MOSCOW STATE FOREST UNIVERSITY

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS

D.G. Schepaschenko, A.Z. Shvidenko, V.S. Shalaev

BIOLOGICAL PRODUCTIVITY AND CARBON BUDGET OF LARCH FORESTS OF NORTHERN-EAST RUSSIA

(Abstract in English)

Schepaschenko D.G., Shvidenko A.Z., Shalaev V.S.
Biological productivity and carbon budget of larch forests of Northern-East Russia. – Moscow: Moscow State Forest University, 2008. – 296 pp.

The book contains a multi-aspect analysis of the current state of forest resources of the Russian North-East based on diverse experimental and inventory data. Ecological and geographical peculiarities of the larch forests are described for Saha Republic, Magadan oblast', Korjak and Chukotka Autonomous okrugs. The system of models which tie together biometric indicators of larch ecosystems in static and dynamics is presented. The dynamics of carbon sequestration by different components of larch ecosystems is quantified. The full carbon budget of larch ecosystems of the study's region is estimated for the period of 1993-2003.

The book is addressed to forest managers and forest inventory experts, ecologists, and global change community.

2008

1. Ecological characteristics of the Northern-East Russia

Northern-East Russia is represented by a combination of mountain ranges and hilly table-lands and swamped plateaus between the ranges. The territory of the region is dissected by rivers Jana, Indigirka, Kolyma, and Anadyr and their tributaries. Diverse elements of relief are presented there – from high mountains (above 3000 m a.s.l.) to vast lowlands at the altitude of 50-100 m a.s.l.

Major part of the region has a very continental climate. The maritime regions are under the impacts of Bering and Okhotsk seas with their cold currents. The amount of precipitation does not exceed 300 mm over a major part of the territory, and the annual average temperature is below -10 °C. The Northern pole of cold (with the absolute minimum of -71 °C) is situated in the central part of Jakutia (settlement Oimjakon).

Cajander's larch (*L. cajanderi* Mayr) is the dominant tree species in Northern-East Russia. Over the areas to south-east from River Lena, it is replaced by Gmelin's larch (*L. gmelinii* (Rupr.) Rupr). Larch is a very plastic tree species and grows well under diverse climatic and soil conditions. Because larch is a deciduous species, this allows it to survive under extremely low temperatures and lack of humidity. Larch is the most light-requiring species among all major forest forming species of Northern Eurasia.

The severe climatic conditions cause a low diversity of formation and typological structure of the larch forests and sparse woodlands of Northern-East Russia. Sparse forests and woodlands with small shrubs, lichens and mosses dominate over the entire region. Larch groups of associations with small shrubs and green mosses grow in river valleys, and ones with *Sphagnum* and *Ernics* (shrub birches) – over swamped parts of relief. Altitudinal zoning of forest types is expressed well. The understory of larch forests is represented by *Pinus pumila*, *Salix hastate*, *S. oblongifolia*, *Betula Middemdorffii*, *Duschekia fruticosa*, *Rosa acicularis*. The green forest floor is represented by different combinations of *Calamagrostis langsdorfii*, *Pyrola incarnata*, *Carex accrescens*, *C. lugens*, *Eriophorum vaginatum*, *Vaccinium uliginosum*, *Vaccinium vites idaea*, *Empetrum nigrum*, as well as by lichens of genus *Cladina*, *Centaria*, *Cladonia*, and mosses of genus – *Aulacomnium*, *Pleurozium*, *Dicranum*, *Hylocomium*, *Ptilidium,* and *Sphagnum*.

The soil cover on gently sloping elements of relief is represented by Thixotropic and Histic Cryosols. Leptosols, Cambic Podzols and Gelic Cambisols are usual on slopes dependently on stonyness and amount of precipitation. Over the east coast Gelic Podzols and Gleyic Stagnosols are also occur.

Over major part of its growing area, Cajander's larch forms typical for the extreme Siberian North sparse forests and open woodlands with growing stock volume 10 to 60 $m^3 \cdot ha^{-1}$. Highly productive stocked stands are developed in more favorable conditions of river valleys. The growing stock of such stands can reach up to 500-700 $m^3 \cdot ha^{-1}$ in southern parts of the region.

Percent of forest cover of the region comprises 38.4 %. The forested area comprises of 357.9 million ha on which it is accounted for 9990.8 million m^3 stem wood. Larch is an absolutely dominated species in the region (88.9 % by area and 84.4% by growing stock) following by pine (11.4% by growing stock). Mature and overmature stands cover 46 % of the territory. However, there is a substantial share of young forests – 21 %. Average site index of larch forests in the region is V.3 and average relative stocking – 0.51. By types of age stand structure, relatively uneven-aged stands mostly dominate in central and southern parts of the region, and uneven-aged stands dominate in the southern part.

Under the harsh climatic conditions, the input of organic matter into litter is much more intensive than its decomposition. Accumulation of organic matter leads to regular and intensive forest fires. Accounting for the fire scars on cross-sections of tree stems show the fire frequency (fire return interval) of 50 to 100 years dependently on site conditions. Fire is one of major driver of age stand structure and spatial distribution of the forests in the region.

Forests and woodlands of high latitudes maintain a fragile equilibrium of natural processes and hinder from degradation of northern landscapes. Forests provide natural environment for aboriginal nations. They are an inalienable background for preservation of their national culture and traditional activities (reindeer-breeding, hunting, fishery). The biospheric role of forest ecosystems of the extreme North is also very important.

2. Larch forest carbon pool

This Chapter contains assessment of live biomass (phytomass) of larch ecosystems of the Russian North-East. A special database of phytomass measurements in Russian forests was developed. The DB also contains detailed biometric characteristics of forests in which the sample plots were established. Currently the database comprises about 4000 sample plots (of which 366 are in larch forests) which were established in territories of the former USSR. The database also includes results of measurements which were provided by the authors of this book in larch forests of northern-eastern Jakutia.

Models of phytomass fractions (stem wood over bark; bark of stems; wood of branches over bark; foliage; roots; understory; and green forest floor) were developed in form

$$R_{fr} = {M_{fr}}/{GS} = c_0 \cdot A^{C_1} \cdot SI^{C_2} \cdot RS^{C_3} \cdot EXP(C_4 \cdot A + C_5 \cdot RS),$$

where M_{fr} – phytomass fractions; GS – growing stock volume, m^3/ha; A – age, years; SI – site index; RS – relative stocking; $c_0, c_1, \ldots, c_5, \ldots$ – parameters of the models.

For understory and green forest floor, M_{fr} instead of R_{fr} has been modeled. Coefficients of the models are presented in Table 2.3.

It is shown that the models developed are statistically significant at 0.05 level and adequately describe the experimental data.

Using the State Forest Account-2003 and developed models, we estimated the amount of live biomass in forests of the Russian North-East. Of the total 7.525 Tg C (or 3.15 kg C m^{-2}), 50.6% are in stem wood, 25.4% in roots, 8/3% in branches, 1.8%

in needles, 2.5% in understory, and 7.4% in green forest floor. Spatial distribution of average phytomass' density is presented in Figure 2.1.

3. Growth and productivity of the larch forest

The Chapter presents models and tables that describe growth and biological productivity of larch forests of the Northern-Eastern Russia. The results discussed in the Chapter are part of a system consideration of the problem for all Russian forests.

Traditionally, the major tool for description of regularities of growth of stands in Russia is growth (yield) tables which contain dynamics of major biometric indicators of stands (average height and average diameter of trees at breast height; basal area; growing stock volume; net and gross growth; mortality) by site indexes or forest types. There are different types of growth tables (GTs) in Russia – general and regional, for normal (fully stocked) and modal (actual) stands. Usually GTs are presented in a numerical form, and the modeling basis of these is very weak or not reported. We provided a comprehensive analysis of GTs that have been developed for the study's region using all available normative and experimental information and developed unified growth models for larch forests of the region. The methodology of the approach and details are available from [Shvidenko et al., 2007]. The Richards-Chapmen growth function has been used as the analytical basis of modeling.

Two regionally distributed models of fully stocked stands and 6 models for modal stands are recommended for the region (parameters of the models are presented in Table 3.2 and a numerical representation of the models – in Appendix B and http://www.iiasa.ac.at/Research/FOR/forest_cdrom). These models describe age development of larch stands by site indexes (stands from IV (rarely III) to Vb site indexes grow in the region). The major driver that affects structure and growth of the larch stands is fire regimes, which are closely tied with landscape specifics and hydrological regimes of sites. The post fire regeneration of larch is intensive that results in forming of rather dense young stands. However, further ground (non-stand replacing) recurrent fires substantially decrease density of larch stands, and the relative stocking after 50-60 years rarely exceeds 0.5-0.6, often less. Dependently upon site specifics and connected to these severity of ground fires, the destruction of the modal stands (i.e. decreasing the basal area and growing stock volume with age) is observed from 120-150 years. Such a development defines specifics of major biometric indicators of stands like growing stock, net and gross growth, mortality etc.

Taking into account peculiarities of structure and growth of larch forests on permafrost (a close interconnection between productivity of forests and landscape specifics; high heterogeneity of mosaic structure of stands; crucial impacts of fire regimes), an attempt of development of growth models on a soil-typological basis has been done. These models are considered as a first stage of development of models of growth which would be most suitable for permafrost conditions under climate change.

Using the developed growth models and models of live biomass dynamics (Chapter 2), models of biological productivity (MBPs) of larch ecosystems of the region have been developed (http://www.iiasa.ac.at/Research/FOR/forest_cdrom). This is a first attempt of development of MBPs for the region. MBPs contain dynamics of live biomass and Net Primary Production for the growth models described above. Live biomass is presented by major fractions (stem wood over bark; bark; wood of branches; needles; roots; understory and shrubs; green forest floor).

The dynamics of live biomass follow major regularities of formation and growth of stands. The maximum of the total live biomass of modal stands is observed at 120-150 years; however, these maximums are not clearly expressed, particularly for forests of low productivity (V-Vb site indexes). Age dynamics of individual live biomass components are components specific. Indicators of biological productivity of fully stocked stands show that suppression of fire regimes could substantially increase amount of carbon stored in larch forests of the region.

Dynamics of NPP have been modeled based on an original algorithm that simulates the growth process of total production of live biomass. NPP is rapidly growing at the first development stages of stands and reaches the maximum at 60-80 years, and for about 20 years later for forests of Va-Vb site indexes. After 120-150 years, NPP slightly decreases, as a result of two contradictory processes – decreasing of NPP allocated in trees and increasing NPP of understory, shrubs and green forest floor.

The method that was used for assessing biological productivity of forests has no recognized systematic errors. In order to estimate the impacts of the amount of experimental data on accuracy of the models of biological productivity, a special simulation procedure has been examined. It is shown that increase of experimental data to a definite limit decreases the uncertainties of the results; further increasing of the amount of data does not decrease the errors significantly. Availability of about 300 sample plots (such an amount was available for modeling of live biomass of larch forests) allows to provide an acceptable level of accuracy.

The developed system of the above mentioned models accumulated available knowledge on growth and productivity of larch forests of the region in a formally well-ordered and operational form. The system makes it possible to introduce physical indicators of environment (temperature, humidity etc.) in traditional empirical growth models that is important in conditions of changing environment.

4. Global change and Northern-East larch forest

Major elements of global change in the study's region include climatic change, environmental changes (basically increase of atmospheric CO_2 concentration, industrial air pollution and water contamination), as well as increasing anthropogenic pressure on natural landscapes. This Chapter analyzes climatic change in the region during several last decades and presents a forecast for 2020 and 2050. The latter is done by using one of widely recognized GCM (HADCM3). According to this forecast, significant warming is expected in Northern-East of Russia. The increase of precipitation is also expected. However, the increase of precipitation across the continental territories of the region will not be enough to compensate the increase of temperature. It means that the increase of climate aridity is expected, particularly during the growth period. Very likely, thawing of permafrost will also impact the hydrological regime on large territories in a mostly negative way and will accelerate the processes of aridization. Substantial increase of thermoerosion and physical destruction of landscapes are expected too.

The future trajectories of dynamics of larch forests under climate change are estimated based on a classification of these in coordinates of heat and humidity. Distribution of forests by elements of relief also plays a substantial role. Most favorable conditions for growth of larch forests are expected in best (under current climate) sites. The substantial increase of productivity of forests is expected here. Shift of forests in non forest territories that is already observed will continue. However, this process is very slow and may occupy substantial areas over very long periods of time that is measured by centuries.

Major part of the region will be exposed to negative impacts connected to increasing climate variability, more frequent and severe climatic anomalies, increasing water stress. Very likely, these climatic peculiarities will cause a dramatic increase of natural disturbances – wild fire over the entire area of the region and insects' outbreaks in its central and southern parts. Unregulated anthropogenic impacts will accelerate the unfavorable consequences of climatic change. Eventually, all this together generates a threat of impoverishment and degradation of forests over vast territories including the processes of northern steppization and green desrtification.

The forests of Northern-Eastern Russia require development of special systems of forest management. The systems should be regionalized taking into account the specifics of individual parts of this vast region, as well as the specifics of global change within those. The overall background of such systems should be based on philosophy, criteria and indicators of the paradigm of sustainable forest management. These systems should be oriented to a special preparation of forest landscapes of the region to global change that would allow to mitigate the negative consequences of global change. Maintenance and increase of biospheric services of forests (particularly, carbon sequestering), as well as the services of protection of environment and natural landscapes as a whole, generate the overall prerequisite of transition to sustainable forest management in the region.

5. Northern-East of Russia larch forest carbon budget

The Chapter contains the first attempt of estimation of the full carbon budget of larch ecosystems of the study's region. The estimation was provided for the period of 1993-2003. Two approaches have been used: 1) assessment of dynamics of major carbon pools (live biomass, dead vegetation organic matter, and soil organic carbon) and estimation of major carbon fluxes for 1993 and 2003 (Net Primary Production, heterotrophic respiration, fluxes caused by disturbances, and lateral fluxes into hydrosphere and lithosphere).

It is shown that the larch ecosystems of the North-East of Russia have lost 1.9 Pg C during the period of the assessment. The major reason of this is the decrease of the area of larch forests at 6.5 million hectares, basically due to acceleration of wild fires in the region. While the average vegetation biomass of the larch forests was increased at 0,36 t C ha^{-1} for the period, these dynamics have been caused by the increase of dead vegetation matter (+ 0,47 t C ha^{-1}). The average amount of live biomass on the forested area has decreased (- 0,11 t C ha^{-1}).

The average densities of major carbon fluxes (NPP and heterotrophic respiration) slightly increased during the period of 1993-2003. Although the share of Net Biome Production is relatively high (constituting about 15% of NPP), it is decreased for about one-fourth (from 0.48 t C ha^{-1} to 0.36 t C ha^{-1}) during the considered decade.

Uncertainties of the reported results (the change of the total carbon pool of the larch ecosystems for 1993-2003 and NBP for 1993 and 2003) were estimated in an expert way at the level of 30-40% that allows to make certain judgments about the impacts of larch ecosystems of the study's region on the global carbon budget.

Conclusion

This book describes the extent and distribution of larch forests of Northern-Eastern part of Russia, considers the specifics of forest forming processes and productivity, and quantifies the full carbon budget of this forest formation. The study's region includes four administrative regions of the Russian Federation – Republic Saha (Yakutia), Magadan oblast', Koriak and Chukotka Autonomous Okrugs. Larch forests of this region are purely understood in many aspects. They grow in the most severe climatic conditions under which forests exist over the globe. The most dramatic climatic change at the planet is expected there.

Theoretical and practical considerations and conclusions of this book are destined for improvements of current understanding of structure, growth and functioning of larch ecosystems of the region; understanding of major regularities of biological productivity; and for improving methodology and accuracy of account of the full carbon budget of larch forests taking into account requirements of the post Kyoto negotiation process.

Structure, growth and productivity of larch forests of North-East of Russia are defined by climatic peculiarities of the region, landscape specifics and by the regime of natural and human-induced disturbances, among which forest fires play the major and pivotal role. Similar regularities of growth and biological productivity of forests are recognized for the region. It allowed to develop a set of mathematical models of growth of larch stands, dynamics of live biomass and Net Primary Production (by major components). The models have satisfactory accuracy and adequacy that allows to recommend them for use in research and practical forest management.

It is shown possibility to develop unified growth models of larch forests using a site index (bonitaet) classification basis aiming at their use in forest inventory, as well as to develop ecological models oriented for assessing the impacts of forests on carbon budget. At the same time, taking into account specifics and high mosaic structure of larch ecosystems on permafrost, it seems promising a more complete inclusion of soil-landscape parameters in the process of modeling of growth and productivity of forests on permafrost.

Estimation of live biomass of forest ecosystems with an acceptable accuracy requires development of non-linear multi-dimensional models. As the input, these models should use biometric characteristics of stands which are measured by practical forest inventory: species composition, age, levels of productivity (site index classes) and relative stocking. Analytical form of the models should be able to describe non-monotonous dependences of live biomass components on variables used in the models. For this reason, traditional approaches that directly use traditional allometric regularities are not always appropriate for development of the adequate enough models.

A new approach, algorithms and software were developed for generating the models and tables of biological productivity of forest ecosystems. The latter includes age dynamics of live biomass and Net Primary Production of larch ecosystems by components and appropriate classification units (site index, forest type). The approach used did not have any previous analogues and is represented by a modeling system which allows consecutive improvement and modification of the models. In order to assess the accuracy of the models, the dependence of their accuracy on amount of experimental data used was quantified.

Dynamics of live biomass of larch forests by major components of live biomass (stem wood over bark; wood of branches; coarse and fine roots; needles; live biomass of understory, shrubs and green forest floor) reveal many specific features which are not resided for more southern taiga forests . In authomorphic conditions, the total live biomass of the ecosystems increases up to 160 years, independently on level of productivity (the range of productivity of larch stands in the region is from IV to Vb site indexes). This is mostly explained by increasing mass of aboveground wood which reaches maximum values at this age. The mass of needles arrives at the maximum for one to three age classes earlier, while live biomass of understory, shrubs and green forest floor continues to increase up to the destructive stage of the stands. Dynamics of live biomass of humid and swamped sites have many common features with upland forests. However, maximums of above ground live biomass of forests on wetlands are less pronounced and shifted to higher ages. This is why, accumulation of total live biomass in meso-hydromorphic and hydromorphic conditions, as a rule, do not reveal any maximum up to 200-220 years. The share of belowground live biomass is substantially higher than in larch forests of more southern latitudes. The share of the mass of fine roots in the total amount is higher than in more productive larch forests of the south and mostly depends on age and level of productivity of forests.

5. Growth and development of larch forests of the region reveal specific regularities of age dynamics of Net Primary Production (NPP), which rapidly grows at young development stages. NPP of modal stands of zones of forest tundra and northern taiga is estimated at 320 g C m^{-2} yr^{-1} by 20 years in stands of III and 160 g C m^{-2} yr^{-1} in stands of V site indexes. Later, the rate of the increase of NPP slows down substantially, reaching the maximum at 60-200 years dependently on specifics of sites and level of productivity. The major reason of such dynamics is peculiarities of post fire restoration of larch forests: very dense young forests are usually formed after fire, but following ground fires on permafrost kill a substantial part of trees of these stands.

6. Larch forests accumulated a significant amount of organic carbon in soil and vegetation. Under stands' development without catastrophic fires, larch ecosystems serve as a net carbon sink practically during all the period of life of stands (up to 200-250, sometimes 350-400 years), although the rate of carbon accumulation decrease substantially in old growth stands. The impacts of forest cover of large northern territories on the global carbon cycle are defined, to a significant extent, by disturbances regimes, mostly by wild fire. Fires that were occurring over the decade of 1993-2003 have decreased the forested area of larch stands of the region at 6.5 million hectares and substantially affected the carbon budget. The estimates of Chapter 5 show that Net Biome Production of the larch forests was negative (the emission to the atmosphere is estimated about 100 million ton carbon per year) and a soil carbon pool was significantly decreased. The expected climate change may dramatically accelerate this process. In addition, unexampled by area outbreaks of dangerous needlegnowing pests that occurred in northern larch forests during the recent decades allow to assume that also this factor will significantly impact stability, productivity and biospheric role of larch ecosystems of Northern-Eastern Russia.

The region's forests are practically unmanaged. Prospects of increasing intensity of forest management in the region are more than problematic in spite of the extremely important environmental role which forests play at the northern edge of their existence. Such a situation hinders introduction of any relevant activities destined to protection of the region's forests and increase of their biospheric role. Evidently, the most important strategic task of the region's forest management is improvement of forest fire protection. Such activities should be part of an anticipating program of preparation and possible adaptation of northern landscapes to negative consequences of climate change.

It has been shown (Chapter 5) that only the full carbon account (including both technosphere and biosphere) corresponds to the eventual goals of the UN Framework Convention on Climate Change. If future developments of the post-Kyoto international negotiation process will lead to a practical implementation of this principle, one could suppose that economic backgrounds for relevant carbon management would also arise in remote larch ecosystems of Northern-Eastern Russia.

Overall conclusions and recommendations on improvements of forest management in the region could be expressed as the following.

- Larch forests continue to sequester carbon over the entire life period of the stands. Thus, the system of forest management should be oriented at a possible prolongation of the life cycle of larch stands including improving forest protection, increasing rotation period in exploitable forests, etc., that would increase resident time of carbon in the ecosystems.
- Low productive northern larch forests that are excluded from industrial exploitation due to economic (or ecological) reasons, are able to provide a substantial sink of carbon. However, in order to provide effective and stable carbon sequestration by region's forests, a special system of forest management should be developed and implemented. In the region, any rational car-

bon management system means obligatory development of an effective system of forest fire management.

- Objectives and major components of carbon management in larch forests of the region should be considered as a subset of those of the sustainable forest management paradigm. Major parts of such a system are: (1) relevant spatial and functional classification of the forests; (2) system of monitoring of forest cover; (3) system of forest fire protection that would be adapted to the region's specifics; (4) development of a regional system of forest use including appropriate technologies of logging, age of harvest, annual allowable cut etc.
- Permafrost thawing is one of most dangerous threats for future state, functioning and even surviving of larch forests of Northern-Eastern Russia. This problem should be considered in two interconnected aspects. The first deals with the undesirable change of hydrological regime on large areas, increasing aridity in combination with physical destruction of northern landscapes due to thermocarst, soliflucation etc. The second one deals with concomitant acceleration catastrophic natural disturbances, mostly forest fire. Very likely, these two processes will dramatically increase already observed processes of northern steppization and "green" desertification. This defines an urgent and mandatory need of development and implementation of a system of adaptation of northern territories on permafrost to on-going and expected global change.