature (above- and below-ground) will influence the composition, growth, health, and reproduction of Russian boreal and temperate forests (Kokorin and Nazarov, 1995; Bonan and Shugart, 1989). In the boreal zone, several scenarios suggest ambient temperature will rise more in the winter than in the summer, and precipitation is likely to increase (Budyko et al., 1991). As incipient global climate change is expressed, precipitation is expected to change insignificantly, while rising ambient temperature will increase evapotranspiration. This could increase terrestrial dryness and reduce river runoff. As global climate change is manifested in the long term, increased precipitation may offset water loss to evapotranspiration and improve conditions for plant growth in major agricultural areas (Budyko et al., 1991; Budyko and Menzulin, 1996). Boreal forest resources, the commodities that flow from these forests, and the forest products industry will all be impacted by these changes (Kokorin and Nazarov, 1995; Krankina and Ethington, 1995).

Adaptive responses of the forest sector to global climate change impacts have been the subject of some preliminary surveys and analyses (Smith, 1995). These reports have primarily focused on temperate forests of North America (Dixon, 1992) and Europe (Eriksson, 1991; Grozev et al., 1996). In general, these reports suggest adaptation measures can and should be applied to manage natural resources in order to enhance any benefits and to mitigate harmful impacts of climate change. In a review of global climate change impacts on ecosystems, Budyko et al. (1991) based on paleoclimatic and paleobotanic data asserts that most global climate change impacts will be beneficial to terrestrial ecosystems, especially boreal forests, and adaptation will be minimal. However considerable uncertainty and controversy surround such projections since human-induced global changes are expected to proceed at an order of magnitude faster pace than Pleistocene/Holocene climatic changes (Schneider, 1993).

The objective of this paper is to examine existing management options and technologies which may be employed to help adapt boreal forest systems to global climate change in the Russian Federation. To the best of our knowledge this is the first analysis of this kind for Russian forests.

2. Russian Forests: Environmental, Economic and Social Functions

Forest ecosystems occupy 884 $\times$ 10^6 ha in the Russian Federation, which accounts for over 20% of the world's forest resources and about 50% of all boreal forests (Krankina and Dixon, 1992; Anuchin et al., 1985). Russian forests stretch up to 2300 km from the northern tundra to steppe in the south, and from the Baltic Sea in the west to the Pacific Ocean in the east including a variety of boreal and subboreal ecosystems (Figure 1). This vast expanse of land is subdivided into four geographic regions, which correspond to longitudinal segments of Russian territory and are significantly different from both ecological and economic perspectives (Krankina and Dixon, 1994).

Russian forests are dominated by a small number of coniferous tree species: Scots pine (*Pinus sylvestris*) and spruce (*Picea excelsea*) to the west of the Ural Mountains, and in Siberia, larch (*Larix sibirica*, *Larix dahurica*), pine (*Pinus sylvestris*, *P. sibirica*, *P. koraensis*) and fir (*Abies sibirica*) (Table I). The forests of Europe-Urals comprise 26% of the total forest area. In the Europe-Urals region forests have been intensively harvested for many decades and at present 61% of the harvesting, 73% of the timber consumption and most of the forest management activities are still concentrated there (Krankina and Dixon, 1992). The anthropogenic effects on forests are most pronounced in the European part of Russia. East of the Urals, the forest resources are abundant, but management activities are limited to the lands around major population centers. Forests in Siberia and the Russian Far East occupy an area the size of the continental U.S. These forests are largely natural and at different stages of recovery from frequent wildfires with mature and overmature stands comprising nearly 50% of the total (Anonymous, 1990). Closed canopy forests cover 45% of Russia's land area; open canopy forests, young forest plantations, unregenerated clearcuts, burned forests and other forest lands that are currently without closed tree cover add 7% more (Anonymous, 1995a).

Russian forests are frequently disturbed by different biotic and abiotic agents including wildfires, timber harvest, droughts, high winds, industrial pollution, pests and pathogens. In 1990 and 1991, forest dieback from all types of disturbance was reported on 354 $\times$ 10^3 and 419 $\times$ 10^3 ha, respectively, within actively monitored forest lands that represent about 60% of the total (Krankina et al., 1994). According to the forest inventory of 1988, 26.5 $\times$ 10^6 ha of dead forests have accumulated in Russia as the result of forest dieback, with over 98% in Siberia and the Russian Far East (Anonymous, 1990). The most wide spread type of disturbance is forest fire that occurs on an estimated 1.4–10 $\times$ 10^6 ha annually. Most wildfire moves quickly and burns forests incompletely leaving older trees alive (Dixon and Krankina, 1993).

The forests of Russia play a prominent role in global environmental stability including primary roles in global biochemical and hydrological cycles. They store an estimated 42.1 PgC in their live biomass, 29.5 PgC in detritus, while 2.9 PgC

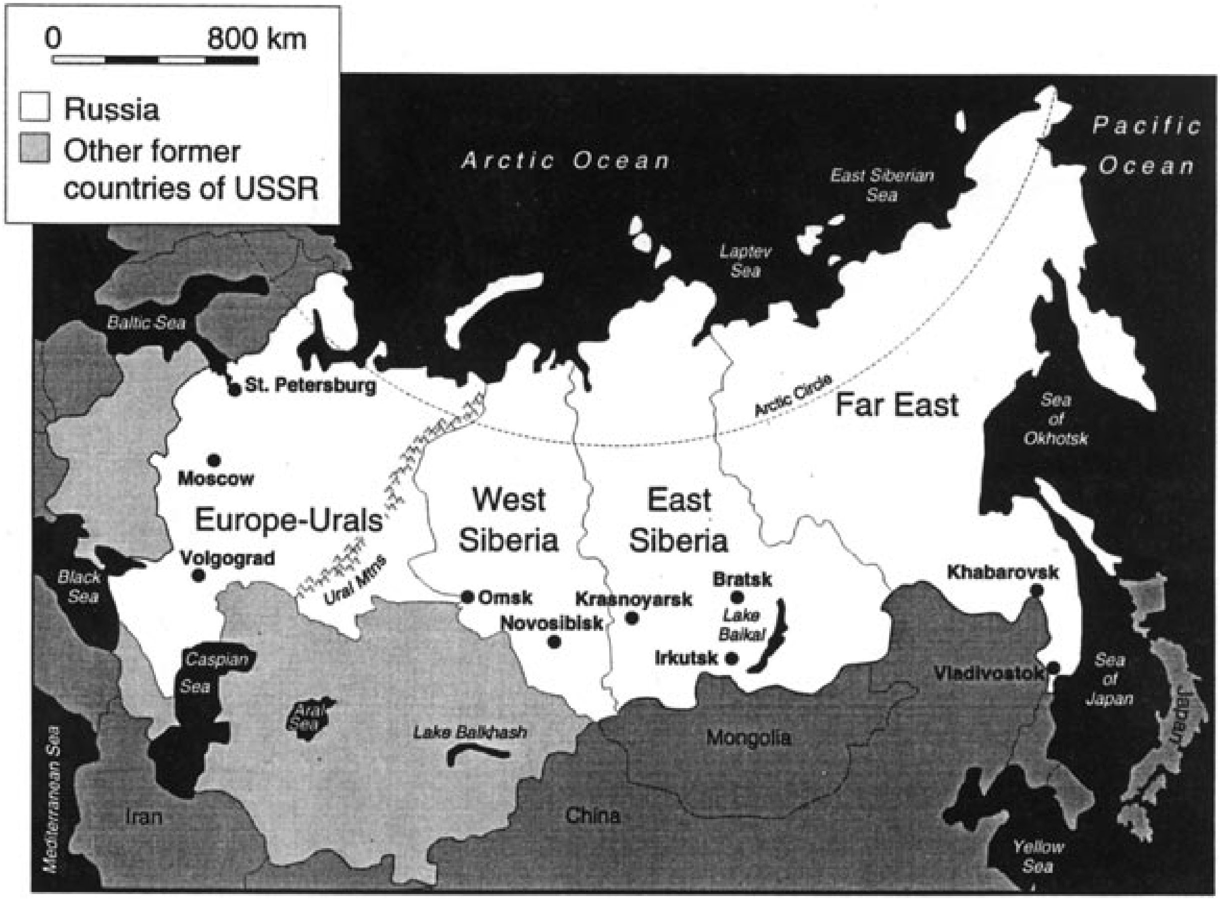

Figure 1. Geographic re gions of the Russian Federation.

Table I

Forest land distribution by dominant tree species in 10^6 ha (after Anonymous, 1990), projected loss of species range due to climate change in the regions of Russia (%, in parenthesis), and species relative adaptation rating

	Europe-Urals	West Siberia	East Siberia	Far East	Total	Adaptation rating[a]
Scots pine (*Pinus sylvestris*)	40.7 (8)	27.8 (0)	32.1 (29)	12.0 (30)	113.6 (17)	2
Spruce (*Picea spp.*)	47.3 (1)	5.4 (0)	2.4 (23)	13.7 (16)	78.8 (13)	3
Fir (*Abies spp.*)	0.7 (0)	3.8 (0)	9.4 (45)	1.8 (28)	15.7 (27)	3
Larch (*Larix spp.*)	0.4 (0)	5.9 (0)	102.8 (24)	168.8 (14)	277.6 (14)	2
Siberian pine (*Pinus siberica, P. koraensis*)	0.7 (0)	12.5 (0)	23.5 (36)	3.4 (19)	40.1 (21)	3
Birch (*Betula spp.*)	30.5 (8)	17.0 (0)	26.4 (24)	11.6 (14)	85.5 (13)	1
Aspen (*Populus tremulae*)	7.1 (9)	4.7 (0)	4.8 (28)	1.1 (20)	17.7 (16)	1
Total forest area[b]	173	96	255	360	884	–

[a] Relative ability of dominant forest species to adapt or mitigate in response to climate change (1 – high, 2 – medium, 3 – low).

[b] Includes other species, burned and dead forest stands, unregenerated clearcuts, open canopy woodlands, and wastelands.

are accumulated in forest products (Krankina et al., 1996). Many plant and animal species find their primary and sometimes only habitat in Russian forests (Anuchin et al., 1985). These forests affect the hydrology of several of the world's greatest rivers across the vast part of Eurasia through their impact on water balance in forested watersheds (Mater and Sdasiuk, 1991). At the local scale forests play a significant role in moderating local climates, regulating stream flow and mitigating soil erosion and effects of wind and drought (Guiriayev, 1989).

Russian forests are a major natural resource for the Russian national economy and provide a significant export commodity. About 800,000 people are employed in forest management and timber harvesting in Russia (Anuchin et al., 1985). Timber harvests have declined by about 50% in the recent years with the collapse of the centrally planned economy in the Former Soviet Union, but as the Russian economy revives and export pressures grow the forest products industry is likely to rebound (Korovin, 1995; Krankina and Ethington, 1995). Historically, the largest proportion of the timber harvest and wood processing was concentrated in the Europe-Urals part of Russia; while the greater part of forest resources was located in Siberia and the Russian Far East (Krankina and Dixon, 1992). Further development of forest resources is constrained by the challenges of developing infrastructure in the regions with severe climate and widespread permafrost (Krankina and Ethington, 1995). Forests in Russia are widely used for non-timber purposes such as recreation, wildlife habitat, hunting, tourism, harvesting of wild fruits, berries, mushrooms, medicinal plants, and firewood (Anuchin et al., 1985). The harvesting and primary processing of non-timber forest products is an important activity in many forestry enterprises. In some, it generates more revenue than timber harvest (Zyabchenko et al., 1992). Further, forests are an important source of food and supplemental income for indigenous people and for the poor, especially in rural areas (Chuprov and Terskih, 1984).

3. Materials and Methods

The information on the current composition of forest resources and their distribution among geographic regions was derived from Russian forest inventory statistics (Table I). The data are collected by the Russian Federal Forest Service's Department of Forest Inventory for the purposes of forest management and the methods used are standard across the entire Russian territory. The field data are collected by visual estimates of forest stand parameters for each forest stand polygon delineated from aerial photographs of inventoried forest land (60% of all forest land) or by statistical methods combining aerial photograph interpretation with ground sampling (Anonymous, 1995b). The data are aggregated at different spatial levels and then regional and national level summaries are published (Anonymous, 1990, 1995a). The potential loss of area for dominant tree species as result of climate change (Table I) was estimated by superimposing the current ranges of species distributions (Anuchin et al., 1985) with the projected distributions of forest dieback and loss due to climate change (Figure 2). This is a conservative estimate since it only includes climate change impacts strong enough to replace forests with a non-forest vegetation type. The relative ranking of dominant tree species adaptation ability (1 – high, 2 – medium, 3 – low) was assessed based on the complex of their individual ecological and silvicultural characteristics (Anuchin, 1985).

The potential effects of climate change on Russian forest ecosystems have been estimated based on bioclimatic classifications and assuming that the correspondence between vegetation and climate will not be changed in the future (e.g., Solomon et al., 1993). The climate change scenario used to simulate the vegetation redistribution is a ‘hybrid’ developed for double CO_2 concentration in the atmosphere for the territory of Russia by the Moscow Institute of Atmospheric Physics (Belotelov et al., 1996). This scenario aggregates the predictions of General Circulation Models (GFDL, GISS, UKMO) and the paleoanalogy scenarios. Future vegetation distribution was simulated based on climate change parameters and the Holdridge Life Zone Classification (Holdridge, 1967), which relates the major plant formations of the world to two independent climate variables: biotemperature and total annual precipitation. These climate parameters were generated from the IIASA climate dataset (Leemans and Cramer, 1991). Areas of Russian territory were identified that are expected to undergo a change of vegetation type as understood by Holdridge Life Zone Classification (Figure 2) (Holdridge, 1967).

The assumptions and constraints of General Circulation Model scenarios should be recognized (Wigley et al., 1990). Specific regional responses of forest systems to climate change impacts cannot currently be predicted with complete confidence (Dixon, 1992). Given these constraints, examples of potential adaptive measures and responses were constructed using the methodology of Smith (1995).

The adaptive measures for forest resources were developed based on projections of country-level vegetation change and knowledge of Russian forest dynamics (Smith et al., 1996). Specific measures presented in this report are based on current infrastructure, technology, and understanding of potential climate change impacts on Russian temperate and boreal forests (Krankina and Dixon, 1992). The assimilation of exogenous or new technology will be important in future decades, but no attempt was made to project its impact. Case studies of selected forest sector options were analyzed. The matrix of potential adaptation options is large; thus, possible future options were qualitatively predicted via analogy (Glantz, 1996). Current status and distribution of forest based industries and infrastructure were assessed based on recent surveys (Korovin, 1995; Krankina and Dixon, 1992; Kuusela, 1992; Burdin, 1991; Barr and Braden, 1988). The adaptive measures presented were not constrained by future financial or logistical limitations, although these factors are likely to be significant (Nordhaus, 1993).

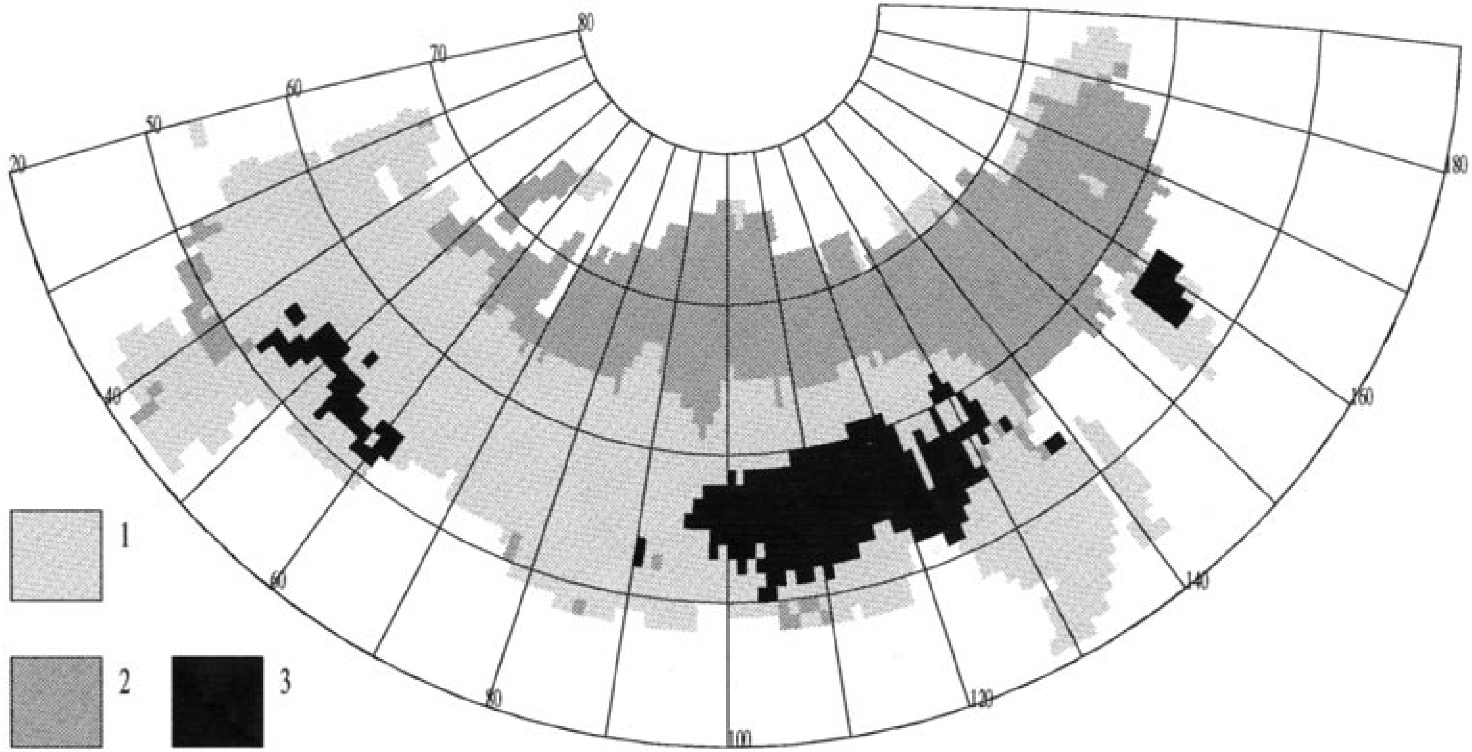

Figure 2. Predicted future forest vegetation distribution in Russia. The vegetation scenario was created using the ‘hybrid’ climate scenario and Holdrige life form classification system (Belotelov et al., 1996). 1 – No change of vegetation type projected; 2 – Projected area of forest expansion; 3 – Projected area of forest decline and deforestation.

4. Forest Resource Vulnerability

Terrestrial systems, particularly forest systems, are among the most vulnerable resources that could be impacted by global climate change. The recent IPCC executive summary predicts the following changes in the boreal forest zone (IPCC, 1995):

- Climate change is likely to have its greatest impact on boreal forests (high confidence);
- Northern treelines will slowly advance into tundra regions (high confidence);
- Increased fire frequency and pest outbreaks are likely to decrease the average age, biomass and carbon store with greatest impact at the southern boundary where temperate-zone pioneer species and grasslands will take place of boreal coniferous species (medium confidence);
- Net primary productivity is likely to increase in response to warming where not limited by water availability; however this effect on the global carbon cycle may be offset by an increased rate of soil decomposition (medium confidence).

Areas where climate change is expected to cause the change in vegetation type are the most vulnerable. Simulation of vegetation distribution suggests that the area of Russia occupied by forest vegetation may increase by 42% due to northward expansion of boreal forests into the tundra (Figure 2). This expansion is expected to be greater than the area of forest decline in the southern part of the forest zone that is predicted to occur on 19% of current forest zone, mostly in the southern part of East Siberia and the Far East. The rapid shift in climate zones may far exceed the ability of Russian forests to adapt or migrate (Smith et al., 1991; Solomon et al., 1993). Climate zones may shift hundreds of kilometers in a century, while natural rates of species dispersal and colonization may be only a few kilometers in the same time period (Bonan and Shugart, 1989). The decline of boreal forest on its current southern limit may occur significantly earlier than its migration North. If the rate of forest migration is taken into account, the area of boreal forest in Russia may decrease by 9% (Belotelov et al., 1996). The forests in the areas of vegetation change will need to adapt to drastically different conditions (Figure 2). Forest resources outside the change areas may also need to adapt since their environment will undergo change as well. Global environmental change could increase existing forest decline and dieback across the entire forest region of Russia (Krankina et al., 1994; King and Neilson, 1992).

Shifts in forest ecosystem (plant and animal) composition and productivity are projected in circumpolar boreal forests (Budyko et al., 1991; Smith et al., 1991). The frequency and intensity of forest fire may increase, as well as the incidence of exotic pathogens and insects (Dixon and Krankina, 1993). All components of boreal forest ecosystems will be impacted, including water resources, soil systems and wildlife, and the combined effect may be even stronger due to interacting factors

(Kobak and Kondrasheva, 1992). Several characteristics of Russian forests make them especially vulnerable, including (1) wide-spread single-species forest stands, both natural and planted, on sites prone to disturbance by fire, (2) current emphasis of forest policy on fire prevention that favors late successional species less adapted to resisting disturbance and regrowing after it, (3) effects of air pollution, mining, and timber harvest that reduce the overall health of forest ecosystems (Krankina et al., 1994). Some other characteristics such as mixed species regeneration after clear-cut timber harvest may help to alleviate the vulnerability of Russian forests (Krankina and Dixon, 1992).

All dominant tree species in Russian forests will be affected by climate change but to a different extent (Table I). Fir species and Siberian pine are expected to suffer the most since a large proportion of their current distribution area in East Siberia and the Far East is expected to be converted by climate change into a non-forest vegetation type. These species also have relatively low adaptation ability as they have low resistance to drought and disturbance and regenerate poorly (Anuchin et al., 1985). The natural distribution range for the fir species and Siberian pine could reduced by 27% and 21%, respectively, under the climate change conditions. The vulnerability of fir and spruce species to climate change may provide an explanation for the currently observed widespread decline of fir and spruce forests in the Russian Far East, as no valid cause of this phenomenon has been found so far (Efremov, 1989). The loss of Siberian pine forest may have grave implications for local communities in East Siberia that are heavily dependent on these forests for food and commercial fur hunting (Krankina and Ethington, 1995). Boreal hardwoods (birch and aspen) can be expected to be the least affected by climate change as a relatively small proportion of their current distribution range is projected to change to non-forest vegetation type and their adaptation ability is expected to be high due to a high level of disturbance resistance and an excellent ability to regenerate naturally (Anuchin et al., 1995). The changes in species distribution will affect the species mix in the Russian timber supply.

During warm periods in the geologic past, when climatic conditions were similar to those predicted for the 21st century, the northern border of the conifer forest zone was beyond 70° N latitude (Figure 2). The broadleaf forests of Russia also ranged farther south than they do today. This forest range within the Russian Federation may represent an approximation of the potential forest cover under future climate conditions (Kobak and Kondrasheva, 1992). Some GCMs predict a rapid expansion of the boreal forest species into Arctic tundra due to favorable site conditions (Dixon et al., 1994). After a decade of warming in the 1930s, the treeline advanced along the river valleys in northern Russia by dozens of kilometers (Bruce, 1993). Receding glaciers during periods of warming altered the hydrology of watersheds, influencing water quantity and quality in rivers and lakes (Mater and Sdasiuk, 1991).

Global climate change will probably impact forest utilization and manufacturing in Russia through its influence on both the industrial infrastructure and the

Table II

Examples of global climate impacts on the forest resource sector of the Russian Federation and potential adaptive measures or responses

Component/system	Potential impact	Adaptive responses
Plant community	Shift in composition, productivity and reproduction; decline, dieback or migration of species; insect and pathogen range shifts	Silvicultural measures such as artificial regeneration, thinning, or fertilization; pest management
Animal community	Shift in composition; loss of habitat and diversity; species migration or invasion problems; pest problems	Habitat or species preservation; migration corridors
Water resources	Change in water quantity and quality; extreme events; loss of habitat	Water management options such as reservoir development, flood protection, habitat protection, fish hatcheries
Soil systems	Water or wind erosion; loss of productivity; shift or loss of micro-organizers, soil moisture changes	Soil protection; fertilization or irrigation; minimize disturbance
Wetlands/peatlands	Southern peat to decompose; taiga peat expands	Peat used as bioenergy; expand agriculture in southern regions

quality and quantity of wood and non-wood products (Tables III and IV). The availability of many softwood species may decrease, while hardwood species can be expected to become more abundant. Shifts in resource quality and supply will also influence the need for transportation, location of manufacturing facilities, and energy transmission and consumption.

The chemical and physical characteristics of wood and paper products may be influenced by shifts in species composition and abundance. Further, an enriched CO_2 environment may influence the specific gravity and wood fiber characteristics in some species – two wood properties extremely important to the production of wood and paper products (Dixon, 1992). During periods of rapid forest decline or expansion, the abundance and composition of non-wood products may change in transition zones.

5. Forest Resource Adaptive Measures

Due to the complexity of forest systems, their relative immobility and longevity, prospects for adaptation have historically been considered dubious for natural forests (Smith, 1995) and possible but costly for managed forests (NAS, 1992). The goal of adaptive measures is to sustain the various functions of forest ecosystems over the landscapes and through time, to minimize the losses, enhance the benefits,

Table III
Examples of global climate impacts on the forest products sector of the Russian Federation and potential

Component/system	Potential impact	Adaptive responses
Solid-wood products	Specific gravity, fiber length, strength, load capacity shifts in response to CO_2 enrichment and changes in tree nutrition	Silvicultural measures to maintain desired wood characteristics; employ non-wood substitutes
Non-wood products	Shift in composition, quality, quantity; decline or dieback of non-timber species; invasion of expansion of pioneer species	Non-wood products market expansion; implement agroforestry practices in transition zones
Paper products	Characteristics of fiber may shift	Alter pulping practices and fiber mix

Table IV
Examples of global climate impacts on the forest resource and forest products sector(s) infrastructure

Component/system	Potential impact	Adaptive responses
Manufacturing	Shift in resource quality and supply, changes in energy and availability; emission reduction restriction	Facility shift; shift in products manufactured; altered production cycles
Energy	Changes in hydropower output; shifts in energy peak needs	Alternative fuels; demand side management
Terrestrial transportation	Roads in tundra and permafrost will deteriorate	Low-impact transportation systems
Aquatic transportation	Water supply shifts in response to flooding or drought	Expand infrastructure to manage water resources

and to facilitate or modify natural succession resulting from climate change. Given the current infrastructure and technology some adaptive measures appear plausible.

5.1. FOREST ESTABLISHMENT

Several strategies can be used to enhance the expansion of boreal forest or to replace trees lost to decline, dieback, and disturbance. The lack of natural seed dispersal due to distance from seed sources and irregular seed years, typical under extreme northern climate, can be addressed by artificial seeding or planting of tree seedlings produced in nurseries (Krankina and Dixon, 1992). In Russia, there is extensive experience with artificial seeding technology, nursery production and tree planting (Stoliarov, 1990), mostly concentrated in the southern regions and in Europe-Urals (Figure 1). Tree improvement methods can be employed to enhance the growth rate and drought resistance of planting stock, especially traditional selection and breeding programs.

Another major impediment to boreal forest regeneration is the widespread occurrence of ground cover (grasses, herbs, and mosses) that limits successful seedling development (Anuchin et al., 1985). For example, mosses increase their growth after clearcutting thus keeping soils colder, increasing water bogging, preventing seedling roots from reaching mineral soil. These effects reduce juvenile growth of seedlings. Site preparation with prescribed burning or soil scarification can substantially improve seedling growth during the early survival and juvenile periods. Drainage of certain types of mires may also improve conditions for tree growth (Ogievskii, 1974). All of these adaptive measures can be employed to stimulate forest regeneration in zones of climate-induced dieback or timber harvest.

The sites and tree species for forestation at taiga-tundra borders should be selected carefully using ecological principles. River valleys, southern slopes and light soils with moderate moss cover could provide better environmental conditions for forest establishment (Anuchin et al., 1985). New forests on these sites could then serve as bridges for forest expansion northward and toward less favorable sites. The historic analysis of tree planting and survival at high latitudes reveals that, outside the current forest zone, some planted trees survived nearly 200 years and successfully produced natural regeneration (Bruce, 1993).

At the southern border of the Russian forest zone, adaptive measures could maintain the current expanse of forests or decrease the advancement of grasslands (Krankina et al., 1994). Possible strategies include forestation with species adapted to drought conditions and shelterbelt systems. Protective forests currently occupy 11.6×10^6 ha or 1.3% of forest area in Russia (Anuchin et al., 1985) and the demand for new shelterbelt plantations is estimated at 3.9×10^6 ha (Guiryayev, 1989). These plantations may improve local climatic conditions for tree growth and agriculture by reducing evapotranspiration, enhancing water retention in soils, and decreasing wind speed (Ogievskii, 1974). Measures aimed at compensating for the loss of some uniquely valuable forests will have to be developed. For example, such measures may be needed to sustain Siberian pine forests that support a variety of wildlife species and serve as an important food plant (e.g., pine nuts) for the local population (Anuchin, 1985; Krankina and Ethington 1995).

5.2. FOREST MANAGEMENT (TABLE II)

Currently, 69.9×10^6 ha of land at the taiga-tundra border are managed by the Russian Federal Forest Service (Krankina and Dixon, 1992). Of the forests in this transition zone, 40% are occupied by closed forests, and 32% are in bogs and mires. The balance is represented by open-canopy forests, burned and dead forests, and reindeer pastures (Anuchin et al., 1985). Clearcutting in most taiga-tundra forests is currently limited, but considering the future value of these forests as animal habitat or migration corridors, the scope and intensity of harvesting activities should be carefully planned to minimize possible adverse impacts of a changing climate (Smith and Tirpak, 1989).

Throughout the present forest zone, adaptive measures should enhance forest stability and minimize disturbance associated with rapid climate change (Budyko et al., 1991). This may be achieved by maintaining mixed species composition where site conditions favor the growth of mixed stands, and by integrated fire and pest management. Some of the current management practices that favor late-successional species poorly adapted to climate change may have to be reconsidered. For example, (1) long-term fire suppression and non-clearcut harvests have favored spruce and fir over pine (Dixon and Krankina, 1993), (2) preservation of natural understory regeneration of late-successional conifers in the process of timber harvest and (3) removal of hardwood species as economically undesirable has increased the abundance of spruce, fir and Siberian pine species (Krankina and Dixon, 1992). The selection of species for plantations should be made with consideration of potential climate change within the life span of the trees (King, 1993; Solomon et al., 1993). Planting trees at the southern limit of their natural range may have to be reconsidered in a rapidly changing climate (Smith et al., 1991). Perhaps the greatest potential challenge to Russian forest managers will be management of non-indigenous pests (insects, fungi, and bacteria) which may migrate with shifting climatic conditions.

In order to maintain tree cover to the degree possible, clearcutting should be complemented by other wood harvesting methods (Rosencranz and Scott, 1992).

Harvest rotations for species that are well adapted to changing environmental conditions should be expanded, while forests that have failed to adapt should be identified and harvested early. Accurate long-term predictions of forest survival at the site level may not be possible, however thorough monitoring of forest health should be maintained for early identification of areas at risk to decline (Krankina et al., 1994). Historically, remote sensing techniques have been applied to monitoring forest health, and this technology should be expanded to assist policymakers in the future (Krankina and Dixon, 1992).

5.3. FOREST PRODUCTS AND MANUFACTURING INFRASTRUCTURE (TABLES III AND IV)

Currently over 61% of the wood harvesting and 80% of the wood processing infrastructure are located in the Europe-Urals (Figure 1), while 75% of the forest resources are east of the Ural Mountains (Krankina and Dixon, 1992). Northward relocation of manufacturing facilities is one adaptive measure to a shifting resource base. Co-locating forest harvesting operations adjacent to wood processing facilities is a viable option (Cardellichio et al., 1990). To accommodate the predicted future abundance of hardwood species, alteration of wood processing technology and products may also be employed. For example, the production of composite wood products may increase relative to solid-wood products. Desirable wood characteristics can be fostered, altering species mix or silvicultural techniques. Non-timber forest product markets may rapidly expand as short-rotation plantations or agroforestry systems are established in forest transition zones (Zyabchenko et al., 1992). Alternative pulping practices and fiber mixes can be adopted in response to a shifting resource base.

Production of forest-based bioenergy may expand in a changing climate, especially if the change occurs over decades rather than centuries (Sampson et al., 1993). Rapid climate change may preclude long-rotation management of forests, but favor production of short-rotation intensive culture in transition zones (Bonan and Shugart, 1989). Short rotation culture (e.g., species, silvicultural practices) permits adaptive flexibility, and the fiber, fuel and fodder that flow from these plantations provide multiple feedstock for bioenergy or manufactured products (Hall, 1991).

Alternative transportation systems will have to be developed in response to global climate change in Russia, in both urban and rural areas (Anuchin et al., 1985). As permafrost recedes in Siberia and the Far East, low impact transportation systems (e.g., large rubber tires vs. steel treads) can be employed in forest harvesting or transportation networks. Reliance on aquatic transportation (e.g., river barges) may increase as a low cost alternative to road building, if not precluded by extreme hydrologic events. Modification of transportation infrastructure is linked to shifts in resources, location of forest sector manufacturing facilities, and emerging consumer markets (Rosencranz and Scott, 1992).

6. Discussion

Most forest resources, forest products and manufacturing infrastructure adaptations will be made as the climate changes (Budyko et al., 1991). The forest sector will switch to alternative species as environmental conditions dictate; manufacturing facilities will be modified as the market demands; and reservoir operators will adjust water levels as river flow changes. These measures are defined as reactive adaptations because they are done in response to climate change (Smith, 1995). In contrast, anticipatory adaptation measures are those taken in advance of climate change (Glantz, 1988). For forest resources, the goal of anticipatory measures is to minimize the impact of climate change by reducing vulnerability and to enable adaptation to occur more efficiently (faster or at a lower cost). The first of these responses can be described as robust (able to absorb surprises), while the latter is resilient (able to recover from failure).

Given the uncertainty of the direction, magnitude, and rate of climate change on a regional scale (Smith, 1991), as well as the long time-frame over which its effects may be manifested (Budyko et al., 1991), society may prefer to react to climate change rather than to try to anticipate it. International and national policymakers are reluctant to implement response measures for impacts that may not occur, especially if the benefits of such anticipatory measures may not be seen for decades (Victor and Salt, 1995). Furthermore, future generations may have more income and sophisticated technologies that can be used for adaptation

(Nordhaus, 1993). Long-term economic analysis of large-scale reactive vs. adaptive responses to environmental change are not sufficiently complete at this time to guide policymakers.

However, employing a cautious attitude with regard to the Russian forest sector adaptation has a number of potential drawbacks:

- The impacts of climate change on forest systems may be irreversible (Budyko et al., 1991). Species extinctions and the loss of rare ecosystems cannot be reversed.
- The costs or impacts of climate change on the forest sector, even after adaptation, may be very high (Nordhaus, 1993). Forests could experience significant reductions in range and productivity over long periods of time (Belotelov et al., 1996). Replacement of manufacturing based on forest products may require intensive, long-term investments (Burdin, 1991).
- Policy and management decisions made now may not be adequate to cope with future global climate changes (Brandt, 1992). For example, trees that are planted today with a life expectancy of decades may not survive to maturity if climate conditions change rapidly (Krankina et al., 1994).
- Rapid reaction to global climate change may imply development of responses to extreme or catastrophic events (e.g., floods, droughts, wildlife). A reactive response policy may be logistically or financially sensible, but it runs the risk of taking short-term incremental approaches and not anticipating future large-scale changes (Smith, 1995; Glantz, 1988).

Although it may be desirable to anticipate climate change, in many cases uncertainties make the design of anticipatory policies challenging, especially for countries with economies in transition (Krankina and Dixon, 1992). The socioeconomic impediments of moving from a planned forest-sector economy to a market economy are well documented (Rosencranz and Scott, 1992; Burdin, 1991; Korovin, 1995). If climate change impacts are concomitant with shifts to a market economy, the challenges of forest sector adaptation could be exacerbated or perhaps consolidated. Dramatic losses of forest sector raw materials would negatively influence the emerging market economy, since Russia is increasingly dependent on wood-product exports to maintain a balance of trade (Rosencranz and Scott, 1992; Krankina and Ethington, 1995). In contrast, regional rehabilitation of manufacturing or transportation infrastructure could be concomitantly implemented to cope with complementary market or climate changes, partially relieving Russia's financial burdens relative to other developed countries (OTA, 1993). The challenge for Russian policymakers will be to balance climate change adaptation priorities with other economic needs (Nordhaus, 1993).

Uncertainties of future global climate change impacts at local or regional scales may limit development and timely deployment of specific adaptive measures in Russia (Smith, 1995). However, identification of 'no regrets' adaptation measures, with favorable positive cost-benefit ratios, may help policy analysts rank future priorities (Victor and Salt, 1995; NAS, 1991). Of the various adaptive measures discussed in this report, options such as maintaining species diversity, transition from fire prevention to fire management, expansion of shelterbelt systems in southern regions, transition from clearcutting to alternative, low-impact harvesting systems, and development of an extensive forest health monitoring system, could provide the basis for 'no regrets' options. These measures that can be applied using existing technology and infrastructure, are considered anticipatory responses, and have been shown to reduce negative impacts associated with rapid global climate change (NAS, 1991).

Adaptive strategies reviewed in this paper represent a substantial departure from traditional Russian forest resource management and utilization (Krankina and Dixon, 1992). Under climate change conditions, forest resource stability and the maintenance of an adequate manufacturing infrastructure may become a high priority in Russia (Budyko et al., 1991). Other developed countries with significant forest resources (e.g., Australia, Canada, Germany, United States, and others) have developed natural-resource-policy response options in their National Communications to the U.N. FCCC. Future climate change policy development in Russia will have to carefully consider the fate of 20% of the world's remaining forests and 16% of the global terrestrial carbon pool that are resident in this vast country (Kolchugina and Vinson, 1993). Significant shifts in forest policy may be implied as Russia develops its National Communications with the United Nations Framework Convention on Climate Change (U.N. FCCC).

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