FOREST CARBON DYNAMICS IN THE PACIFIC NORTHWEST (USA) AND THE ST. PETERSBURG REGION OF RUSSIA: COMPARISONS AND POLICY IMPLICATIONS

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Abstract. Forests of the United States and Russia can play a positive role in reducing the extent of global warming caused by greenhouse gases, especially carbon dioxide. To determine the extent of carbon sequestration, physical, ecological, economic, and social issues need to be considered, including different forest management objectives across major forest ownership groups. Private timberlands in the U.S. Pacific Northwest are relatively young, well stocked, and sequestering carbon at relatively high rates. Forests in northwestern Russia are generally less productive than those in the Northwestern U.S. but cover extensive areas. A large increase in carbon storage per hectare in live tree biomass is projected on National Forest timberlands in the U.S. Pacific Northwest for all selected scenarios, with an increase of between 157–175 Mg by 2050 and a near doubling of 1970s levels. On private timberlands in the Pacific Northwest, average carbon in live tree biomass per hectare has been declining historically but began to level off near 65 Mg in 2000; projected levels by 2050 are roughly what they were in 1970 at approximately 80 Mg. In the St. Petersburg region, average carbon stores were similar to those on private lands in the Pacific Northwest: 57 Mg per hectare in 2000 and ranging from 40 to 64 Mg by 2050. Although the projected futures reflect a broad range of policy options, larger differences in projected carbon stores result from the starting conditions determined by ownership, regional environmental conditions, and past changes in forest management. However, an important change of forest management objective, such as the end of all timber harvest on National Forests in the Pacific Northwest or complete elimination of mature timber in the St. Petersburg region, can lead to substantial change in carbon stores over the next 50 years.

1. Introduction

The United Nations Framework Convention on Climate Change and its Kyoto Protocol indicate the intent of some members of the international community to address the problem of climate change by managing the processes of global C cycling. The future success of this first-ever attempt by humans to manage their global environment requires comprehensive understanding of human interaction with terrestrial ecosystems. An example is land-use and land cover changes that are among the major driving forces that determine the transition of forest stands, landscapes, and regions from carbon (C) sinks to sources and back (e.g., Kurz and Apps, 1999, Houghton et al., 1999; Caspersen et al., 2000). Historical changes in land-use were identified as the dominant factor governing the rate of C accumulation in

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the eastern United States, with tree growth enhancement contributing far less than previously reported (Caspersen et al., 2000). Natural factors and socio-economic processes interact in diverse ways and complicate the analysis of causes and consequences of land use and land cover change (LULCC). Projecting the effects of social and economic processes on C stores in terrestrial ecosystems remains a key research challenge and subject of ongoing scientific debate. In fact, a priority of the U.S. Global Change Research Program is to improve scientific understanding of how humans cause changes in the earth system (U.S. Global Change Program, 2000).

Rates and causes of LULCC and associated changes in C stocks vary by region and forest ownership group (e.g., U.S. National Forests) and change over time. For example, changes in forest disturbances caused the transition of Canadian forests from a net sink of C in 1980's to a small net source (-0.068 Gt C yr^{-1}) by the early 1990s (Kurz and Apps, 1999). Recent Food and Agriculture Organization (FAO) statistics on 55 countries in the temperate and boreal zone indicate a general increase in live tree biomass of 0.88 Gt C yr^{-1} (UN-ECE/FAO, 2000). The C sink in live woody vegetation was on the order of 10% of the fossil fuel CO_2 emissions in the United States and in western Europe, and was higher in the 1990s than in the 1980s. These relatively high sequestration rates are not a result of active policies aimed at climate mitigation, but a consequence of general trends in LULCC. In many regions, large C losses in the past (Houghton et al., 1999; Kurz and Apps, 1999) have created opportunities for C sequestration in the present. Since the mid 20th century, forest area has been increasing in some regions of the boreal and temperate zones, partly because agricultural yields have improved and partly because the profitability of marginal agriculture has declined (Waggoner 1994; Alig et al., 2003; Kauppi et al., 2001).

Forests of the United States and Russia play a major role in the exchange of greenhouse gases, especially carbon dioxide (CO_2) between the land and the atmosphere. Such forests are part of northern boreal and temperate forests that cover about 1.8 billion ha, primarily in North America, Europe, and Russia. These forests contain most of the world's supply of softwood timber and are potentially a significant C sink. Increased C sequestration by trees, other forest ecosystem components, and wood products can partially ameliorate increasing atmospheric CO_2 output, providing time for other control measures to be brought into place (Kauppi et al., 2001). In addition, there are multiple auxiliary benefits as measures designed to increase C sequestration can be consistent with forest conservation objectives, such as improved water quality, enhanced species habitat and biodiversity, and amenity improvement (Kauppi et al., 2001).

Much of the landscape in the U.S. Pacific Northwest and northwestern Russia is currently in a "regrowth" phase, with younger forest stands having substantial growth potential. A key question is how C stocks in the two forest regions and across forest ownerships may vary under different policy scenarios. Projections provide value in charting the future to provide ideas to policy makers about effects of land management on U.S. and Russian forests, carbon, and related goods and services. We examine scenarios of forest sector development and compare the resulting change of C stores in forest biomass in the Pacific Northwest U.S. and northwestern Russia. The scenarios are based on policies that are not directly formulated to address global warming. Forest resources and forest management can vary markedly across forest ownerships, including the likelihood and timing of timber harvests, and thereby influence future trajectories of aggregate forest C storage (Alig, 2003).

2. Past Studies of Regional Forest Carbon

Previous work offers a general framework to aid in analyzing the natural and human interactions with forest C systems. Four major components identified in modeling studies include: (1) land base changes, (2) tree growth, (3) timber harvest, and (4) investment in intermediate forestry practices between tree establishment and harvest, such as forest fertilization and precommercial thinning (Alig et al., 1984). The potential for changes in these components varies notably by public (e.g., USDA Forest Service National Forests) versus private forest ownership and the role of private forest owners was the primary focus of research in the United States. In Russia, the ownership of forest lands has been federal and is expected to remain federal in the near future (Kukuev et al., 1997), but market forces are playing an increasing role in land and forest management.

The first component, how land is allocated among different uses and cover types, is a reflection of socioeconomic forces that motivate human settlement and the land management decisions of private landowners. In addition to existing forest resource endowments differing by ownership, land management practices can also differ notably by ownership. Afforestation, deforestation, and reforestation are major land base management decisions that influence forest C stocks and flux (Alig, 2003), and their application can vary significantly across public, private industrial, and non-industrial private owners. Therefore, owner objectives and land use decisions can have significant implications across a regional landscape with mixed ownerships.

For the second component, tree growth typically has received the most mitigation–related attention by foresters and in the literature. For example, Birdsey et al. (2001) summarized how the amount of carbon stored in forests via tree growth can be affected by forest management and can change through the adoption of land management practices that allow more land in forest cover, incorporation of more plant materials into forest soils, and changes in forest age structure. McCarl et al. (2000) considered tree growth options and included the ability to alter the intensity of forest management (e.g., rotation age) among owners and regions.

For the third component, drivers of timber harvest differ notably by ownership class. Private timber harvest is influenced by stumpage prices, interest rates, initial timber inventory, and exogenous nonforest income (Adams and Haynes, 1996). Private timber harvest in the United States over the next two decades will be strongly influenced by current timber inventory characteristics, particularly the limited areas and timber volumes in older merchantable age classes in most regions. Changes in owners can result in a shift in owner objectives and a change in likelihood of timber harvest. Timber harvest is typically the most frequent disturbance on private timberland and can lead to significant changes in land cover (Alig and Butler, 2004). On federal lands in the United States, timber harvests are often set in public planning processes. For example, in the U.S. Pacific Northwest, planning objectives have shifted from ones based primarily on even-flow levels of timber harvests to ones that are aimed at providing a broader set of goods and services, including protection of wildlife habitat in late-successional forest reserves.

The fourth component, forest investment, is a critical element in the long-term modeling of U.S. forest resources, and is also important in forest C analyses. Investments in enhanced forest regeneration practices or intermediate stand treatments (e.g., fertilization) affect growth and influence intertemporal decisions about harvest timing. For example, U.S. private timberlands have considerable potential for additional wood production and more C sequestration under intensified management (Alig et al., 1997), however, the requisite levels of aggregate private investment would be well beyond those observed in recent years.

In past large-scale assessments, more attention has been devoted to modeling C storage on private versus public timberlands in the United States. Plantinga and Birdsey (1993) developed a forest C budget model to examine the effects of forest management practices on C storage on private timberlands. They projected an increase in C storage on private timberlands by 2040, however, this increase was largely offset by C emissions resulting from harvesting. Adams et al. (1999) expanded the context to bring in the potential of private land exchanges with agriculture, the influence of international trade, and direct consideration of the cost of sequestering carbon in private forests.

A gap in the literature has been the potential role of U.S. federal timberlands in forest C sequestration. Changes in federal timber management appear to have increased the potential for increased C sequestration. However, the federal land management policies are directed at other objectives (e.g., protection of wildlife habitat), and a question is the compatibility with carbon-related goals.

The research on the role of Russian forests in the C exchange with the atmosphere has focused largely on the extensive forests of Siberia and the shifting fire regimes that drive forest succession (Kasischke et al., 1999; Conard et al., 2002; Kasischke and Bruhwiler, 2002). Estimates based on national forest inventory data indicate a significant net sink between 1961 and 1998 (433 Tg C yr^{-1} total, 155 Tg C yr^{-1} in live forest biomass) (Shvidenko and Nilsson, 2003) and an increase in productivity of forests of 20–25%, primarily in the Western part of Russia (Alexeyev et al., 2004). To improve understanding of human interactions with terrestrial ecosystems and C fluxes and make realistic predictions, a more narrow regional focus is necessary. We chose the St. Petersburg[1] region because of data availability and previous work on examination of C dynamics (Treyfeld et al., 2003; Krankina et al., 2004a,b).

Two caveats should be stated:

1. we examined live forest biomass only; because other C pools in forest ecosystems and in forest products are not synchronized with live biomass (Harmon and Marks, 2002), a more comprehensive analysis may lead to somewhat different results.
2. we did not consider the impact of fire. Fire is typically controlled and burned timber is salvaged on private lands in PNWW and in the St. Petersburg region; so that including fire is not going to change the results for these two categories. Fire plays a greater role on public lands in the PNWW and not all burned timber is salvaged, therefore, including the effect of fire could reduce the projected gain in C stores on public lands.

3. Modeling

We compare two forest regions with contrasting climate, productivity, land-use history, forest ownership, and with active ongoing changes in land management: the U.S. Pacific Northwest and the St. Petersburg region in northwestern Russia (Table I). In both regions, forests play a major role in land cover, in C stocks, and in regional economies (Harmon, 2001; Krankina et al., 2004 a,b). A regional scale (several million ha) is appropriate for this study because prices are set in markets where wood products are traded across broad areas and many land-use policies and socio-economic processes are region-specific. Moreover, routine statistical and survey data are collected and aggregated by administrative regions and this facilitates the integration of socio-economic and environmental drivers in a single analysis system. Examining historical trends can provide helpful guidance in identifying key factors that are likely to influence forest regeneration, timber harvest, and other changes in forest resource conditions in northwestern Russia and the U.S. Pacific Northwest in future years.

3.1. STUDY REGIONS

The *U.S. Pacific Northwest Westside* (PNWW) is the U.S. timber supply region that includes the territory of western Washington and western Oregon between the Pacific Ocean and the crest of the Cascade Mountains (Figure 1, and Table I). Douglas-fir (*Psuedotsuga menziesii (*Mirb.) Franco) is the primary timber species and the dominant forest cover type on timberland in the region (Smith et al., 2001). The most productive sites are capable of yielding 14 cubic meters per ha per year of wood, and many other sites can yield at least 8 cubic meters. In the maritime zone of the PNWW region are some of the tallest trees in the world, and the most productive coniferous forests in the Northern Hemisphere. The Douglas-fir forest type is managed under a broad range of management regimes, from custodial

TABLE I
Study areas.

	Pacific Northwest-West	St. Petersburg region, Russia
Latitude (°)	42–46	57–62
Elevation range (m a.s.l.)	0–4400	0–250
Mean annual t ° (C)	2–10	3–4
Annual precip. (mm)	300–3500	600–800
Dominant vegetation	Moist temperate conifer forest	Southern taiga forest
Total area (million ha)	14.0	8.5
Forested area (million ha)[1]	10.9[2]	4.7
Mean growing stock (m^3/ha)	230	147

Sources – Krankina et al. (2004a) and Smith et al. (2001)
[1] >10% canopy closure in the PNWW, >30% relative stocking in the St. Petersburg region.
[2] National forest lands comprise 28% of this total; private forests comprise 53%. Other public lands (e.g., Bureau of Land Management) make up the remaining 19%.

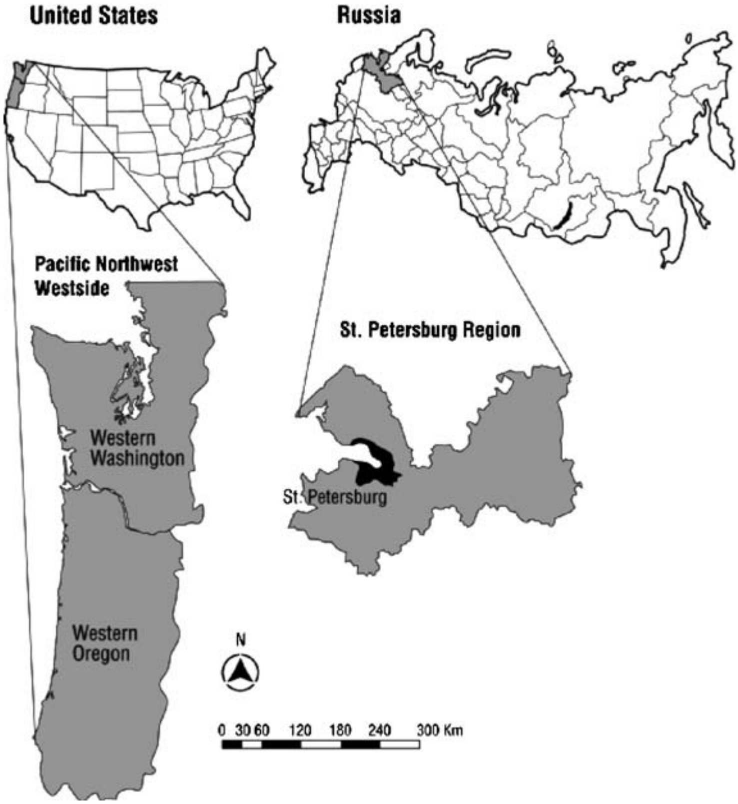

Figure 1. Western Washington and Western Oregon regions of the United States Pacific Northwest and the St. Petersburg Region of Russia.

management to plantings with genetically improved stock, precommercial thinning, and fertilization resulting in substantial differences in growth by treatment (Alig and Butler, 2004; Haynes, 2003). The dominance of the Douglas-fir forest type and species in the region is a result of the species' high growth capacity, its adaptability to high-intensity management (e.g., its ability to reforest clearcuts), and the high economic value of its wood.

The forests of the PNWW region are continually changing in response to harvesting patterns and natural succession (Alig et al., 2000). The forest dynamics of the region are in a transitional stage, with some historical patterns being altered by current economic and social factors, such as ownership patterns, timber markets, forest management regulations, and changing management objectives. Although approximately two-thirds of the region's forest land is publicly owned, timber harvests in the region currently come mainly from private timberlands. Timberlands are forestland that is not reserved from timber harvest and meets a productivity criterion, with about half of the region's timberland under private ownership. The Northwest Forest Plan in the early 1990s curtailed logging on federal land in Washington and Oregon (Figure 2), whereas previously a large proportion of the timber harvested in the region came from national forests. The federal regulations under the Northwest Forest Plan promote protection of the northern spotted owl (*Strix occidentals caurina*) and other species deemed dependent upon late-successional forest habitat for parts of their life cycles. In total, timber harvest in the PNWW region has dropped from about 90 million cubic meters in 1980 to about 50 million in 2000 (Haynes, 2003).

As the level of federal timber harvests decreased, the importance of timber harvested from private lands increased. In 1952, private forests contributed 60% of the total timber harvest, and that grew to about 90% by 2000 (Smith et al., 2001). This has led to shorter timber rotations on private timberlands and more opportunities for converting between forest cover types (e.g., other softwoods type to Douglas-fir) at time of regeneration (Alig and Butler, 2004; Haynes, 2003). Such changes are influencing forest C storage levels in the region.

Historically, in aggregate, PNWW timber inventory levels declined from 1952 to 1997, especially for the two largest holders of inventory, forest industry and federal owners (Figure 3). The period of sharpest decline was between 1976 and 1986, when federal timber harvests were at recent historical high levels. Since then, management of the Northwest's old-growth forests, mainly on federal lands, is one of America's most contentious natural resource issues. Old-growth forests can be defined in varying ways, but here we use the definition of forests with trees more than 250 years old, with big fallen logs, having large standing snags (dead trees), and with the potential to store a high amount of carbon (Harmon and Marks, 2002). With a mixed and multi-layered canopy broken by occasional light-filled gaps, trees may grow up to 100 meters high and over 2 meters in diameter.

In 1991 the softwood growth/removal balance in the PNWW National Forests was 1.2. For every cubic foot of wood products removed, more than 1.2 cubic

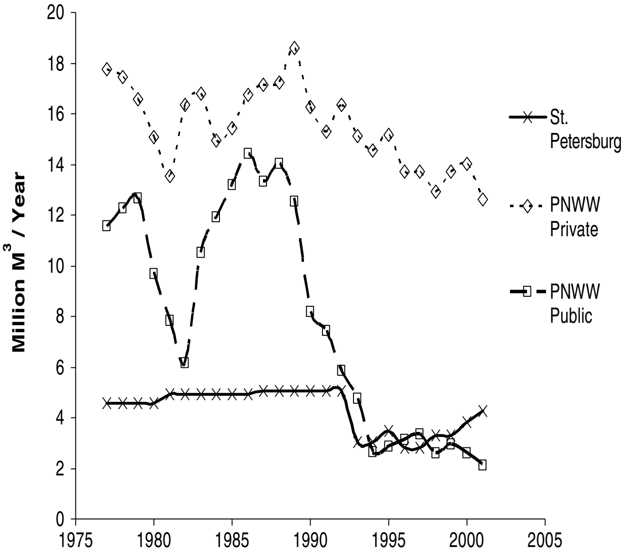

Figure 2. Historic timber harvest for St. Petersburg and private and public ownerships in the Pacific Northwest Westside. PNWW: Sources – Washington Department of Natural Resources and the Oregon Oregon Department of Forestry. St. Petersburg: Final harvest on federal forest lands. Source – R.F. Treyfeld, personal communication based on data on file at the Northwestern Forest Inventory Enterprise.

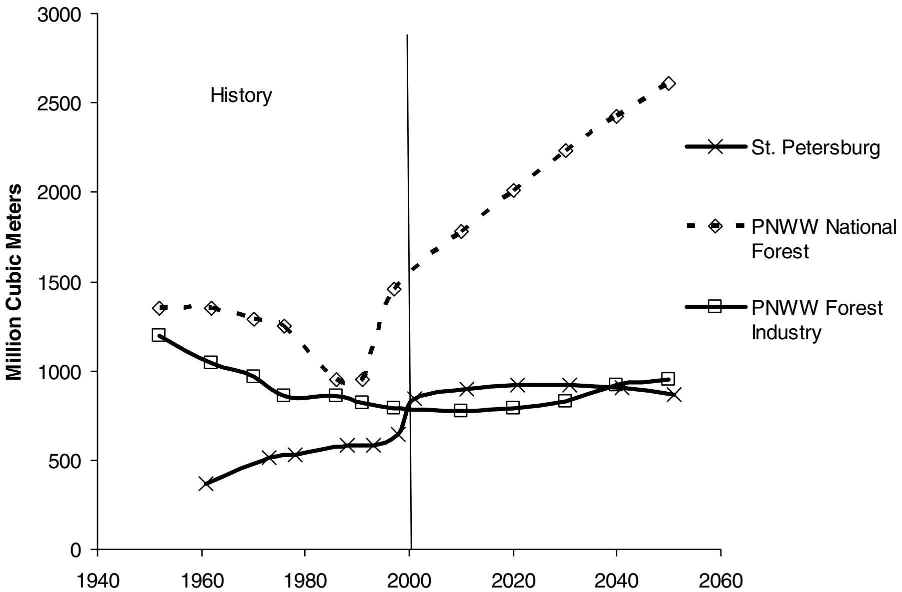

Figure 3. Historic and future softwood timber inventories for the Pacific Northwest Westside. Inventory for the St. Petersburg Region of Russia is for the base case and includes all species.

feet of wood were being added. However, by 1996 the growth/removal balance in the national forests had risen to 11.8, or almost 12 cubic feet added for each foot removed. In contrast, for forest industry timberlands the growth/removal balance is close to one (Figure 4).

The amount of live tree C in private forests in PNWW has followed a decreasing trend from 1970 to the present (Figure 5). This decrease begins to level off near 65 Mg C ha^{-1} around year 2000. For national forests the decline in live tree C reversed in the late 1980's and began increasing following the large reduction of timber harvests on federally owned lands. The upward trend in C accumulation leveled off in the late 1990's.

The *St. Petersburg region of northwestern Russia* (Table I, and Figure 1) has a maritime climate, with cool wet summers and long cold winters. Mean temperature in July ranges from 16° to 18°C, and in January it is −7° to −11°C. The mean daily temperatures are below zero from November until March. Annual precipitation is 600–800 mm.

The natural vegetation of the area is southern taiga; major dominant conifer species include Scots pine (*Pinus sylvestris L.*) and Norway spruce (*Picea abies* (L.) Karst.), growing in both pure and mixed stands. After disturbance, these species are often replaced by northern hardwoods, including birch (*Betula pendula* Roth.) and aspen (*Populus tremula* L.). Most of the region is part of the East-European Plain; the terrain is flat and consists of ancient sea sediments covered by a layer of

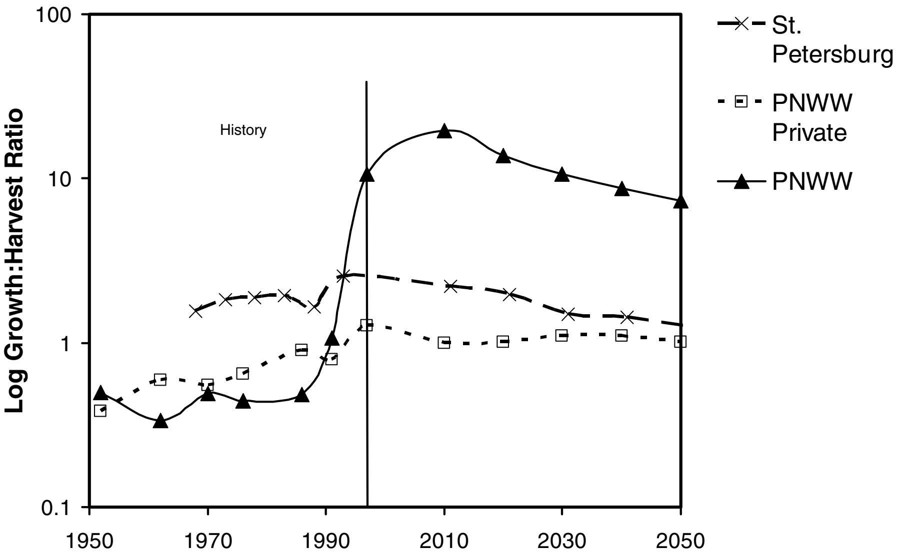

Figure 4. Base case growth to harvest ratio for PNWW National Forest and privately owned forests. The growth to harvest ratio is shown for the base case (historic average level of harvest) for the St. Petersburg region.

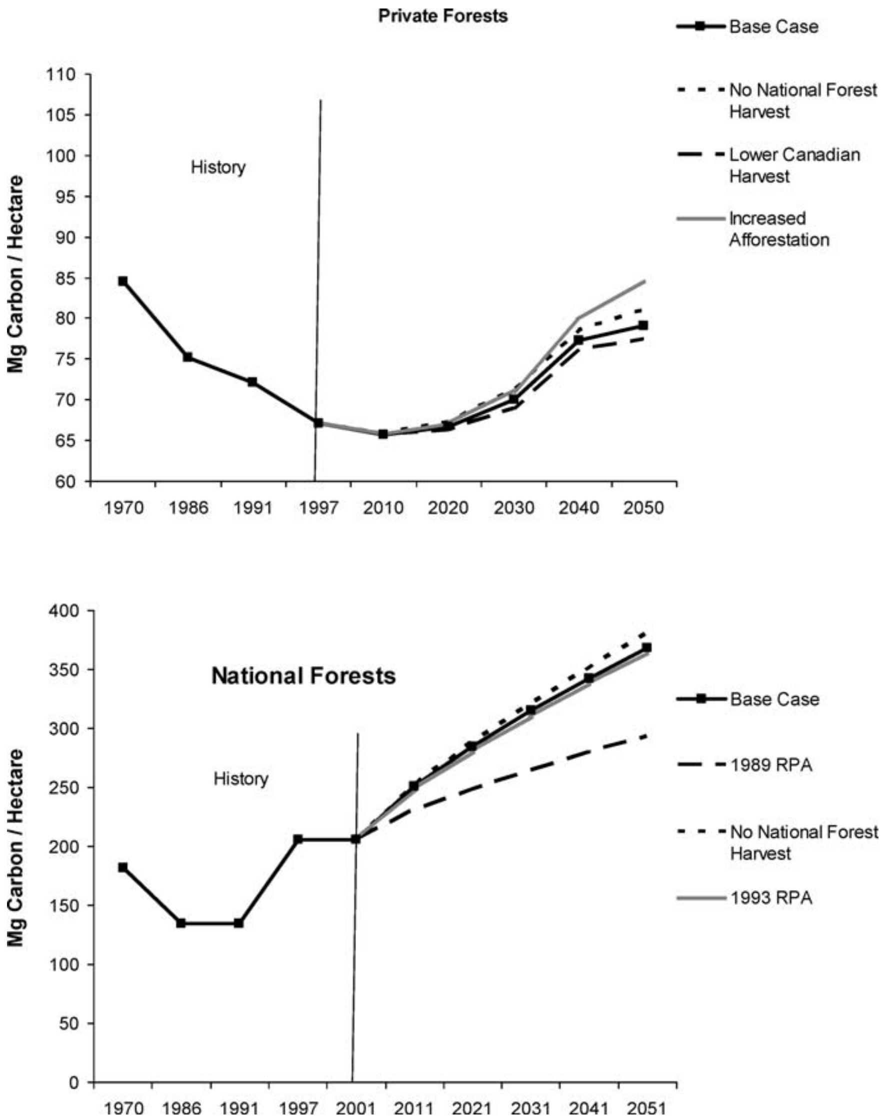

Figure 5. Historic change and future projections of carbon stores in live forest biomass for private ownerships and National Forests in the PNWW region. Units are in megagrams of carbon per hectare.

moraine deposits. Toward the northwest, glacial features dominate the landscape and bedrock topology is more prominent. Soils are mostly podzols on deep loamy to sandy sediments.

The St. Petersburg region has a long history of agricultural and forest management dating from the 18th century. Most of the forests are second-growth. The land-use history is similar to that found in Scandinavia but distinct from many other boreal regions, such as Siberia and Alaska. The human population of the region is close to 7 million, with over 5 million people living in the city of St. Petersburg (Krankina et al., 1998). The St. Petersburg region is part of the Europe-Urals geographic region of Russia, which is the most densely populated and economically developed part of Russia (Kukuev et al., 1997).

Management and administration of Russian forests are undergoing a process of profound changes as Russia transitions from administrative management to a market-based economy. As a result, the stable administratively determined harvests during the 1970's and 80's were replaced by market-driven fluctuating levels beginning in the early 1990's (Figure 2). Transition to a market economy initially produced a depressed market environment in the early to mid 1990's, with a sharp decline in timber harvest in the St. Petersburg region and throughout Russia (Krankina et al., 2004 b), but recently Russia has been among the fastest-growing economies in the world.

3.2. CALCULATION OF REGIONAL C DYNAMICS

To reflect the interactions of biophysical/ecological, economic, and social factors in influencing future levels of forest biomass and carbon, we used a bioeconomic modeling framework that included consideration of social or institutional elements. For the PNWW region, we employed the framework used in periodic national forest resource assessments in the United States that consists of four submodels (Haynes, 2003):

(1) the timber assessment market model that models the solid wood products sector and also provides linkage between product markets (solid wood and pulpwood) and the timber inventory (Adams and Haynes, 1996);
(2) the North American pulp and paper model that is an economic model of the pulp, paper, and paperboard sector with detailed treatment of fiber supply including recycled material (Ince, 1999);
(3) an Aggregate TimberLand Analysis System (ATLAS) that uses a biological modeling structure for projecting timber growth and inventory over time, given timber harvest and disturbances, such as land use changes and forest cover changes (Mills and Kincaid, 1992); and
(4) an area change modeling system that explains the shifting of timberland between forest and nonforest uses and among forest cover types (Alig et al., 2003; Alig and Butler, 2004).

The timber resource data for the U.S. modeling are drawn from periodic remeasurements of more than 180,000 permanent forest plots by the USDA Forest Service, Forest Inventory and Analysis (FIA) (e.g., Smith et al., 2001). Measurements include forest growth, mortality, cover changes, and timber harvest and other disturbances. The biological projection component of the modeling system represents forest inventory as a collection of age classes, and advances or adjusts those classes over time to simulate the growth and development of the forest (Haynes, 2003). The timber yield estimation process projects volumes for a modeling cell (e.g., stratum representing region, owner, forest type, and age class) period by period in a fashion consistent with the inventory stand age classes. The yield tables and associated yield projection inputs required for the timber growth models were derived from timberland inventory plot data collected by various USDA Forest Service FIA units.

In the modeling system, cells can shift in growth, area, harvest, and timber management intensity. Over time, for example, a forest inventory cell can be lost from the forest land base to nonforest uses due to socio-economic drivers (e.g., increase in population that prompts conversion of forest land). Another major human-caused effect on timber inventory levels is timber harvests. Harvest estimates are used in adjusting timber inventories (and broad-scale vegetation conditions), given changes in forest growth and timberland loss and gain. Timber harvest levels are related to demand-side factors such as population and personal income levels in a market-level model (Adams and Haynes, 1996). Other details about the various input assumptions used in the modeling system are described by Adams and Haynes (1996), Alig et al. (2003), and Haynes (2003). Because they deal with the unknowable future, projections of future scenarios can not be strictly validated, however, modelers have conducted historical simulations with the different component models to evaluate their performance, e.g., Adams and Haynes 1996. For example, historical validation of ATLAS modeling involved using data from permanent forest survey plots, where model predictions are compared with field measurements.

The process of converting the timber volume projections to C involved modifying a set of assumptions used by Turner et al. (1995). We multiplied volume (m^3) by a factor of 1.01 to add the volume of noncommercial species. The average value for the specific gravity (443 kg m^{-3}) of the Douglas-fir and western hemlock-Sitka spruce forest type was then multiplied by the cubic volume to derive an estimate of tree bole biomass. The product for the ratio of sapling to tree biomass (0.057) and bole biomass was added to the value for bole biomass. The amount of C in the bole of a tree is estimated to be roughly half the value of bole biomass, therefore, tree bole biomass was divided by 2 to produce an estimate of tree bole C. The amount of C contained in nonmerchantable tree components such as tops, stumps, branches, roots, and cull trees was added to the tree bole C value by multiplying by adjustment factors from Turner et al. (1995).

The source of the Russian data is the regional forest management planning document on file at the St. Petersburg Forest Academy in St. Petersburg, Russia: *"The general plan for organization and development of forestry in the Leningrad Region."* The plan was developed by the North-West State Forest Inventory Enterprises, Leningrad-St. Petersburg, Russia in 1983. This is the most recent available comprehensive data summary representing age-class distribution and timber harvest by tree species for all forest lands under state forest management in the St. Petersburg Region. These lands cover an area of 4.6 million ha and contain an estimated 87% of all forest lands in the region; the remainder is largely managed for non-timber purposes by agricultural cooperatives, municipalities, resorts, etc. (Filimonov et al., 1995).

The source data were grouped into 20-year age classes for conifers and 10-year age classes for hardwoods. The oldest age-class included all forests older than 100 years for conifers and older than 50 years for hardwoods because the common harvest age for conifers and hardwoods is 100 and 50 years, respectively. The source data on area and volume distribution for four major tree species in the region (pine, spruce, birch, and aspen) were updated to year 1991 using the historic harvest statistics, assuming that the average per ha bole volume and harvest distribution by species did not change between 1981 and 1991. We split 20-year age classes into two classes to bring the age-class distribution for all species to a single 10-year class system, aligned with the projection time-step and to refine the estimates of C.

Because C stores in tree biomass continue to increase well beyond the harvest age, we think it is important to estimate the distribution of the aggregate "mature and older" age class in our source data by regular 10-year age classes. We approximate this distribution for each species using a sample of stand-level forest inventory data for 7 individual forests in the region (Krankina et al., 2001). These data were collected in 1992–93; our sample includes nearly 216 thousand forest stand records and covers 1.1 million ha or about 20% of all forest lands in the region. Using the entire regional set of these more recent data is not practical because of access restrictions. Thus, we extended the age-class distribution to 100 years for hardwoods and 200 years for conifers. The same sample of stand-level forest inventory data was used to calculate the average C store per ha for all four species by 10-year age class. Biomass for each forest stand in the sample data set was calculated from detailed forest inventory data (dominant species, forest age, and wood volume) and available allometric equations (Alexeyev and Birdsey, 1998) and was averaged by species and age class.

The procedure for calculating timber volume and C store for each 10-year projection interval involved moving the area associated with each age class forward into the next older age class. Total wood volume and C store for the age class were calculated by multiplying the estimated volume or C store per ha associated with the age class by the area for the same age class. The harvest area for each scenario was distributed among species using a 1981 distribution and assuming it remained constant over time. The harvest area is then subtracted from old age classes: greater than 100 years for conifers and greater than 50 years for hardwoods in proportion to the areas of forests in each age class older than harvest age. The entire harvested area is then added to the youngest age class.

3.3. SCENARIOS FOR PROJECTIONS

Four scenarios each were selected for the PNWW and St. Petersburg regions, based on the historical patterns of socio-economic and resource development in each region and on current policy deliberations in the respective regions. Several of the four PNWW scenarios are specific for private timberlands versus National Forest timberlands to reflect factors likely to have the larger impacts on the respective forest ownership groups. Timber assessment models were drawn upon to project the forest resources until 2050, to provide a sufficient time period for effects of human interventions such as changes in timber management to be played out for several decades. The base case represents a starting point, assuming no fundamental changes in existing forest policies or environmental regulations. The various alternative futures that we employed reflect differences in one selected element of the base case, so that we could observe how that change would affect future timber inventories and potential forest C storage.[2] The PNWW scenarios are based on policy analyses in national Resources Planning Act (RPA) Assessments (e.g., Haynes, 2003).

The three alternative PNWW futures for National Forest timberlands reflect changes in the goals for federal timberland management in the United States. Although there have been many proposals for modification of National Forest harvest levels, we selected three scenarios that illustrate the range of recent policy discussions. During the 1990s, timberland management changes were set in motion by wildlife habitat conservation requirements for the northern spotted owl, which reduced regional harvest levels by more than 75%. We have chosen alternative projections or scenarios for National Forest harvest levels to represent different views of the future as characterized in past national assessments. Thus, the three PNWW scenarios for National Forest timberlands are: (1) no harvest on National Forest timberlands, which are managed by the USDA Forest Service (Haynes, 2003); (2) National Forest harvest levels projected in a previous RPA assessment in 1989 (Haynes 1990), or in the pre-spotted owl period; the projected amount of timber harvest in 2010 is more than four times larger than that in the base case; and (3) National Forest harvest levels projected in the 1993 RPA assessment update, with projected amounts of timber harvests on National Forest timberlands falling between those of the base case and those from the 1989 RPA assessment, as described by Haynes (2003). In the zero cut scenario, the annual reduction in National Forest harvest represents about 6% of the U.S. softwood harvest.

National Forests hold a significant amount of timber inventory in the PNWW region and the actions on National Forests have implications for the private ownerships because the model reflects interregional linkages in timber markets and prices (Haynes, 2003). For example, increasing timber harvest on federal timberlands would be expected to exert downward pressure on timber prices for private landowners in the PNWW region. Increased timber harvest on federal timberlands would effectively reduce the demand for timber on private lands in the PNWW region, leading to lower harvest levels from those lands. Forest management on National Forests is typically more multiple use in nature than for private forests, and less responsive to changes in timber markets.

The three alternative scenarios for U.S. private timberlands are:

(1) no harvest on National Forest timberlands managed by the USDA Forest Service, beginning in 2002; this is the same scenario as used for National Forests above, as eliminating harvests from the National Forests would impact private forest management, in response to reduced U.S. softwood lumber production and consumption and increases in softwood lumber prices (Haynes 2003);
(2) decreasing Canadian sawtimber harvest, with harvest reduced to lower levels of the late 1970s, as a result of increasing environmental concerns and pressures to provide lands for native peoples (Haynes, 2003); this scenario would act to shift some demand to PNWW private timberlands, exerting upward pressure on domestic timber prices and leading to more private timber harvest; and
(3) increased afforestation on nonindustrial private lands relative to the base case, with an additional 2.5 million ha of agricultural land afforested, mainly in the U.S. South (Haynes, 2003); the implications of afforestation elsewhere in the United States for timber harvest in the PNWW include effects on timber prices and harvest volumes in other regions, as owners may adjust timber harvest and planting in response to perceived timber supply changes from afforestation that can affect timber prices and net present value of expected profits.

Scenarios for the St. Petersburg region reflect possible future developments in the forest sector within the larger European part of Russia. The scenarios cover a wide range of possibilities from minimal harvest activity that may result from renewed economic crisis to rapid growth of forest use to the point of complete resource utilization within the limits allowed by current environmental regulations.

The base case simulates the average level of harvesting in the St. Petersburg region over the past 30-years from 1972 to 2001 −4.2 million m^3 per year. This base case is analogous to the U.S. base case in assuming no fundamental change in forest policy of recent history. Alternative scenario 1 assumes future harvest at the level of 1993. This was the year of economic crisis in Russia, which resulted in the lowest level of harvesting since 1963 – 3.55 million m^3/year. (Figure 2). Alternative scenario 2 simulates the complete utilization of the 2001 allowable cut (7.6 million m^3 per year) at each projection interval. The State Forest Inventory Agency determines the level of allowable cut for each Forest Management Enterprise (FME) based on the volume of mature and overmature forests, state imposed limits, and economic conditions in each FME. Alternative scenario 3 begins with the 2001 level of harvest (4.2 million m^3 per year, as in the base case) and then assumes an increase to the level of allowable cut (7.6 million m^3 per year) by 2011. Further, all available mature timber is harvested (38.4 million m^3 in 2021, 13.4 in 2031, 8.6 in 2041, and 6.6 in 2051). This scenario presumes that by 2020 there is enough demand for wood and economic investment in harvesting operations, while state imposed limits on harvest are lifted except those that reserve forest lands for non-timber uses (watershed protection, major highway, buffers, recreation, etc.). Although this scenario appears unlikely at present, the state regulation is a hotly debated issue and there is a general trend towards reduced regulatory measures.

4. Results

4.1. PNWW

Future projections show that forest C accumulation will increase in the long-term future, with the increase coming mainly on National Forest lands (Figure 5). The trajectory of C storage on National Forest timberlands in the PNWW region is strongly upward between 2000 and 2050. The C storage in live tree biomass expands with a constant, almost linear, increase through 2050 for all scenarios. The three scenarios have an increase of 157–175 Mg of carbon per ha on National Forest timberlands over the 50-year projection (Figure 5). The net change in live tree biomass C from 2000 to 2050 is roughly an order of magnitude higher than for PNWW private timberlands or for St. Petersburg forests (Figures 6 and 7).[3]

Regrowth in the younger stands leads to an increase in timber volumes per ha on many areas. With less timber harvest on National Forests, timber volumes per ha expand with increased growth and stocking. Timber growth compared to harvest has increased significantly on National Forest lands since the early 1990s (Figure 3) and the introduction of the Northwest Forest Plan that greatly reduced federal

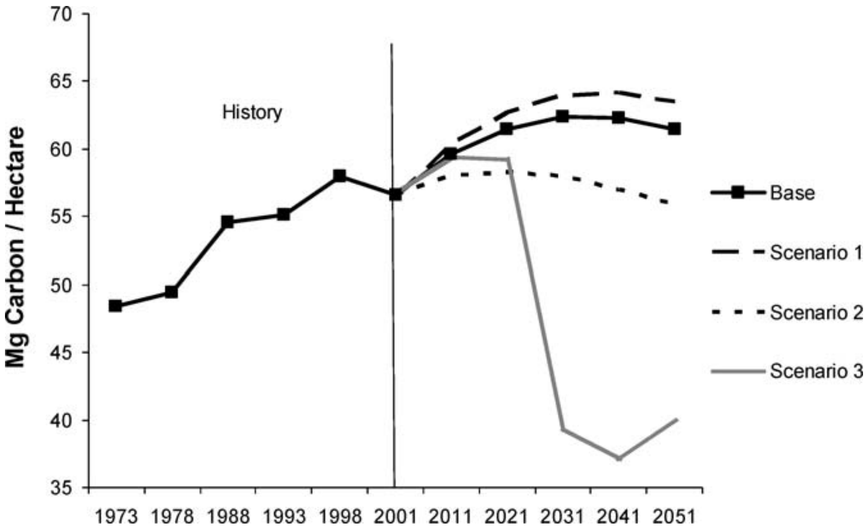

Figure 6. Historic change and future projections of carbon stores in live forest biomass for the St. Petersburg region of Russia. Units are megagrams of carbon per hectare.

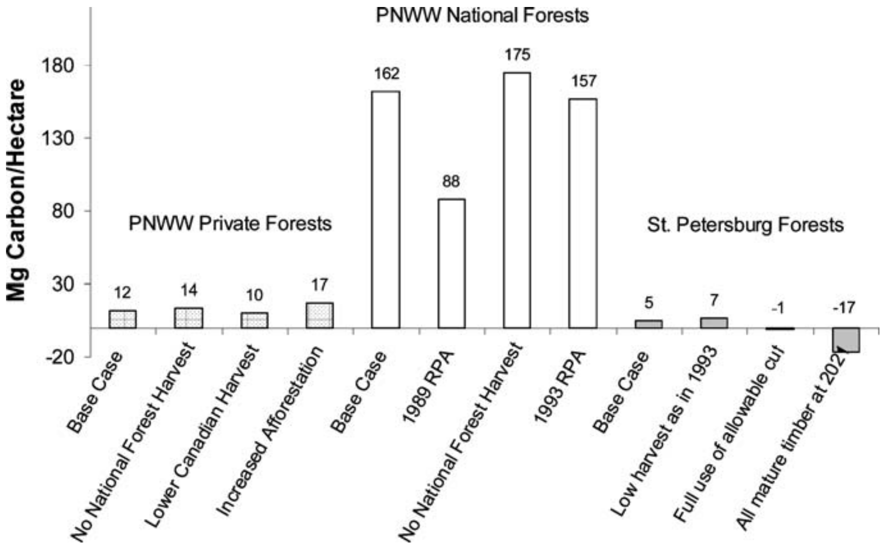

Figure 7. Net change in carbon stores from 2001 to 2051 for St. Petersburg region forests and National Forest and private forests of the PNWW region.

timber harvests in the PNWW region. The increase in C per ha across scenarios over the next 50 years is from about 35% to 85%. The "no timber harvest" scenario leads to C storage levels per ha that exceed 375 Mg.

For private timberlands, amounts of C per ha in live tree biomass across scenarios are projected by 2050 to be roughly what they were in 1970 (Figure 5), before timber inventory levels were reduced when timber harvest exceeded net growth (Figure 4). The projection trajectories approximate a sigmoid growth pattern, where the rate of increase in C begins to decrease notably around year 2040, near values of 80 Mg C ha^{-1}. Now with smaller trees on average and relatively rapid regrowth of stands harvested over the last several decades, the projection is for a turnaround in forest C storage levels in live trees.

Base case results in the PNWW vary markedly by ownership and are materially affected by management of federal timberlands. Figure 4 shows that private timberlands are being managed at roughly sustainable levels of timber harvest and private industrial softwood timber inventory rises slowly over the projection period (Figure 3). In contrast, federal timberlands have timber growth well in excess of harvest, and inventory levels are projected to approximately double by 2050 (Figure 3). Likewise, the C storage per ha of National Forest timberland approximately doubles between 2000 and 2050 (Figure 5). The aggregate ratio of timber volume per ha on National Forest timberlands to that on industrial private timberlands grows from a ratio of about 1.5 in 1992 to about 4.5 by 2050.

Forest ownership affects projected timber harvest levels and results across scenarios illustrate the sensitivity of future forest C stores to assumptions about timber harvest behavior. For National Forests, as might be expected, C accumulation is highest for the scenario with no timber harvest on National Forest lands (Figure 5). The amount of timber harvest in the base case is relatively small compared to historical levels (Figure 2), and the base case is projected to have a similar but smaller level of C accumulation than the scenario without National Forest timber harvest. In contrast, C accumulation under timber harvest levels reported in the 1989 RPA is lower relative to the other three scenarios, leading to the largest departure from the base case projections.

For private timberlands, afforestation (which is projected to occur primarily in the southern U.S., outside our study region) has the largest potential in the long-term to increase aggregate C storage (Figure 5). However, the largest impacts are several decades into the future, as the planted trees mature and move into age classes containing substantial timber volumes per ha. The future forest area distribution by age class for private PNWW timberlands varies by scenario and over time. By 2050, for the base case and other scenarios, less forest area is projected to be in the youngest age class compared to the existing distribution (Figure 8). The largest effect of the scenarios is the increase in area with timber around 50 years of age under the afforestation scenario.

4.2. ST. PETERSBURG REGION

C stores in live forest biomass were estimated at 57 Mg C/ha in 2000 (Figure 6). The base case assumed total harvest of 210 million m^3 over the 50-year projection period and resulted in a net increase in the regional C stores in live forest biomass of 11 Tg C or 4% of the initial store. By comparison, scenario 1 resulted in a larger net increase in regional C stores. Scenario 1 involved a harvest of 178 million m^3 of timber, with a gradual increase in the regional C stores of 33 Tg C (or 12% of the initial C store) over the first 30 years of projection. This was followed by a slight decrease (by 12 Tg C or 4% by year 50), for a net increase of 21 Tg C (8%). These two scenarios represent the lower range of the possible forest resource utilization scenarios. Scenario 2 projected total harvest of 380 million m^3. The regional C stores increase slightly over the first 20 years of projection (by 8 Tg C or 3%), followed by a gradual decline for a net loss of 15 Tg C (6%). This indicates that the calculated allowable cut for the region does allow for sustained levels of timber harvest but it does not maintain the regional C stores in tree biomass.

Applying maximum harvest at the second projection interval, preceded by allowable cut at the first projection interval (scenario 3), produces an interesting pattern. The C amount drops sharply at the second interval, followed by less of a decrease at interval 3. Accumulation increases at the end of the projection period, however, as nearly all of the forested area that was once in older age classes moves into faster growing age classes represented by young forest. Scenario 3 projected the highest total harvest of 724 million m^3, more than three times higher than the base

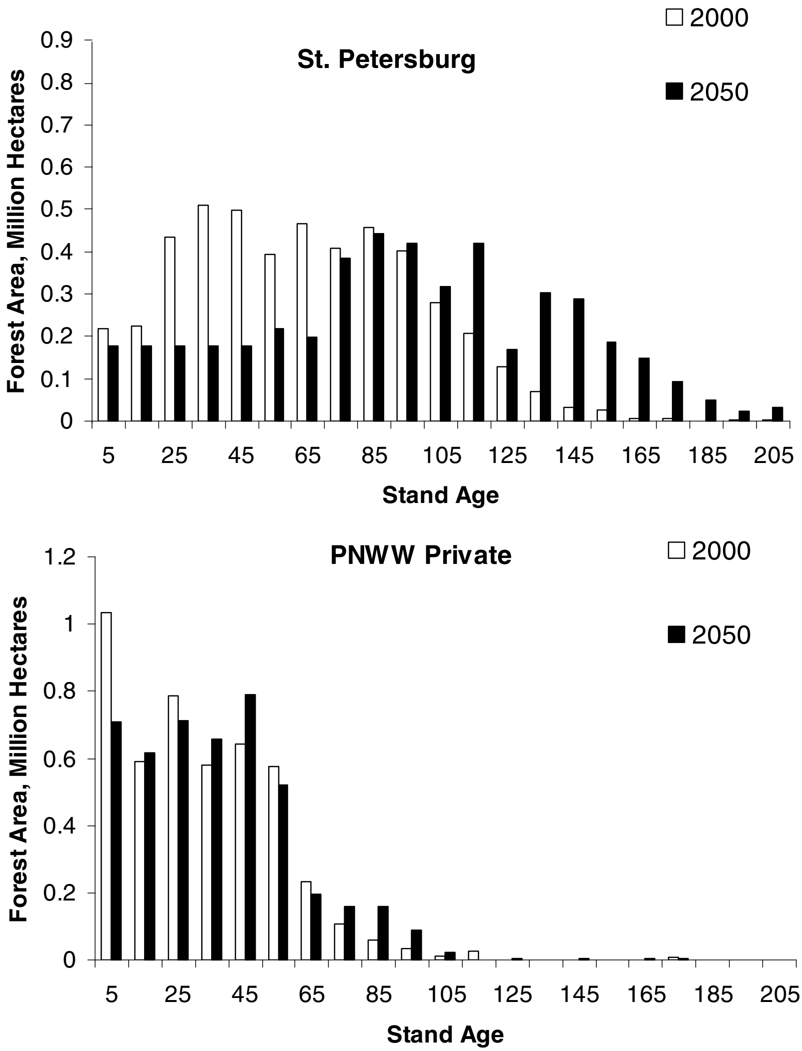

Figure 8. Initial and final area, in million hectares by stand age, for the St. Petersburg (base case) region of Russia and privately owned forests in the PNWW region (base case). Values include hardwood and softwood forests.

case level. Because of the assumed gradual initial increase in harvest, the regional C stores increased somewhat over the first 20 years (by 12 Tg C), then dropped dramatically over the next 20 years, as the entire stock of mature timber was being eliminated. Finally, C stores begin to increase gradually, resulting in a net loss of 79 TgC or 29% of the initial store over 50 years.

The increasing C stores during the first 20–30 years of the projection continue the historic trend in the region (Figure 6). This results from the historic pattern of timber harvest that concentrated the largest area in age classes 30–100 during the

1990's. However, as the largest age cohorts of forest stands advance in their age beyond the peak of productivity, the rate of C accumulation declines. The third scenario approximates a complete shift in the forest management approach from tightly regulated low timber harvest to unabated forest utilization. This is the only scenario than projects a drastic decline in C stores, with the projected 2050 level per ha more than one-third smaller than for the base case.

The projected differences in harvest scenarios produce different patterns of forest distribution by age classes. The base case and scenarios 1 and 2 maintained the overall pattern, with the peak shifting over time towards the older age classes and the extent of re-distribution from older to younger classes proportionate to the level of timber harvest. Scenario 3 concentrated 35% of forest area in a single age class, resulting in more than 50% of the forest under age 40 at the end of the projection period.

4.3. COMPARISONS ACROSS REGIONS AND OWNERSHIPS

Comparing forest C history and projections for the two regions has isolated several factors that led to differences across regions: land use history in each region, basic forest productivity, and the role of legislation and public policies regarding the economy and forests in each region. A reflection of the influence of such socio-economic factors is the current forest age-class structure, an important consideration when modeling forest C levels. In the PNWW region, the old-growth forests were virtually eliminated on private lands (Figure 8) and drastically reduced on public lands by the early 1990's. Currently, about one-fifth of the National Forest timberland has trees 200 years or older, with stand age in the region spanning several hundred years of age. C storage for an older PNWW stand, such as a 250-year old one, may contain 300 metric tons of carbon per ha, a multiple of that for typical older stands in the St. Petersburg region. The area of old growth on National Forests in the PNWW region is increasing, as policy makers responded to socio-economic signals and reserved many older forest stands from harvest to promote more habitat for threatened or endangered wildlife species. At the same time, this influences timber rotations on private timberlands, leading to shorter timber rotations and an age class distribution weighted towards forest stands 55 years and younger (Figure 8).

Historical land-use change in the St. Petersburg region started earlier than in the PNWW region and the old-growth forests there largely disappeared in the beginning of the 20th century (Aksenov et al., 2002). The period of relatively low timber harvest during 1960-80's (Figure 3) led to accumulation of a large stock of mature forest, but a very small area approaching the old-growth condition and a relatively small area of young forest (Figure 8). Because the loss of old-growth forest occurred earlier, there is little public concern in the region about the preservation of old-growth conditions. Rather, the public debate and environmental legislation focuses on maintaining timber production, forest cover, and recreational value of forests.

The St. Petersburg region does not have the influence on C storage levels from forest ownership as for the PNWW region. Thus, contributions of differences from elements of public policy scenarios are relatively more important in the St. Petersburg region. Timber harvest is a key driver. The projected regional C stores in the St. Petersburg region change over time and by harvest scenario in inverse proportion to the amount of timber harvest.

Private forest lands in the PNWW and forests in the St. Petersburg region have somewhat similar current and projected forest C stores per ha (Figures 5–7) in spite of great differences in forest productivity. The harvest rotation for conifers in the St. Petersburg region is twice longer than for private timberlands in the PNWW region and the large proportion of older St. Petersburg forests compensates for lower productivity to produce a similar level of average C storage on forest lands. The inverse J-shaped age-class distribution of private forest lands in the PNWW was formed during the period of intensive harvest well in excess of growth (Figures 2 and 4). A similar shape of age-class distribution can form in the St. Petersburg region under Scenario 4 that assumes harvest of all mature timber. The stabilization and recovery of C stores in 2040–2050 in the St. Petersburg region follows a pattern similar to that on private lands in the PNWW during 2000–2010. The range of changes in average C stores on forest lands managed primarily for timber production is limited to 10–15% depending on scenario, while a complete change in management objective (as on PNWW public lands or scenario 4 in the St. Petersburg region) can lead to much greater change.

5. Discussion and Conclusions

Major differences contributing to C storage levels are a combination of biophysical and socio-economic factors, where the latter include reduced federal timber harvests in response to society's changing expectations for public land reservation and management. The influence of ownership and associated forest management practices on C storage potential for the U.S. Pacific Northwest (e.g., USDA Forest Service National Forests) and northwest Russia are reflected in historical trends that are quite different for the two study regions. One outcome is a larger area of older forests in the PNWW region, which provides a foundation for subsequent projections of large changes in C storage per ha in live tree biomass.

Our results indicate that the trajectories of C accumulation 50 years into the future on lands managed for timber production tend to continue the historic patterns in both the PNWW and St. Petersburg regions. With the exception of the "liquidate mature timber scenario" in the St. Petersburg region, the projected future C stores for a given initial condition deviate within 20% of each other. Even though the projected futures reflect a broad range of policy options, larger differences result from the starting conditions determined by ownership, regional environmental conditions, and past changes in forest management.

Socio-economic forces have notably influenced the progression of forests in the last half century, and are expected to continue to significantly affect the future path of forests in both regions under alternative scenarios. In the PNWW, the dramatic difference in C stores between ownerships demonstrates the profound effects of different management objectives: C stores on private lands are lower even though productivity is higher, because the age-class distribution is truncated, and young forests dominate. Federal polices to date in both regions affect C storage primarily through adjusting timber harvest levels and protection of forests. Of the four major components affecting C storage levels in live forest biomass – area in forest, forest growth, timber harvest, and forest investment (e.g., fertilization) – adjustments in timber harvest have been the main human intervention in recent decades. A striking example is the reduction of federal timber harvests in the PNWW region, which allows projected levels of forest inventory and C storage to rise well above those in the historical period covered by consistent forest inventory data.

Translating society's multiple forestry objectives into policies and management actions has become more difficult as society's objectives have become more complex; however, interest in ecosystem services, such as forest carbon storage, is increasing. Protection of forests can affect forest growth and harvest possibilities as well as other ecosystem goods and services, and climate change may be altering policy concerns about stresses on ecosystems and the need for altered protections, especially for fire. One non-timber harvest risk related to the broader age class distribution is the possibility of mortality from insects, diseases, and fire that can affect C storage and release. To reduce risks from forest fires, current policy debates focus on restoration, with forest thinnings proposed for treatment of hazardous forest fuels on U.S. federal lands (e.g., Adams and Latta, 2004). A human-caused disturbance impacting forest age class structure is land use conversion on private timberlands in the PNWW region. Population growth and increases in average personal incomes are socio-economic forces contributing to more forestland conversion for urban and developed uses. The rate of such deforestation increased in the 1990s, rising to about 400,000 ha annually nationwide, compared to the 1980s (Alig et al., 2004), resulting in more concern about loss of forest sinks for C sequestration. The different ownership pattern in the St. Petersburg region involves less such land available for conversion. Also, among disturbances to forest ecosystems, timber harvest is relatively more important in affecting forest stocks in the St. Petersburg region.

Forest management issues in both regions include institutional questions, such as the regulatory framework and the mixture of market allocation principles and possible government intervention (e.g., Kyoto Protocol) in forest resource management and allocation (Murray et al., 2002). The role of U.S. public timberlands in C storage has been less discussed than for private timberlands, but as this study suggests, there is considerable potential for forest C sequestration. Value of C sequestration is likely to increase and will enter more into forest management decisions involving trade-offs between biophysical and socio-economic components of ecosystems.

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Notes

[1]After Leningrad was renamed St. Petersburg, the administrative region retained its old name "Leningrad oblast."

[2] C storage opportunities exist on both private and public forests, and costs of storage will depend on a combination of forest sector, producer, and market conditions, as well as what happens in other sectors and to the Kyoto Protocol under the Framework Convention on Climate Change. Significant uncertainty surrounds that social aspect of global climate change, with the United States not currently a participant (Murray et al., 2002).

[3]Note that carbon stored in other forest ecosystem components and in wood products is not included in these estimates.

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