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Comparison of Carbon Dynamics of Two Conifer Forest Regions: Northwestern Russia and the Pacific Northwest, USA

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Introduction

A workshop entitled *Comparison of Carbon Dynamics of Two Conifer Forest Regions: Northwestern Russia and the Pacific Northwest* was held at the Department of Forest Science, Oregon State University, Corvallis, Oregon on April 9-23, 1995 as part of an international LTER project funded by the National Science Foundation. The project compares the carbon dynamics of two significant forest regions of the globe, the Pacific Northwest, USA and northwestern Russia. The main objective of this project is to determine the major factors controlling the spatial and temporal patterns of carbon stores and fluxes within these two major coniferous ecosystems at three spatial levels: stand, landscape and region. This analysis is based on the synthesis of long-term weather records and ecosystem process measurements, forest inventory data, aerial photography, and remote sensing imagery for both regions. For both regions we plan to use the same complex of modeling tools to analyze carbon dynamics at three spatial levels as well as to assess the impact of timber harvesting and carbon storage in forest products. We have made significant progress on this activity in the Pacific Northwest (see bibliography). For northwestern Russia these models have yet to be calibrated and tested. Therefore, the primary task is to compile and synthesize existing data including long-term observations on permanent plots, local growth tables and biomass equations, forest and soil inventory data, weather data, remotely sensed images and timber harvest, and processing parameters.

The two study areas represent contrasts in potential productivity and land-use patterns. The St. Petersburg region is located in the forest zone of northwest Russia. It has a long history of agricultural and forest management dating from the 18th century. Given the recent political and economic changes, this region may be entering a period of increased timber harvest. In contrast, the Pacific Northwest forests are just ending a long-term period of heavy timber harvest of primary forests, in which a significant amount of carbon has been released to the atmosphere. Both forest zones may play a significant role in the global carbon cycle, either because of their extent (Russian taiga) or their high potential carbon density per unit area (Pacific Northwest).

The Russian study area is located at about 59 degree northern latitude and between 31 and 32 degrees Eastern longitude in the St. Petersburg Region (Leningrad Oblast) of Northwestern Russia. The climate is cool maritime with cool wet summers and long cold winters. Mean temperature of January is -7.7 C; mean temperature of July is 17.8 C. The incoming solar radiation is significantly reduced by cloud cover. Annual precipitation is 67 cm, evenly distributed throughout the year. The area is a part of the East-European Plain with elevations between 0 and 250 m above the sea level; terrain is gentle and rests on ancient sea sediments covered by a layer of moraine deposits. Soils are mostly of podzol type on deep loamy or sandy sediments. Natural vegetation of the area belongs to southern taiga types; major dominant conifer species include scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) both growing in pure and mixed stands. After disturbance, they are often replaced by hardwoods including birch (*Betula pendula*) and aspen (*Populus tremulae*).

The Pacific Northwest study area is west of the Cascade Range crest of Oregon and Washington at 45 degrees northern latitude and 123 degrees western longitude. The climate is Mediterranean, with wet cool winters and warm dry summers. Mean annual temperatures are typically 10 C along the coast, but decrease to <2 C at the highest elevations. Annual precipitation ranges from 30 to 350 cm within the region, increasing with elevation and from east to west. The area contains the Klamath Mountain, Coast and western Cascade Ranges, Puget Sound, and High Cascade geological provinces. With the exception of the Puget Sound province, topography is steep, with elevations ranging from 0 to 4400 m above sea level. Soils are highly variable between and within geologic provinces. They have developed in a variety of substrates, including volcanic ash, basic and acidic volcanic rocks, uplifted marine sediments, laucustrine deposits, glacial till, alluvial deposits and colluvial mixtures of these materials. Several soil orders -- entisols, inceptisols, mollisols, spodosols, alfisols, and ultisols -- occur within the Pacific Northwest. The natural vegetation is highly productive temperate conifer forest, dominated by *Pseudotsuga*, *Tsuga*, *Thuja*, *Abies*, *Picea*, and *Pinus*. An interesting feature of the area is that extensive natural ecosystems (i.e. National Parks and Wilderness Areas) are juxtaposed with areas of intensive land use, providing the opportunity to compare natural and managed ecosystems across many spatial scales.

This project requires significant planning and coordination with Russian colleagues. To address this we invited a group of our collaborators from St. Petersburg Forest Academy, Komarov Botanical Institute, State Hydrological Institute and Northwestern Forest Inventory Enterprise (all in St. Petersburg, Russia) to attend a symposium and a workshop at Oregon State University in April 1995. This allowed all participating scientists to learn firsthand about the two regions, participating institutions, and to share the results of ongoing research. In addition to that, we 1) developed detailed procedures and protocols for data assembly, synthesizing, and sharing; 2) defined the research responsibilities of Russian and US collaborators; 3) planned joint publications in English and in Russian. An overall goal of this project is to encourage further international partnerships in long-term ecological studies as well as make valuable new Russian data resources available to the US scientific community. To help meet this latter goal we have compiled abstracts of papers that were presented by both Russian and OSU scientists at the 2-day symposium on April 11-12, 1995. Additionally we have included abstracts submitted to us when the authors could not attend for different reasons. This publication contains the materials both in English and in Russian, an English only version is available on the World Wide Web at_____________________.

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Carbon sequestration processes in the Pacific Northwest: an overview

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We combined modeling, remote sensing, and a geographic information system to examine the effects of logging on carbon flux from a 1.2 million ha portion of the Pacific Northwest (PNW) region of the United States (an area of about 14 million ha), where over the past century large scale conversion of primary forest to secondary forest has occurred. Extrapolation of our findings suggests that between 1972 and 1991 forests of the PNW region were a net source to the atmosphere of 1.13 x 10^6 g C ha^{-1} yr^{-1}. Although this region is only 0.34 % of the total global forest area, our estimate is that it accounts for 1.76 % of the estimated current carbon flux from global land use activities. Moreover, unlike previous studies, this northern temperate forest region is now identified as a source, rather than a sink for carbon.

Forest dynamics in the St. Petersburg Region over the last thirty years

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The St. Petersburg region is located in the central part of the boreal forest zone in northwest Russia. The Russian Federal Forest Service manages 80% of the total forest area. Forest area has increased by 5% over the last 30 years, due to land transfer and successful reforestation. Forest harvest has decreased over the last few years, and at present achieves 41% of the allowable cut. This reduction is associated with the overall economic crisis resulting from restructuring (perestroika). All of the forests of the St. Petersburg region are included in the on-site inventory program; the last inventory was conducted 2-3 years ago. Average site productivity class is 2.6 based on the 5-class scale of M.M. Orloff.

Over the last 30 years, 171.9 million m^3 of wood were harvested from the forests of the St. Petersburg region and about 270 million m^3 were lost to natural mortality. Since the growth increment was greater than harvest, total growing stock of forest in the St. Petersburg region has increased from 467.4 million m^3 in 1963 to 830.7 million m^3 in 1993. The stock of dead wood in the closed canopy forests of the region is : 27.4 million m^3 of snags (standing dead) and 45.7 million m^3 of logs, for a total of 73.1 million m^3. In spite of the overall crisis in the economy, reforestation work has been successful. Over the last five years 73,000 hectares have been planted. Fire control is a major forest management problem.

Modern global climate warming and its influence on forest ecosystems

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The analysis of 100-year trend of mean annual global surface air temperature revealed two noticeable warmings: the warming of the 1930`s and more pronounced warming of the 1980-90`s. Temperature increase over 1981-91 (compared with mean values for 1951-75) is 0.33 C for the Northern Hemisphere and 0.25 C for the Southern Hemisphere. Currently the greatest temperature anomalies in the high and middle latitudes of the Nothern Hemisphere are detected during winter and spring, and in the tropical zone in spring, summer and autumn. On more than 80% of the globe the anomalies are positive. Annual precipitation anomalies for 1980-1990's are relatively small for most continental regions. They are similar to natural precipitation fluctuations over similar period before the 1980's.

Modern global warming is likely to affect the biomes and natural zones. Paleo-climatic reconstructions show that natural zones experienced significant changes during climatic fluctuations in the past. To determine the translocations of natural zones with the global warming by 1-2 C, we used the maps of projected evapotranspiration, developed using the complex method of M.Budyko, and maps of annual precipitation anomalies expected for warming by 1 and 2 C and the relationship between geographic zones distribution and climate factors (potential evapotranspiration, aridity index and for mountanous regions the continentality index). Noticeable changes in location and areas of natural zones are expected with global warming: natural zones tend to shift northward, modern tundra is predicted to be predominantly occupied with coniferous forest, mixed forest would also shift northward by about 10 degrees, broad-leaved forests are projected to increase their area, extending both northward and eastward. Total forest area of FSU is supposed to contract by 5-8% with global warming by 2 C. Carbon pools of phytomass and soils would change most significantly in tundra and forest-steppe. Total decrease in carbon phytomass pool is equal 0.6% of its modern value, and decrease in soils pool is 2.2%.

Simulation model of soil organic matter dynamics

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SOMM is a simulation model of soil organic matter mineralisation, humification and nutrient release. The model takes into account the rate of the processes depending on nitrogen and ash content in the litterfall, temperature and moisture of litter and topsoil. The model is based on previously published data of laboratory experiments in controlled conditions and represents a system of linear differential equations with variable coefficients. The functioning of the major groups of soil decomposers is reflected in the model by six separate kinetic parameters. The results of the simulation show the applicability of SOMM for a wide range of environmental conditions from tundra to tropical rainforest on a daily time step. Model output represents the rate for the above-mentioned processes. The model can be used for modelling soil system and ecosystem dynamics at the site level, and at the landscape/regional levels after modification.

Soil organic carbon in a mountainous, forested region: relation to site characteristics

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Soil organic C content (SOC, kg C/m^2) and its relation to site characteristics are important in evaluating current regional, continental and global soil C stores and projecting future changes. Data were compiled for 499 pedons in the largely forested, mountainous western-Oregon region. SOC of mineral soil ranged from 0.9 to 24 kg C/m^2 (mean = 6.5) for 0 to 20 cm depth and 2.3 to 88 kg C /m^2 (mean = 15.8) for 0 to 100 cm depth. Variability in each of the three terms that determine SOC -- C concentration, bulk density and rock volume -- contributed substantially to SOC variation. Regression analysis of 134 forest pedons indicated combinations of site characteristics explained up to 50% of the SOC variability. SOC increased with annual temperature, annual precipitation, actual evapotranspiration, clay, and available water-holding capacity, and decreased with slope. Relations for western Oregon differed qualitatively and quantitatively from those for other regions and contrasted with the decrease in SOC associated with increased temperature in Great Plains grasslands. Of the variability not explained by regression analysis, half may be due to the combined uncertainty associated with measurements of C concentrations, bulk density, and rock volume; natural within-site variability; and site characteristic measurements. Other unexplained variability is likely due to potentially important but poorly documented site characteristics, such as recent vegetation composition, geomorphic disturbance regime, and fire history.

Forest inventory and planning in Russia: collection, processing and storage of information

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The Forest Fund lands of the Russian Federation are surveyed by 13 federal forest inventory and planning enterprises which are directly subordinate to the Federal Forest Service of Russia (Rosleskhoz).

In accordance with the Principles of Forest Legislation of the Russian Federation, the inventory and planning system is determined by the Rosleskhoz. The Russian Forest Fund lands are studied using three methods: ground-based surveys, aerial photo- and satellite image-based statistical analysis, and aerial visual observation. On the basis of the ground-based inventory, a document of project organization and development is compiled for each forest management unit (leskhoz). As a rule, these project documents are compiled every 10 or 15 years. They include data on leskhoz forest lands, changes in inventory, on leskhoz district economics, local forest use history, harvest volumes, forest management recommendations for the current period, and a forecast of changes in the forest lands if management recommendations are carried out. State-wide summary project documents are then compiled for Rosleskhoz.

According to the Principles of Forest Legislation of the Russian Federation, the document of project organization and development is an obligatory report, serving as a technical norm for planning and forecasting. The aerial photo- and image-based statistical evaluation and aerial visual study does not imply compilation of a project document for forest organization and development. The initial (primary) information, by the smallest survey unit is stored in data archives on storage media.

A federal forest census is performed by forest districts for forest management units, and by state-level units of the Russian Federation, for Russia as a whole. Forest census data include: distribution of forest lands by owner, land cover types, age classes, thinning, forest restoration, and other information. The federal forest census is carried out every five years. These data provide governmental forest management organizations at all levels with necessary information about forests, forest harvest levels, and management efforts.

Remote sensing in forestry and forest inventory.

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The total forest land area of the Russian Federation is approximately 1182 million ha, 65% of which is covered by closed forest stands with the total volume of wood of approximately 81.6 billion m^3. A small proportion of forest lands (81 million ha) is leased by various state committees, ministries and other organizations and 15 million ha by agricultural cooperatives. The State Forest Service controls 1167 million ha of forest land, including 756 million ha of closed forest stands with 79.8 billion m3 of wood. Almost all forests of Europe-Ural zone of Russia and especially, the forests of the Northwestern territories are the subject of active forest management including - harvesting, thinning, sylviculture, drainage, forest protection and others. In addition a large portion of the Europe-Ural forest zone is a subject of various disturbances: forest fires, industrial pollution, land-use change (power-lines, roads of various classes, non-commercial agricultural use (so-called week-end users), recreation and many other types of land-use category transformation). All these factors resulted in significant decrease of available forest resources in North-West forest zone of Russian Federation, and cause environmental inpact at the international scale.

The factors affecting the forests' growth and development may be classified into 4 groups: 1. The changes as a result of natural biological and climate factors, such as: changes of species areas, land-use transformation within forest land categories, tree-stands parameters changes. These are especially important for non-mature tree-stands, clearcuts, unused agricultural lands and other land categories capable of quick transformation. 2. The changes after abnormal spontaneous and biological features: windstorms, insect invasions, hydrology regime changes etc. 3. The changes as a result of various kinds of management activity: harvesting and reforestation, drainage, fields and soils protection, forest plantation organization, thinning, industrial land-use and many other ways to change a land category. These kinds of changes are well represented in European forests of Russia. 4. The changes as a result of forest fire influence. Forest fires are able to totally change the structure of forest lands of huge territories, especially in the zone of extensive forestry, in the distant and partly inaccessible areas.

These reasons make the necessity of monitoring and permanent mapping of forests obvious. Forest cartography in Russian Federation is the responsibility of special cartography-geodesic divisions of regional forest inventory enterprises and is based on remotely sensed data for both topographic and information purposes. About 95% of annual forest inventory work (nearly 40 million ha) is usually done on the basis of aerial and satellite imagery interpretation, primarily photographic materials. Forest inventory uses aerial photoes in European zone and both aerial and satellite photos in Siberia. The most useful materials for forest mapping are aerial and satellite black-and-white, color spectrozonal (an infrared sensitive film) and multiband images. High resolution, good geometric features and interpretation possibilities made these pictures the most suitable for forest mapping - about 60% of the information needed for thematic forest mapping may be extracted by professional interpretation (in some cases - about 90% of special information may be extracted directly from the photos). A wide range of aerial and satellite photos for different scales are used for forest mapping. In order of their value for forest professional or inventory mapping (but not for the mapping of forest lands from the geographic point of view) these data sources are: -overlarge scale - 1:2,500 and more; -large-scale - 1:2,500 - 1:10,000; -middle-scale - 1:10,000 - 1:30,000; -small-scale - 1:30,000 - 1:50,000; -over-small scale - 1:50,000 and less; -satellite photos - 1:80,000 - 1:2,500,000 (original and enlarged).

For the specific forestry and forest industry purposes forest inventory enterprises have to produce a set of forest maps in order to meet the needs of forest enterprise or forest industry organization. All basic and thematic maps for forestry, environmental protection, and forest industry include: 1). The set of forest inventory basic maps (rangers' and technicians' maps), the file for any forestry and forest industry activity registration during 10-12 years inter -inventory period. 2). Tree-stands and land categories maps for the forest enterprise and for the forest management units (forester's maps) including: a - Maps of forest inventory project realization; b - Harvesting maps; c - Maps of berry-fields, herbs, edible mushrooms, and vegetation of special values; d - Tree-stands maps of the forest enterprise and forest management units subdivisions; e - Forest sites maps and the other thematic maps of forest enterprise to meet special requests of the forest service; f - Schemes of forest inventory objects (small-scale); g - Regional and republican maps of forest resources and some other cartographic presentations of requested information.

First-class forest inventory mapping is usually based on the materials of field work and the results of interpretation of large-scale color spectrozonal 1:10,000 aerial photos. Many problems of forestry and forest industry (previous activity evaluation, forecasting etc.) have to be decided with the small-scale mapping assistance. For these special purposes the unified technology of forest mapping was produced. The system is based on the multistage system of collection and processing remotely sensed data with selective ground control. The technology includes: 1) - First step - satellite imagery processing with the topographic base of map organization, topographic and thematic interpretation of all mapped territories with the black-and-white and color-multiband photos. 2) - Second step - airborne (aerial photography and control flights for the results of satellite photos interpretation verification). Collected data are adequate for both large and middle-scale forest mapping. 3) - Third step - field work, so-called ground truth data collection.

Topographic maps are very helpful to deliniate landscape features that helps us to classify the terrain into relatively homogenous objects of interpretation. This means that for successful mapping it is necessary to have set of topographic maps and color spectrozonal or color multiband photos taken in the proper season. Resolution of remote sensing materials have to be in accordance with the scales of future maps (1:2,500,000 - not less than 100 m; 1:1,000,000 not less than 30-50m; 1:500,000 - 1:200,000 not less than 20 m).

Use of remote sensing to model landuse effects on carbon flux in forests of the Pacific Northwest, USA

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Reducing the uncertainty in the global carbon budget will require better information on regional carbon budgets. We discuss the use of a simple "metamodel", in conjunction with satellite data, to quantify carbon flux from a 12,000 km^2, forest-land study area in Oregon. The model tracks carbon storage in living, detrital and forest products pools. Between 1972 and 1991, total carbon flux from this study area to the atmosphere averaged 1.13 Mg/ha/yr with values ranging from -4.7 to +15.8 Mg/ha/yr. This spatial variability was related to site quality, land use and historical factors. These results are used to illustrate the natural and anthropogenic sources of heterogeneity that can influence carbon budgets at the regional scale and how remotely sensed data can be used to help quantify this heterogeneity.

STANDCARB: a model to simulate stand level carbon dynamics

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STANDCARB, a new model to simulate the accumulation of carbon over succession in mixed species, mixed-aged forest stands is described. The approach used in STANDCARB is to utilize the features of a gap model to simulate species composition and an ecosystem "process" model to simulate the growth, mortality and decomposition of plants within a plot. STANDCARB uses a number of levels of organization to follow changes in carbon stores. Each stand is comprised of a number of **cells**, each of which contains up to four **layers** of vegetation, six **detrital pools** and a **stable soil carbon** pool. The four layers of vegetation that can occur in each cell are upper trees, lower trees, shrubs, and herbs. The two tree layers can have different species, whereas the shrub and herb layers are viewed as single "species". Each cell can have any combination of layers except that lower trees can only occur when upper trees are present. Each of the layers can potentially have six live **parts**: 1) foliage, 2) fine roots, 3) branches, 4) sapwood, 5) heartwood, and 6) coarse roots. Each of the live parts of each layer contributes material to a corresponding detrital or dead **pool**. Thus foliage adds material to the dead foliage, fine roots to the dead fine roots, branches to dead branches, sapwood to dead sapwood, heartwood to dead heartwood and coarse roots to dead coarse roots. Finally, all the detritus pools in a cell can potentially add material to a stable soil pool. The model can be used to investigate the stand level effects of various regeneration strategies, effects of thinning, patch cutting, tree species replacement by design or by natural succession, site preparation, and wildfires. As with gap models, a simulation run does not consist of a single plot, rather a stand is simulated by running many replicate plots or cells which are then averaged to predict stand level means and standard errors for each year.

Woody detritus dynamics and stores: a comparison of Northwest Russia and the Pacific Northwest of the USA

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Our study examines dead wood dynamics in a series of permanent plots established in closed, productive second-growth forest stands of northwest Russia and in temporary plots that represent different successional stages and types of disturbance. Dead wood stores measured on 63 plots 0.2-1.0 ha in size range from 1-8 MgC/ha in young to mature intensively managed stands, 17 MgC/ha in an old-growth forest, 20 MgC/ha on a clear-cut, and 21-39 MgC/ha following a severe windthrow. A total of 122 logs, snags, and stumps aged by long-term plot records was sampled for decay rates and to develop a system of decay classes. Annual decomposition rates are: 3.3% for pine, 3.4% for spruce, and 4.5% for birch. Based on these decay rates the average residence time of carbon in the dead wood pool is 22-30 years. The mortality input on the permanent plots was 23-60 MgC/ha over 60 years of observation or 15-50% of the total biomass increment. These data suggest a dead wood mass of 10-22 MgC/ha would be expected in these mature forests if salvage had not occurred.

In old-growth forests, dead wood comprised about 20% of the total wood mass, a proportion quite similar to the larger, more productive forests of the Pacific Northwest (USA). If this proportioning is characteristic of cool conifer forests, it would be useful to estimate potential dead wood mass for old-growth forests without dead wood inventories. However, the use of a single live/dead wood ratio across the range of successional stages, a common practice in carbon budget calculations, may substantially over- or under-estimate the dead wood carbon pool depending upon the type of disturbance regime. Intensive forest management including short harvest rotations, thinning and wood salvage reduces dead wood carbon stores to 5-40% of the potential level found in undisturbed old-growth forest. In contrast, natural disturbance increases the dead wood carbon pool by a factor of 2-4.

Wood decay by lignin-decomposing fungi in relationship to physical condition

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The decay of wood can be described by the following equation:

$$4\ C_6H_9O_4 + 25\ O_2 \dashrightarrow 24\ CO_2 + 18\ H_20 \quad [1]$$

It is easiest to determine the intensity of CO_2 emissions experimentally, but to use measurements of wood bulk density to calculate the loss of mass. An S-shaped curve appears to describe the kinetics of decay much more accurately than an exponential curve. The decay rate constant is (10^{-3} day^{-1}):

$$K_2 = Q/K_1 \times \rho/\rho_o \times (1 - \rho/\rho_o), \quad [2]$$

where:

Q - the intensity of CO_2 emissions, mg g^{-1} day^{-1};

$\mathbf{K_1}$ - is a constant, indicating how many parts of CO_2 are generated by the loss of one part of wood mass; according to equation [1], $\mathbf{K_1}$ = 1.82;

ρ_o and ρ - initial and current bulk density, g cm^{-3}.

Moisture and air content are also associated with bulk density, and K_2 can be expressed through them. For example:

$$K_2 = Q/K_1 \times (w_o + h)/(w + h) \times [1 - (w_o + h)/(w + h)], \quad [3]$$

where:

$\mathbf{w_o}$ and **w** - are initial and current absolute moisture of dead wood, %;

h - is a constant characterizing the moisture regime, dependent on the quantity of metabolic water released and retained after wood decomposition, %; according to equation [1], **h** = 56.

As demonstrated by calculations and measurements of the physical parameters of dead wood in natural conditions, $\mathbf{w_o}$ and **h** determine the rate and trajectory of change in the process of wood decomposition.

The role of mires in sequestering carbon in Northwestern Russia

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Mires are major carbon pools. Globally, mires cover 500 million ha and contain 300 Gt of carbon (Armentano 1980), while the mires of the former USSR cover 164.8 million ha, contain 214 Gt of carbon, and accumulate annually 52 Mt of carbon (Botch et al. 1994). Considering the significance of mires in carbon cycling, it is important to evaluate their role in carbon pools and flux in Northwestern Russia where mires cover 14% of the total land area or 2.18 million ha, including 1 million ha in the St. Petersburg region, 541.2 thousand ha in the Pskov region, and 641.6 thousand ha in the Novgorod region. These mires are estimated to contain 6,876 million tons of peat, of which 10.6 million tons are removed annually. About 85% of mires belong to raised bog type, 15% belong to fen type. Based on mire occurrence and type, 36 provinces can be identified in Northwestern Russia.

In Part 1 of my proposed study, the data on bog area, peat types and stores will be reviewed and updated. Carbon stores and flux will be calculated for each of 36 provinces. The data will be derived from mire maps of St. Petersburg, Pskov, and Novgorod regions and from peat inventories that include data on mire area, peat stores, etc. Part 2 will be dedicated to mire vegetation dynamics and productivity over 20 years. The data was collected on permanent plots near lake Ladoga (Nizhnesvirskii nature preserve) and in the southern St. Petersburg region in the Volkhov River basin. The plots were set up to study the dynamics of species composition and productivity, which depends on plant community type and annual variation of weather conditions. This data will allow us to revise the existing information on carbon accumulation in mires depending on weather conditions. Data on carbon stores and flux associated with mires will substantially improve regional estimates of carbon dynamics. Part 3 will concentrate on the decomposition of mire plants under different conditions (mire type, nutrient content and water balance). Decomposition of 15 plant species, including trees, shrubs, herbs and mosses, was studied in different mire types over a period of 10 years. This work indicates that decomposition rates depend on plant chemical composition and site conditions.

Dynamics of tree mortality in softwood and mixed softwood-hardwood stands

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Mortality is the result of competition between the trees in the process of growth. The study of mortality allows one to evaluate site productivity and the amount of wood that can be potentially utilized as well as refine our understanding of carbon and nutrient cycling. Information on mortality dynamics is necessary for designing forest management plans, for assessment of regional cycling processes, and for the development of forest monitoring parameters.

The most reliable methods to study mortality involve long-term observations on permanent plots (PP). This paper provides the results of observations conducted over 60 years in spruce, pine and birch stands of the Leningrad (now St. Petersburg) and Novgorod regions. In birch stands there is an understory of spruce. The PP are 0.20-0.25 ha. Data of short-term observations are used as well. Each permanent plot series consists of several thinned plots and a control plot, where the dead trees were removed, and on some control plots sample trees were cut in the end of the experiment with the purpose to evaluate wood quality and bole shape. Plots were remeasured once every 5 years, occasionally once every 10 years.

During the time of the experiment, distinct age dynamics of the tree mortality wood volume was not observed. One can see only a slight tendency of increasing mortality in pine stands. At the same time there is a considerable variation of mortality from year to year depending on the weather. The greatest variation is observed in birch stands. Among spruce stands weather conditions affect mortality mostly in young stands. As the growing stock increases with age the share of mortality decreases, but this tendency is not always noticeable because of the impact of weather. In stand from 20 to 100 years old the volume of mortality varies by species and depends on site conditions, on the stand origin and weather conditions. At the same time age dynamics are not observed. Similar result was obtained in Germany. Such stability makes management calculations easier. The share of annual mortality by volume and by number of trees decreases with age and with growing stock. The share of accumulated mortality in total productivity over the period of observations makes 21-32% of the gross wood production in pure softwood stands and in birch canopy. In a mixed stand and in spruce plantations it is greater. On lower productivity sites this share increases. The variation of mortality share in growing stock is similar. It is within the limits of 30-50%. Thinning significantly reduces both volume and share of mortality, they allow one to increase the total harvest, but have no impact on total productivity of pure stands unless they go beyond the permissible limits. Thinning increases productivity of mixed stands. Compared to published data on old-growth temperate forest the share of annual mortality (number of trees) in young forests is significantly greater, while the share of annual mortality in growing stock is smaller, assuming that weight ratio is approximately equal to volume ratio. On control plots mortality depends on site productivity. The larger a tree, the greater the probability of survival. Practically all trees with initial diameter less than average died by the end of the experiment. Thinning can only extend slightly their lives. Long-term observations over tagged trees allowed to simulate the probability of mortality and rank change of trees.

These studies prove the significance of mortality in total productivity of forest stands, in carbon and nutrient cycling. Accumulation of data on mortality rates and dead wood stores will allow more accurate estimates of dead tree role in forest ecosystems. Inventory methods of mortality evaluation in stands of different age do not yield reliable results. Inaccuracies are increased by lack of information on previous forest management activity.

Modeling growth dynamics of spruce stands and several conclusions regarding long-term thinning experiments

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Effective use of forest resources requires the development of various means of forecasting, including modeling methods. During the formulation of complex, multi-factor models of forest ecosystems, the first and most important stage is to model stand growth dynamics. Existing models are inadequate because they are based either on growth tables or on short-term observations. In the first instance, changes in site conditions within a stand during development are not taken into account, while in the second only the time period of actual stand observation is accurately modeled. Our modeling project is based on a 60-year time series of observations of the dynamics of stand parameters.

Inputs for mean (H) and maximum height (HB), mean diameter (D), height multiplied by a form coefficient (HF), and total productivity (TP) were estimated using the Drakin- Vuevskii equation:

$$y = a_o(1-e^{a1x})^{a2},$$

where y is any of the above listed variables and x is stand age.

Estimation of basal area (G) was made using a 3rd order polynomial, having the following form:

$$y = a_o + a_1x + a_2x^2 + a_3x^3,$$

where y is basal area and x is stand age.

The model coefficients were determined by regression. An estimation error was calculated for each indicator. The error never exceeded 2.9%, and in most cases was less than 1%. In this manner, the selected models describe the growth dynamics of parameters of spruce stands quite well. It is worth noting that the greatest forecasting will be for stand dynamics for the period of time of observations on the permanent plots.

On the basis of the model results, a growth table was assembled for each experimental plot. Stand growth dynamics can be modeled for any time step. The models permit us to fill in data gaps in the time series, which arose for a number of reasons. It is also possible to hindcast stand dynamics prior to the beginning of long-term plot observations, and to forecast into the future. It is true, however, that the accuracy of these prognoses will be lower than those for the time period covered by the data. Future research on the permanent experimental plots will improve model accuracy and permit us to cover a longer time period with accurate forecasts.

Aside from modeling, the long-term observations on the permanent plots have allowed us to make some interesting conclusions:

1. In high productivity conditions (spruce-Oxalis forest type) there is an increase in site index on the order of 1-3 classes during stand development. This increase is not taken into account in growth tables, which leads to errors in forecasting stand productivity.

2. Growth increments are variable over time. Thinning initially increases the amplitude of the variability, which then diminishes until the next thinning. This characteristic change is evidence of the resilience and self-regulatory nature of forest ecosystems. Peak growth increments in pure spruce stands occur at age 50-65 years. On thinned plots, the maximum increment during this period is greater in absolute terms, than on the control plots.

3. In mature stands, there has been an observed increase in annual growth increment in growing stock at 90-100 years. Additional research will need to be conducted to explain this occurrence. It is possible that climatic conditions led to this increased growth increment.

4. Stand density does not affect total productivity.

5. At maturity, a stand consists 90-95% of the trees, which at 40-45 years had a relative diameter close to or greater than the mean. In other words, those trees which lagged in growth were, as a rule, the ones that died.

6. Thinning permits almost complete elimination of mortality.

7. In the process of stand development, environmental site factors change in the direction of richer forest types.

8. Real changes in soil pH related to thinnings were not observed. This provides evidence about the stability of spruce ecosystems on drained habitats in the southern taiga with regard to thinnings.

Modeling long-term patterns of tree utilization in the Pacific Northwest, USA

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We have developed a model, called HARVEST, which predicts the mass of woody detritus left after timber harvest in the Pacific Northwest forests. Inputs to the model include the species, diameter and age distribution of trees, the minimum tree size to be harvested, the species, diameter and age distribution of trees, the minimum top diameter, stump height, and slope steepness. Model output includes the absolute and proportion of bole biomass removed as well as that left as stumps, tops, breakage, and decay. The model also predicts the biomass of non-merchantable parts such as branches, coarse roots and fine roots left after harvest. We used the model to predict changes in the biomass left after harvest in Pacific Northwest forests from 1910 to the present. Model predictions were significantly correlated to residue levels reported in the literature over this period. Both model output and historical data indicate that the total amount of above-ground woody residue left after logging has decreased at least 25% over the last century. This means that release of carbon to the atmosphere and nutrients to the soil from woody residue has decreased a similar amount.

The accumulation of carbon in forest products in the Pacific Northwest, USA

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A new model, FORPROD, is used to estimate the carbon stored in various forest products within the Pacific Northwest. FORPROD considers two aspects of this problem: the manufacture of raw materials (i.e., logs) into products and the fate of these products during use and disposal. Historical patterns of raw log harvest, manufacturing efficiencies, product use, and disposal were used to estimate the accumulation of forest products related carbon in Oregon and Washington from 1900 to 1992. Pools examined included long- and short-term structures, paper supplies, mulch, open dumps, and landfills. Our analysis indicates that of the 1692 Tg of carbon harvested during this period, 396 Tg or 23% is estimated to be currently stored. Of the forest products currently stored, Long-term structures and landfills comprise the largest fraction, storing 74 and 20% of the harvested carbon, respectively. Landfills currently have the highest rates of accumulation, but total landfill stores are relatively low because they have only been used in the last 40 years. The majority of carbon release occurred during the manufacturing process, with 45-60% lost to the atmosphere depending upon the year. Sensitivity analysis of recycling, landfill decomposition and replacement rates of long-term structures indicated these parameters could be changed by a factor of two and change the estimated fraction of total harvested carbon stored less than 2%.

Effect of dendrophagous insects on carbon cycle

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Net Ecosystems Production (NEP) is determined by the difference between the Growth Primary Production (GPP) and Total Respiration of a system, R, (Kobak, 1988). Outbreaks of dendrophagous insects lead to severe or total defoliation of trees, or their dieback, over large areas. In these situations, GPP decreases almost to zero in taiga ecosystems, and R increases due to the growth of the number of heterotrophs such as invertebrates (annelids, nematode worms, and so on), fungus, and microorganisms living in dead organic material, leaves, or pest excrements.

There are three groups of pests in Russian boreal forests which can cause outbreaks and affect carbon balance. 1. **Leaf-eating moths.** Outbreaks of *Leucoma salicis L., Euproctis chryssorrhoea L. (Orgyidae), Malacosoma neustria L. (Lasiocampidae), (Tortricidae),* and other leaf-rollings species are mostly known (Ilinskiy and Tropinin, 1965). In the majority of cases, forests do not die after outbreaks of these pests. Some specialists believe, however, that they can be the main cause of dieback of deciduous forests. For instance, outbreaks of Gypsy moth (*Lymantria dispar L.*) and leaf-rolling moth (*Tortrix viridana L.)* in 1991 alone caused dieback of deciduous forest in Russia over the areas of 12 and 51 thousand of hectares, respectively (Krankina et al. 1994). 2. **Needle-eating moths and sawflies.** With regard to the carbon balance, the most important species of all is *Dendrolimus sibiricus L.* (Lasiocampidae). As a result of the outbreaks of this species from 1870 to 1964 coniferous forests died on more than 13 millions hectares. Outbreaks of moths *Panolis flammea Schiff. (Noctuidae), Bupalus piniarius L. (Geometridae) and Neodiprion sertifer Geoffr. (Tenthredinidae)* in the Europe-Ural region of Russia caused forest dieback on 0.8, 2.1 and 18.5 thousand of hectares, respectively. *Dendrolimus pini L. (Lasiocampidae), Lymantria monacha L. (Orgyidae)* and other species from this group may also kill coniferous forests on large areas (Ilinskiy and Tropinin, 1965). 3. **Bark - beetles.** Outbreaks of these pests cause forest dieback. *Ips typographus L., Pityogenes chalcographus l., Tomicus piniperda L., Dendroctonus micans Kugel.*

and some species from family *Cerambycidae* are the most important (Kataev, 1983). For instance, outbreaks of *Ips typographus* resulted in dieback of spruce forests in Saxony and Thuringia in 1947 and 1948 on 13.5 thousand of hectares (Quaschik, 1953), and in the European part of Russia in 1991 on 8.5 thousand of hectares (Krankina et al., 1994).

Existing data allows to estimate the effect of outbreaks of insects on NEP in framework of the StandCarb model. For this it is necessary to determine the following: 1. - areas of forest where leaf longevity is greatly diminished; 2. - the time by which the functioning of leaves is shortened; 3. - the area of forest dieback after outbreaks.

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The ratio of sapwood to heartwood in a mixed age spruce stand

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The axial organs of woody plants (boles, roots and branches) serve as different types of pools, where the basic reserve of most of the organic matter in the ecosystem is stored. Most of the species in the taiga zone, beginning at a certain age, form and accumulate ripe wood, or heartwood. The peculiarity of heartwood is that it does not participate in vital processes and has, in comparison to sapwood, a lower moisture content and poor penetrability for water and gases.

Spruce is a ripe-wood species. In every individually taken bole the ratio of heartwood to sapwood is different and depends on age and growth rate. The formation of heartwood begins between 6 and 14 years, when the diameter of the bole reaches 4 to 6 cm. The proportion of heartwood increases with age. The ratio of heartwood to sapwood also changes with bole height (see table). The proportion of heartwood is greater in the branches than in the boles at the same point in time. At the same age, samples of branch diameter were 3-6 times less than the diameter of boles.

When studying the gas exchange of axial organs, it is essential to consider only the physiologically active wood, or the sapwood. For this reason it is essential to establish the proportion of heartwood to sapwood. Heartwood content can be determined with acceptable accuracy and little effort by measuring bole diameter and tree age. It is known that at the same diameter, the sample with a higher proportion of heartwood is the one which is older. At the same age, the proportion of heartwood is greater in the sample whose diameter is smaller.

Table. The Distribution of Phytomass in a Spruce Bole by Functional Element (tree height 23.6 m, age 76 yrs)

Height from root line (m)	Age of section (yrs)	Diameter of section w/o bark (mm)	Ratio of bark to mass (% of total)	Ratio of sap-wood in cross-section (%)	Ratio of heartwood (%)
0.3	74	250	11.4	22.6	77.4
1.0	70	215	6.8	17.8	82.2
4	65	200	5.8	19.0	81.0
7	59	185	5.7	25.0	79.5
10	53	168	7.2	30.6	69.4
13	48	148	8.2	39.6	60.4
15	43	125	9.1	42.2	57.8
17	37	105	8.1	49.0	51.0
19	30	75	8.5	64.0	36.0
21	20	45	12.1	69.2	30.8
22	13	28	18.5	91.8	8.2
23	5	16	28.2	100.0	0

Biomass of lower canopy layer vegetation in relation to the association structure of a spruce forest

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The species diversity and abundance of plants in the lower layers characterize the soil-ground conditions and are structural elements of the system. Forest plant ecosystems are comprised of various ecobiomorphs. Their role in the functioning of the whole system is determined by position, active surface area, and the biomass of the individual species.The dominant and edaphic species in the tree canopy is spruce, comprising 90% of the biomass of the system. Vegetation in the lower canopy layers makes up only 1.5% of the total biomass (Table 1).

Table 1. The life forms in a spruce forest.

Plant life forms	**Dry biomass**	
	T/ha	**%**
1. Trees: spruce	163.50	90.30
other species	14.80	8.20
2. Shrubs	0.20	0.11
3. Low shrubs	0.15	0.09
4. Herbs	0.60	0.33
5. Mosses and lichens	0.71	0.39
Spruce undergrowth	1.01	0.56
Spruce natural regeneration	0.02	0.01
Total	**180.99**	**100.00**

However, the understory play a significant role in the functioning of the forest ecosystem, due to the rapid regeneration of phytomass through the short nutrient cycle turnover period. The relative abundance and organizational structure of the lower layers are controled by spruce. The plant association structure consists of primary and secondary associations (Table 2). The appearance of

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secondary plant associations is related windthrow and tree mortality (snags). Primary plant associations are predominant, and they reflect the site conditions. The species composition of lower canopy layers is richer in primary plant associations. The vertical profile of the associations is diverse. The most complex profiles are characteristic of associations with representation from all canopy layers: understory, shrubs, and live ground cover.

Table 2. Number of species and abundance of plants in the lower canopy layers of a spruce forest

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Associations	Understory		Shrubs		Live ground cover	
	# of species	#, in thous.	# of species	#, in thous.	# of species	projected cover, %
1. Spruce-mountain ash	3	9.2	1	0.2	17	70
2. Spruce-spruce fern	4	0.8	4	0.6	15	98
3. Spruce-aspen	8	2.6	5	0.5	24	87
4. Spruce-birch	8	3.1	5	2.1	28	91
5. Spruce-mixed grass	7	2.7	3	1.1	26	94
6. Windthrow gaps	2	0.4	-	-	12	100

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New data about the role of CO_2 in soil air for tree growth

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It is known that the CO_2 content in soil air is determined by the quantity of organic matter and the conditions of air exchange. For this reason, the largest concentrations of CO_2 are characteristic of turf soils. As a result of draining forest mires, the concentration of CO_2 in soil air, as a rule, increases. The richer is the turf in its botanical composition, the higher the CO_2 content and the better the tree growth. This apparent paradox inspired us to organize special field experiments on the artificial enrichment of soil air with carbon dioxide gas. Multi-year observations of tree growth in these conditions has shown that at a CO_2 content 3-5 times greater than the control level, growth increments in height increased on average 1.5 times (pine) and 4.4 times (spruce). Our experiments and a review of the most recent published data demonstrate that CO_2 does not appear to be toxic to tree roots, as was earlier believed. Evidently even quite high concentrations of CO_2 in soil air appear to be an important ecological factor in tree growth. It is imperative to continue and broaden the experiments with the goal of revealing the dependence of tree growth on gaseous factors in soil air.