CARBON BALANCE AND THE EMISSION OF GREENHOUSE GASES IN BOREAL FORESTS AND BOGS OF SIBERIA

E.A. Vaganov, S.P. Efremov and A.A. Onuchin
V.N. Sukachev Institute of Forest SB RAS, Krasnoyarsk, Russia

Abstract: Zonal patterns of above-ground phytomass dynamics and carbon storage in above-ground vegetation, phytodetritus and humus were revealed based on the study of the carbon balance and its components in forest ecosystems of the Yenisei meridian transect. Results indicate that the carbon storage ratio in different plant layers is determined by climatic regimes. For example pine stands were used to calculate the full carbon budget using data on its fluxes and storage in different biogeocenosis components. Biological productivity indices and the carbon pool of hydromorphic complexes are highly dependant on the mineral nutrition regime and morphological characteristics of the stands. Experimental study results show the importance of forest and bog ecosystems as carbon cycle regulators is determined by the complex interaction of zonal-climatic and forest conditions as well as by forest vegetation characteristics (which depend on varying carbon balance structure and energy- mass exchange processes).

Key words: greenhouse gases; forest ecosystems; post- fire carbon emissions; phytomass of forest bogs.

1. INTRODUCTION

Forests and bogs are dominant ecosystem types in middle and high latitudes of the northern hemisphere. The present paper details the results of studies into the role of Siberian forests and bogs in the global carbon cycle and outlines some trends for further studies. Carbon stocks and fluxes formed by Siberian forests and bogs make a significant contribution to the global system, based in part on its great size (approx. 10 million km^2).

S. Lombardi et al. (eds.),
Advances in the Geological Storage of Carbon Dioxide, 17–34.

The carbon cycle is fundamental in forest ecological and climatological studies due to the uptake and release of various natural and anthropogenic greenhouse gases during the life cycle of plants (the so-called temporary carbon depots). Siberian forests and bogs have several peculiarities with respect to their participation in the global carbon cycle: 1) tree stands typical of Siberia (with 5 coniferous species as dominants) as well as forest-bog and bog ecosystems provide long- term carbon conservation; 2) most Siberian forests are located in the permafrost zone, which has low productivity (about 100 m^3 per ha, or 1.27 m^3 per ha / year) but extra potential for carbon sequestration in soil; 3) a large portion of Siberian forests periodically suffer wild fires (variable in different taiga subzones) (Furyaev et al., 2001) that greatly shift the balance towards emission of C containing gases to the atmosphere.

2. STUDY METHODS

The information outlined above explains the great interest of the scientific community in studying the carbon cycle of Siberian forest and bog areas. At present more than 20 joint international projects are aimed at examining this problem. The methods used in these projects can be divided into direct and indirect, ground-based and remote-sensing, and combination techniques (i.e. methods based on direct measurements combined with simple models which compute the difficult or non-measured characteristics of the cycle).

Direct methods physically measure carbon cycle parameters, such as carbon content measurements within the forest litter, in different soil horizons, in gases below and above ground or in flowing water which removes carbon compounds from the ecosystem.

Methods for measuring respiration (stem and soil respiration, etc.) as well as the eddy-covariance method used for measuring carbon dioxide fluxes along the vertical profile of ecosystems are also direct ones. The eddy-covariance method requires special towers which are less than or much higher than the tree canopy and which are equipped with a series of gas analyzers located along its length (Shibistova et al., 2002a,b,c; Schulze et al., 1999). Vertical concentration profiles of carbon dioxide and other carbon containing greenhouse gases given in papers by Levin and Lloyd are more spatially integrating (Levin et al., 2002; Lloyd et al., 2002), and these measurements are used as a base for computing exchangeable carbon within the biogeochemical cycles of vast forest areas (up to hundreds of thousands of square kilometers).

Flux measurements of carbon-containing gases made using tall (up to 300 m) towers have a special importance in this group of methods (Bakwin et al., 1998), as the surface atmospheric layer (c. 0-200 m) is characterized by eddies induced by the friction of air flowing against earth surface roughness. However, the dynamics of the overlying layer (200-2000 m) is determined by heavy convective mixing during the day and by layer degradation or the absence of turbulence during the night. This interval is known as the mixing layer, and a wide range of diurnal carbon signals within the surface layer are smoothed and weakened in the mixing layer. Therefore, the mixing layer is an efficient integrator both of diurnal carbon cycles and of small-scale ecosystem heterogeneities. It enables not only the precise measurement of gas / aerosol compositions and their vertical profile dynamics but also to compute exchange fluxes of carbon containing gases which are integrated for the tower footprint area (about 40,000 km^2).

Some meteorological instruments also host partially-automated systems for measuring the absolute concentrations of CO, CO_2, O_2, N_2, CH_4 N_2O and the stable isotope ratios of $^{13}C/^{12}C$ in CO_2, CH_4 and CO, $^{18}O/^{16}O$ in CO_2 and $^{15}N/^{14}N$ in N_2O. Isotope ratios can be used to differentiate carbon sink and release processes. For example CO has information on anthropogenic emissions since the incomplete burning of fossil fuels is one of its main sources.

Concentration measurements of CO_2 fractions having different C and O isotopic signatures make it possible to separate oceanic and terrestrial carbon fluxes (Keeling et al., 1996) due to the strong contrast in the number of heavy carbon isotopes in CO_2 adsorbed during terrestrial C_3 photosynthesis compared to oceanic photosynthesis. Measurements of $^{18}O/^{16}O$ ratios in atmospheric CO_2 also help assess respiration intensity of terrestrial ecosystems (Mortazavi and Chanton, 2002). Modeling has shown that respiration and evaporation are the main factors responsible for spatial and seasonal changes of $C^{16}O^{18}O$ content in the atmosphere (Ciais et al., 1997; Peylin, 1999). Observations of methane will help to better understand the relationships between climate and ground vegetation since trends in methane (and its isotope $^{14}CH_4$) indicate changes in the respiration of peat bogs and permafrost soils.

Construction of the tall tower in the middle of the taiga forest region (Zotino, Krasnoyarsk krai) will provide measurements of energy- and mass exchange characteristics in real time, with a high temporal resolution and an assessment of the impact of meteorological conditions on exchange processes.

Studying carbon cycle parameters on the scale of Siberia requires the use of remote sensing methods owing to its great size and the limited access of many of its regions. For example satellite images can be used to determine species composition, the age of tree stands, phytomass stocks and other large scale forest ecosystem characteristics.

Computation of the total carbon budget of forests using periodic forest inventory data is one of the most developed approaches for understanding the role of Russian forests in the global carbon cycle This can be considered a combined approach, as forest inventory data is not enough. Instead, theoretical estimates of some carbon budget parameters should be introduced and models should be applied which take into account the age and species composition of the forest ecosystems in different physical and geographical regions. The total carbon budget of Russian forests was calculated in a cooperative project involving Russian forest research institutions and the Institute of Applied System Analysis (Austria). In this work a special database was established which includes a geographic information system (GIS) model. The multi-layered GIS contains land status data (landscapes, soils, vegetation, forests, land use etc.) and attributive data (phytomass, heterotrophic respiration, disturbed lands and forests etc.) which is based on focused studies and forest inventory reports as well as some auxiliary models (Shvidenko et al., 2003; Nilsson et al., 2000; Shvidenko and Nilsson, 2003).

Even the most thorough measurements and assessments of carbon cycle parameters will show only a small part of its value if they are not coordinated with other studies within an integrated description of the functioning ecosystems. Reducing together the minimum set of both direct and indirect (forest inventory or remote sensing) measurements of carbon cycle parameters needed for a relatively complete description is possible only within integrated models due to the different spatial scales of the various methods. An adequate model of ecosystem functioning not only links measurement data obtained by different methods but it is also able to assess the processes which has the most errors. For example the inaccuracy of assessing carbon emissions caused by forest fires is one of the key factors resulting in imprecise descriptions of the carbon cycle in Siberian forests (Vaganov et al., 1998; Arbatskaya, 1998; Conard and Ivanova, 1997; Conard et al., 2002). Great variability in the area of Siberian forest burned annually (from 1 to 10 million ha) greatly affects the balance between carbon accumulation and emission (Isaev et al., 1998).

3. RESULTS AND DISCUSSION

3.1 Spatial variability of carbon stocks in forest ecosystems along the Yenisei meridian

During several years researchers at the Forestry Institute SB RAS carried out detailed studies of the structure of the Yenisei transect forest ecosystems in order to assess their diversity and composition as well as various dynamic components, such as carbon, nitrogen and water turnovers (Forest ecosystems, 2002). Availability of all boreal forest subzones in the transect area makes it possible to link the stock and annual phytomass productivity indices, the rate of organic decomposition, heterotrophic respiration, detritus stocks, frequency and intensity of wild fires, as well as potential assessments of carbon emission during and after forest fires as a result of the main climatic factor - temperature. Latitudinal regularities in the forests of the Yenisei meridian can be considered as a spatial analog of changing ground vegetation structure due to large climate changes, such as the shifting of forest zones during warming (Furyaev et al., 2001; Tchebakova et al., 1994).

Tree stand phytomass and ground vegetation stocks show appropriate changes along the meridian and agree well with average annual temperature changes and growing season length (Forest ecosystems, 2002). The growing stock increase in forests of middle and southern taiga, as compared to the northern taiga, parallels the decrease of ground vegetation phytomass like mosses, lichens, grasses and small shrubs. In the more northern ecosystems the contribution of ground vegetation to the formation of annual ecosystem production is commensurable or exceeds wood growing stock contribution (Knorre, 2003).

The organic matter (OM) carbon pool in the soil cover (i.e. the soil layer equivalent to the organogenic and mineral horizon thickness, 0-50 cm depth) of forest tundra and boreal forests of the Yenisei meridian is 114 t ha^{-1}, which is divided between forest tundra (17%) and northern (23%), middle (39%) and southern (21%) taiga. Stable humus consists of 60.5 t ha^{-1}, 33.4 t C ha^{-1}, which is concentrated in mobile organic matter and 19.8 t C ha^{-1} is in phytodetritus on the soil surface and below (Fig. 1).

The upper 20-cm soil layer is characterized by a maximum accumulation of both mobile and stable carbon. The light mineralised OM fraction makes up 40% of the carbon stock in this part of the soil profile. With regards to carbon accumulation in the litter the fraction share increases to 50% of total carbon stock. In terms of structure, 19.8 t C ha^{-1} is phytodetritus carbon which takes an active part in exchange processes between phytomass, soil humus and the atmosphere while 21.3 t C ha^{-1} consists of soil organic matter involved in biological turnover and possibly rapid overturn. It is this latter which would be used during changing environment conditions and which controls the ratio of mineralisation and humification processes during decomposition. The ratio of carbon stocks in phytodetritus and in mobile soil OM (as in the most labile reserve during changing ecological states) decreases 5 times from forest tundra to southern boreal forests, the ratio of $C_{phytomass}$: $C_{phytodetritus}$ stock increases 6 times in the latitudinal range and C_{humus} stock in the mineral soil thickness (0-50 cm) varies from 72 to 121 t ha^{-1}.

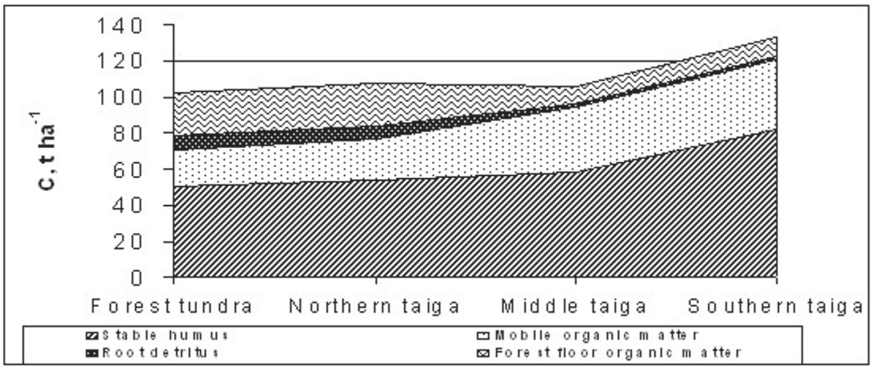

Figure 1. Carbon stocks in soil organic matter components.

Maximum phytodetritus stock in coniferous stands of forest tundra and northern taiga is clearly followed in latitudinal diapason. Existing permafrost, the high location of frost in the soil profile, its slow and shallow retreat during vegetation, low temperatures and high soil moisture contents determine the formation of specific ground vegetation. This vegetation usually consists of thick, often continuous coverage consisting of green mosses (of the genera *Pleurozium*, *Hylocomium*, *Politrichum*) as well as bushy lichens (of the genera *Cladonia*, *Cladina*, *Cetraria*). The slow decomposition of these plants due to numerous stable compounds (lignocellulose complex, cellulose etc.) results in the accumulation of variously decomposed moss and lichen remains on the soil surface. Their stocks are more than ten times that of tree leaf-fall remains. Soil mass cryoturbation (frost heave, frost cracks etc.) result in an increase of detritus in the upper mineral soil depth.

Phytodetritus stock increases towards the south, from middle taiga, are related to changes in the structure of the forest-forming tree species, to forest productivity increases and, as a result, to annual leaf fall amount. In addition, the southern taiga forests are characterized by increased dead wood (deadfall, stumps).

In ecosystems of all forest-forming tree species the distribution of phytodetritus components, up to class V of stand age, is: litter > root detritus > stem wood. Prevalence of over mature stands results in detritus accumulating due to slowly decomposed fallen stems. The latter clearly shows itself in southern taiga larch forests, pine forests and spruce forests.

Overall carbon accumulation in forest tundra and taiga ecosystems of the Yenisei meridian (in blocks “vegetation” and “soil”) equals about 16,000 billion t (156 t C ha^{-1} of forested area). Approximately 26% consists of above and below ground phytomass, while the rest is accumulated in the organic matter of the upper 50 cm of the soil (39% in stable humus, 13% in mobile humus and 22% in phytodetritus). Studies in other countries show comparable values: forest ecosystems in the Netherlands are characterized by a similar ratio with 113; 59 and 19 t C ha^{-1} in humus, phytomass and dead plant residues, respectively (Nabuurs and Mohren, 1993, 1995); in Finland 34 t C ha^{-1} was found in phytomass and 72 t C ha^{-1} in the 0-17 cm soil interval (Kauppi et al., 1997); while in the USA Birdsey (1992) found 59% in soil, 31% in the phytomass and 9% in plant residues on soil surface.

Carbon stocks in both blocks increase in the meridian direction. The redistribution of pools between them varies along the transition from forest tundra to the northern taiga, such that the C_{soil} / $C_{phytomass}$ ratio diminishes from 4.8 to 2.9 and remains equal in ecosystems of middle and southern taiga (2.6 and 2.4, respectively). As Utkin et al. (2001) found, the C_{soil} / $C_{phytomass}$ ratio for subzones of western and eastern Siberian macro-regions equals 3.3. From the estimate of Shvidenko and Nilsson (2003) it follows that this ratio in the forested Russian area equals 6.8, 2.4 and 2.8 in forest tundra and northern taiga forests, middle and southern taiga, respectively.

Intensity of mineralised carbon flux to the atmosphere is practically 90%, determined by phytodetritus decomposition. Between 68% (in southern taiga) and 87% (in forest tundra) of its emission is formed via litter decomposition. Root detritus contribution does not exceed 11-17%, while stem fall increases from forest tundra and northern taiga towards middle and southern taiga (from 2-3 to 14-17%). Soil humus mineralisation in ecosystems varies from 3 to 13% in the southern taiga and from 2 to 6% in northern forests. The 2 - 5% of detritus being decomposed are humificated in southern taiga forests and 0.1-0.2% of it in forest tundra and in larch forests of the northern taiga.

Experimentally determined phytodetritus decomposing rates, averaged for forest zones and subzones of the Yenisei meridian, are given in Table 1. For the period having an average daily air temperature above 5°C the phytodetritus decomposition rate increases 3-fold (from 0.4 to 1.1 mg C g^{-1} day^{-1}) in the direction from forest tundra to southern taiga.

Table 1. Indices of phytodetritus decomposition rate.

Zone and subzone	Forest litter		Root detritus	
	k, year^{-1}	T $_{½}$, years	k, year^{-1}	T $_{½}$, years
Forest tundra, n = 41	0.035 ± 0.002	20	0.036 ± 0.003	17
Northern taiga, n = 35	0.046 ± 0.004	15	0.048 ± 0.007	14
Middle taiga, n = 49	0.089 ± 0.007	8	0.072 ± 0.007	10
Southern taiga, n = 44	0.211 ± 0.024	3	0.085 ± 0.011	8

Young forest ecosystems (tree stands of classes I-II in age) of the main Siberian forest-forming species, the southern taiga pine forests and birch stands and larch ecosystems of the northern taiga are a sink for atmospheric carbon. Prevailing over mature tree stands of southern taiga larch forests in the forested area of the subzone are considered as negative balance ecosystems with regards to carbon production and destruction processes (thus a C source to the atmosphere). Forest tundra ecosystems are considered at equilibrium.

The carbon sink (net ecosystem production) of young forest ecosystems consists of 50 to 70% of carbon net primary production (NPP) and is formed via the accumulation of phytomass (73-78% of NEP value), and conservation in phytodetritus (6-20%) and soil humus (5-18%). Pine and birch forests of the southern taiga are a sink for 16% of the photosynthetic assimilation of atmospheric carbon in the net primary production. NEP of larch forests of the northern taiga make up 30% of net primary production. The major part of the sink consists of ground vegetation and accumulation in the phytodetritus and only 9% on tree stand biomass.

3.2 Direct measurements of carbon dioxide fluxes by eddy- covariance methods

The assessment of spatial and temporal distributions of carbon sinks and sources in terrestrial ecosystems can be obtained based on data of regular vertical soundings of the atmosphere (Tans et al., 1996; Gloor et al., 2000). Measurements of vertical concentration profiles of carbon dioxide, methane and stable isotopes make it possible to characterize seasonal cycles and gas exchange intensity between the earth surface and atmosphere at a regional scale (Levin et al., 2002; Lloyd et al., 2002).

Since the eddy covariance method registers integrated CO_2 fluxes between the ecosystem and atmosphere, it can be difficult to assess separate carbon exchange constituents because of the difficulty of interpreting the balance between photosynthetic assimilation and the release of carbon dioxide during the respiration process (Grace et al., 1996). As such gas exchange chambers are used as an alternative approach which can give a quantitative estimation of CO_2 fluxes in separate ecosystem components (photosynthesis, soil respiration, tree stems, crown) as well as to register spatial and temporal variability.

Continuous research has been conducted on the carbon balance of a forest ecosystem in the southern subzone of middle taiga (60°45′N, 89°23′E) since 1998. The measurement system was installed in an even-aged (200-year old) pine tree stand of V bonitet class, growing on sandy soils. Mean tree height is 22 m, basal area is 30 m/ha, leaf area index is 1.5 of the projective cover, and crown closure is 0.7 (Wirth et al., 1999). Lichens pp. *Cladina spp*. *Cladonia spp.* dominate the ground vegetation. The grass-shrub layer mainly consists of *Vaccinium vitis-idaea* (L). Avror., while the presence of green mosses and *Vaccinium myrtillus* (L). is minor.

Photosynthetic activity was observed in the ecosystem from early May to late September. During the long autumn-winter period the tree stand was transformed into a weak CO_2 source to the atmosphere (average CO_2 flux equaled 0.05 mol C m^2 day^{-1} - Shibistova et al., 2002). On the whole, during the vegetation season the studied ecosystem was considered as a CO_2 "sink" and the accumulating activity (up to 0.4 mol $C{\cdot}m^{-2}{\cdot}day^{-1}$), in spite of a lesser leaf area index, was rather high and quite comparable with values characteristic of European and Canadian boreal forests (Schulze et al., 1999; Goulden et al., 1997; Jarvis et al., 1997).

The gross primary production (GPP) value of the studied tree stand was much less compared to European forests. For example, GPP values of the order of 100, 85 and 126 mol C m^2 $year^{-1}$ were observed for forest ecosystems in Sweden, Finland and the European part of Russia, respectively (Valentini et al., 2000; Milyukova et al., 2002). Nevertheless this index, varying in experiments from 46 to 53 mol C m^2 $year^{-1}$ (Shibistova et al., 2002; Lloyd et al., 2002), was similar to the 60 ±10 mol C m^2 $year^{-1}$ value obtained for Canadian forests (Ryan et al., 1997). It should be noted that the coefficient of GPP "expenditures" for autotrophic respiration ($\varphi = 0.64$) also agreed with computations given for coniferous forests of Canada (Baldocchi et al., 1997; Ryan et al., 1997).

Analysis of integrated CO_2 fluxes has shown a great variability in net gas ecosystem exchange (NEE) values, showing the difference between values of gross primary production and total constituent respiration during the vegetation season. These fluctuations reflect a complex effect of abiotic factors (photosynthetic active radiation, deficiency of aqueous tension and air temperature) on photosynthetic activity (Shibistova et al., 2002; Lloyd et al., 2002), and moreover they depend on the start time of photo-assimilating stand activity (Suni et al., 2003). The integrated value of annual net gas exchange of the ecosystem varied from 13 to 15 mol C m^2 $year^{-1}$.

The net gas exchange of forest ecosystems is considered to be primarily determined by respiration intensity (Valentini et al., 2000). From this point of view the CO_2 emission value from soil, which makes up to 60-80% of the total ecosystem respiration (Shibistova et al., 2002 a,b,c; Kelliher et al., 1999; Hollinger et al., 1998:), is a key component of carbon cycle.

Thus the direct measuring of carbon dioxide fluxes by the eddy covariance method has shown that the studied tree stand is a large accumulator of atmospheric CO_2. Carbon accumulation, on average, consisted of 1.8 t year $^{-1}$ per hectare of forest area for the studied period.

3.3 Total carbon budget of Russian forests

Two main fluxes, net primary production (with positive accumulation) and heterotrophic respiration (with negative carbon emission), are decisive in the carbon budget of Russia (Nilsson et al., 2003; Shvidenko et al., 2003). Net production results from green phytomass (~49%), above ground tree mass (~26%), and underground processes (~25%). Heterotrophic respiration is mainly determined by ground vegetation respiration, with 15% caused by above and below ground detritus decomposition. Carbon emission fluxes by wild fires are 37%, due to ecosystem disturbances, while biotic factors (most significantly insect reproduction) contribute the same amount. Carbon accumulation in the hydro- and lithosphere contributes no more than 2.2% of the net primary production, which means that over approximately 40-45 years the annual volume of organic matter assimilated by vegetation is essentially removed from the biological cycle. This is not so large a value relative to the inherent time scale of the biological cycle, however it is significant over geological time. Summarizing the various pools and fluxes shows the net biome production (absorbing carbon from the atmosphere) of Russian forests to be at a rate of 7.6% of the net primary production.

From flux assessments it follows that for the studied period of time Russian forested areas have absorbed about 240 Tg (million ton) of carbon per year from the atmosphere. It is now known that the “controlled” (by forestry measures) part of the carbon budget is limited by disturbances and other possible transformations of non-wooded lands to forested ones (forest regeneration and forest propagation). Better integrated and temporally averaged values were obtained when assessing the total carbon budget parameters for the other time periods. Thus for 38 years (1961-1997) Russian forested areas absorbed, on average, 430+/-70 million tons of carbon per year from the atmosphere, the third part of which was determined by changing ground vegetation. Due to disturbances in forest ecosystems the total flux varied from 90 to 400 Tg of carbon per year. Net biome production averaged in 5-year periods shows less variations: from 240 to 320 million t of carbon per year.

Assessment of the total carbon budget (Nilsson et al., 2003; Shvidenko et al., 2003) shows that: 1) the Russian forests are presently a huge reservoir of additional carbon sequestration (about 200-600 million t C / yr); 2) the assessed potential carbon sequestration may be obtained only for vast areas and using sustainable forest management; 3) realizing sustainable forest management requires a new state policy in managing the forestry sector, however this does not conflict with traditional forestry activities aimed at high forest productivity, improved forest protection and maintaining forest biodiversity.

3.4 Wildfires and carbon emissions – the main source of uncertainties in estimating parameters of carbon cycle of Siberian forest ecosystems

Official statistics show that between 20,000 and 40,000 fires occur annually in Russia, affecting an area of 2 to 3 million ha of forest and other lands (Davidenko et al. 2003). The fires are detected and controlled only in the so-called "protected forests" and on pasturelands. However, the application of space-borne sensors, such as the NOAA/AVHRR Terra/Aqua/MODIS, ENVISAT/MERIS and Terra/ASTER, have improved considerably the detection of active fires along with a better estimation of burned areas and large-scale impacts (Sukhinin et al., 2004a).

For example, before the 1980s it was believed that, on average, fires annually burned 1.5 million ha in the boreal forests within the former Soviet Union. Recent investigations based on satellite imagery revealed that the magnitude of the fires has been greatly underestimated, and now it is believed that boreal zone fires annually destroy an average of 8 million ha, with considerable annual fluctuation (Conard et al., 2002). For example, in 1987 satellite image evaluation revealed a total area burned in boreal forests and other lands in the East-Asian regions of Russia of about 14 million ha (Cahoon et al., 1994).

The Krasnoyarsk satellite receiving stations at the V.N. Sukachev Institute for Forest and the Russian Ministry of Emergency are now capable of downloading and processing both NOAA/AVHRR and Terra/MODIS data. They cover the whole Asian part of Russia, which consists of approximately one billion ha of vegetated land between the Urals to the West and Sakhalin Island in the Far East. The surveyed area includes all vegetation types (forest, tundra, steppe, etc.)(Soja et al., 2004).

Dynamics of the total area burned and number of fires in the Asian part of Russia, based on satellite monitoring data for 1996-2003, indicates an increase in both values (Sukhinin et al., 2004b). The fire seasons of 2002 and 2003 were especially catastrophic in Eastern Siberia (Sukhinin et al., 2003, 2004b) (Table2).

Table 2. Observed and remote sensing data on forest fires in 2002 and 2003 in Eastern Siberia.

Year	Governmental agencies reports based on ground and aircraft observations			Satellite-based data (NOAA/AVHRR)		
	Fire number mentioned in reports	Total area of burn scars, (ha)	Forest burned area, (ha)	Number of surveyed fires	Total area of burn scars, (ha)	Forest burned area, (ha)
2002	35 000	1 834 000	1 200 000	10 300	11 767 000	No data
2003	28 000	2 654 000	2 074 000	15 440	21 527 000	18 862 000

The differences between ground / aircraft-based observations versus satellite monitoring of forest fires are obvious. Data from the Aerial Fire Suppression (Avialesookhrana) Institute also do not provide the full overview of the situation.

Considering the large discrepancies between different satellite datasets on the one hand and conventionally collected fire data on the other, the question of absolute accuracy of satellite data seems to be of minor concern. Instead it is most important to close the extremely large gap between the statistics of the forestry services and the remote sensing institutions. For example, the satellite-derived burned forest area provides a total area affected by fire which is almost ten times higher than the assessments by aerial observations for the same region. According to the results of aerial surveys carried out in Buryatia and Chita in September 2003, it was decided that about 20% burned in Irkutsk and Buryatia area and that at least 10% of the Chita area was affected by crown fires because of extremely dry weather (Goldammer et al., 2004).

Rough assessments of carbon release to the atmosphere from fires of various intensities and duration based on 2003 satellite data and some empirical assumptions (Soja et al., 2004; Goldammer et al., 2004; Kasischke et al., 2005) gave a value about 46-100 Tg as a prompt release, and 190-400 Tg as post-fire release. This scenario of 2003 carbon emissions represents a crude assessment of the effect of fire on carbon release and probable patterns of carbon decrease dynamics (i.e. its sequestration). The most important source of errors in estimating fire emissions is the incomplete research into forest fuels and their full combustion depending on weather and environmental conditions.

3.5 The role of forest- bog and bog ecosystems in carbon accumulating in Siberian area

In spite of researcher efforts to make known the contribution of Siberian bogs to the global organic carbon cycle, this problem remains as urgent as before. Presently only the process of intensive accumulation and study of new data can be stated (P'yavchenko, 1985; Peat resources of RSFSR, 1991; Vompersky, 1994; Vompersky et al., 1999; Efremov et al., 1994; Efremova et al., 1997, 1998; Makhov et al., 1994; Panikov et al., 1993; Naumov et al., 1994; Naumov, 1997; etc.).

The main barriers to an objective assessment of this contribution are: a) absence of total and reliably differentiated account of boggy and peaty areas; b) geographically uneven and quantitatively insufficient measurements of peat deposits; c) fragmentary information on the group and fractional structure of organic matter of peat deposits and the transformation of carbon forms in these peat deposits related to environmental dynamics (e.g. T, moisture, redox potential); d) the weak experimental basis for the current retrospective assessments and prediction of the depositional effect of bogs and boggy forests of Siberia.

According to the forest mapping made by Korotkov (1994) two forest oblasts make up part of the western Siberian continental sector: the Altai-Sayan mountains and the western Siberian plains. Each is differentiated into forest provinces (FP), of which the first oblast covers 7 FP, and the second covers 3 FP.

The correlation of areas, peat stocks and deposited carbon for peaty bogs of the region are given in Table 3. One can see that plain areas, and taiga forest zones in them with a specific index distribution in subzones, have a decisive importance. Moreover, a rather contrasting increase of total peat and organic matter stocks from the north to the south at the more "smoothed" differentiation of bogs area is observed here.

Deposited peat stocks converted to bone-dry organic matter (BDM) within the BVB reach almost 18 billion tons, which can be subdivided into oligotrophic (50.2%), mesotrophic 18.1% and eutrophic (31.7%) peats. Uptake and long-term isolation of atmospheric carbon by BVB equals 9.3 billion tons (oligotrophic - 49.4%, mesotrophic - 18.2%, eutrophic - 32.4% of organic carbon). Based on calculations the biosphere contribution of BVB to the C- depositing indices of forest- bog- peat complexes of the western Siberian plain may be presented in generalized form as follows: in area – 6.7%, in deposited ACB – 16.5%, in organic carbon of peat deposits – 17.2%.

Table 3. Correlation of areas, peat stocks and deposited carbon in peaty bogs of western Siberian forest zones.

Ecoregions	% of total bog area	% of total peat stock	% of total carbon stock
Zauralsk- Yeniseisk FP			
pretundra forests and open forests:	15,3	3,6	3,5
Tundra	4,8	0,1	0,05
Forest tundra	10,5	3,5	3,5
Zauralsk- Yeniseisk FP			
taiga forests:	77,8	90,4	90,6
northern taiga	22,1	18,7	18,6
middle taiga	24,8	28,1	28,1
southern taiga	30,9	43,6	43,9
Plain steppe and forest- steppe	4,6	3,6	3,6
Total in plain area	97,7	97,6	97,7
Mountain and pre- mountain area	2,3	2,4	2,3
Total in western Siberian macro-region	100	100	100

Progressing climate warming will undoubtedly result in the heating of peat deposits, the fall of soil water level and the increased aeration of bog ecosystems, which will in turn increase microbiological and fermentative soil activity. This will result in accelerated decomposition of the organic matter in peat and in their humification. Polysaccharides will be transformed first, however eventually all groups and organic fractions will be affected, including even more stable components like lignin, humic coal and wax resins. The earlier stated proportions will be shifted in the group and fraction composition of humus, and it will be stabilized at another level which corresponds to the new oxidative- regenerative situation.

4. CONCLUSIONS

It is recommended that future studies focus on the following items: i) elucidation of the reasons for the discrepancy in assessing carbon pools and fluxes determined by various methods for some regions or smaller areas; ii) climate change impact on the dynamics of pools and fluxes, at different temporal and spatial resolutions; iii) the more precise assessment of carbon emissions as a result of forest area disturbance caused by cuts, wild fires, land use, outbreaks of mass insect reproduction, man-made pollution; iv) elaboration of a system of carbon cycle models at different spatial levels; v) study of models for assessing scenarios of carbon emission accumulation via different climate changes; vi) elaboration of ecological- economical models of the carbon budget for forest and bog areas.

ACKNOWLEDGEMENTS

The authors thank the researchers of the V.N.Sukachev Institute of Forest SB RAS, including Vedrova E.F., Verkhovets S.V., Efremova T.T., Kruglov V.B., Sukhinin A.I., Shibistova O.B., for presented materials and their help in preparing this paper.

REFERENCES

Arbatskaya, M.K., 1998, A long- term variability of climate, tree growth and fire occurrence in taiga forests of Middle Siberia, PhD thesis abstract, Krasnoyarsk, 21. (in Russia)

Bakwin, P. S., Tans, P. P., Hurst, D. F., and Zhao, C., 1998, Measurements of carbon dioxide on very tall towers: Results of the NOAACMDL program, *Tellus* **50B:**401-415.

Baldocchi, D., Vogel, C.A., and Hall, B., 1997, Seasonal variations of carbon dioxide excange rates above and below a boreal jack pine forest, *Agric. For. Meteorol.* **83**:147-170.

Birdsey, R.A., 1992, Carbon storage and accumulation in United States forest ecosystems, USDA Forest Service. General Technical Report WO-59. 51 p.

Cahoon, D.R., Stocks, B.J., Levine, J.S., Cofer, W.R., and Pierson, J.M., 1994, Satellite analysis of the severe 1987 forest fires in northern China and southeastern Siberia., *J. Geophys. Res.* **99** (D9):18627-18638.

Ciais, P., Denning, A.S., Tans, P.P., Berry, J.A., Randall, D.A., Collatz, G.J., Sellers, P.J., White, J.W.C., Trolier, M., Meijer, H.J., Francey, R.J., Monfray, P. and Heimann, M., 1997, A three dimensional synthesis study of δ18O in atmospheric CO2. Part 1: Surface fluxes, *Journal of Geophysical Research* **102**:5857-5872.

Conard, S.G., Ivanova, G.A., 1997, Wildfire in Russian boreal forests – potential impacts of fire regime characteristics on emissions and global carbon balance estimates, *Enviromental Pollution*. **98(**N3): 305-313

Conard, S.G., Sukhinin, A.I., Stocks, B.J., Cahoon, D.R., Davidenko, E.P., Ivanova, G.A., 2002, Determining effects of area burned and fire severity on carbon cycling and emissions in Siberia, *Climatic Change* **55**(1-2): 197-211.

Davidenko, E.P., Furyaev, V.V., Sukhinin, A.I., and Goldammer, J.G., 2003, Fire management needs in Russia's boreal forest zone, Paper presented at the *3rd International Wildland Fire Congress,* Sydney, Australia, 3-6 October 2003..

Efremov, S.P., Efremova, T.T., Melentieva, N.V., 1994, Carbon stocks in bog ecosystems, Carbon in forest and bog ecosystems of Russia, *Krasnoyarsk* 128-140. (in Russia)

Efremova, T.T., Efremov, S.P., Melentieva, N.V., 1998, Water resources of bogs of Russia and assessment of their chemical composition, *Geographia and prirodnye resursy (Geography and natural resources)* **2**:79-84. (in Russia)

Efremova, T.t., Efremov, S.P., Melentieva, N.V., 1997, Stocks and content of carbon compounds in bog ecosystems of Russia, *Pochvovedenie (Soil science)* **12**:1470-1477. (in Russia)

Forest ecosystems of the Yenisei meridian, 2002, Pleshikov, F.I., (ed) Novosibirsk, Publ. House of SB RAS,: 356 p. (in Russia)

Furyaev, V.V., Vaganov, E.A., Tchebakova, N.M., Valendik, E.N., 2001, Effects of Fire and Climate on Successions and Structural Changes in the Siberian Boreal Forests, *Eurasian J. For. Res.* **N2**: 1-15.

Gloor, M., Fan, S.-M., Pacala, S. W., and Sarmiento, J. L., 2000, Optimal sampling of the atmosphere for purpose inverse modelling: a model study, *Global Biogeochem. Cycles* **14**:407–428.

Goldammer, J.G., Sukhinin, A.I., Chisar, I., 2004, Existing fire situation in Russian Federation: conclusions for extending international cooperation in UNO frames and global programs in monitoring and assessing fires. In: *Forest fire control at the ecoregional level,* World Bank, Publ House “Alex”, Moscow,: 26-66. (in Russia)

Goulden, M.L., Daube, B.C., Fan, S.-M., Sutton, D.J., Bazzaz, Munger, J.W., Wofsy, S.C., 1997, Physiological responses of a black spruce forest to weather, *JGR-Atmospheres* **102(D24)**:28987-28996.

Grace, J., Malhi, Y., Lloyd, J., McIntyre, J., Miranda, A.C., Meir, P., Miranda, H., 1996, The use of eddy covariance to infer the carbon balance of Brazilian rain forests. *Global Change Biol.* **2**:209-218.

Hollinger, D.Y., Kelliher, F.M., Schulze, E.-D., Bauer, G., 1998, Forest-atmosphere carbon dioxide excahnge in Eastern Siberia. *Agric. For. Meteorol.* **90:**291-306.

Isaev, A.S., Korovin, G.N., Zavarzin, G.A., 1998, Carbon turnover on the Russian area, Moscow, RAS, C. 63-95. (in Russia)

Jarvis, P.G., Massheder, J.M., Hale, S.E., Moncrieff, J.B., Rayment, M., and Scott, S.L., 1997, *Journal of Geophysical Research*. **102**:28953-28986.

Jenkinson, D.S., Rainer, J.H., 1977, The turnover of soil organic matter in some of Rothamsted classical experiments, *Soil Sci.* **123**(5):298-305.

Kasischke, E. S., Hyer, E. J., Novelli, P. C., Bruhwiler, L. P., French, N. H. F., Sukhinin, A. I., Hewson, J. H., and Stocks, B. J., 2005, Influences of boreal fire emissions on Northern Hemisphere atmospheric carbon and carbon monoxide, *Global Biogeochem. Cycles* 19: GB1012, doi:10.10292004GB002300.

Kauppi, P.E., Posch, M., Hänninen, H.M., et al., 1997, Carbon reservoirs in peatlands and forests in boreal regions of Finland, *Silva Fennica.* **31**(1):13-25.

Keeling, R.F., Piper, S.C. and Heimann, M., 1996, Global and hemispheric CO_2 sinks deduced from measurements of atmospheric oxygen concentration, *Nature* **381**:218-221.

Kelliher, F.M., Lloyd, J., Arneth, A., et al., 1999, Carbon dioxide efflux density from the floor of a central Siberian forest, *Agric. Forest. Meteorol.* **94:**217-232.

Knorre, A.A., 2003, Use of registering structures at assessing annual production of components of phytocenoses in forest and bog ecosystems of Priyeniseisk Siberia, PhD thesis abstract. – Krasnoyarsk,: 21p. (in Russia)

Korotkov, I.A., 1994, Forest regioning of Russia and of republics of the former Soviet Union, Carbon in forest and bog ecosystems of Russia. Krasnoyarsk,: 170 p.

Levin, I., Ciais, P., Langenfelds, R., Schmidt, M., Ramonet, M., Sidorov, K., Tchebakova, N., Gloor, M., Heimann, M., Schulze, E.-D., Vygodskaya, N.N., Shibistova, O. and Lloyd, J., 2002, Three years of trace gas observations over the EuroSiberian domain derived from aircraft sampling a concerted action, *Tellus*, **54B(5):**696-712.

Lloyd, J., Langenfelds, R., Francey, R.J., Gloor, M., Tchebakova, N., Zolotukhine, D., Brandt, W., Werner, A., Jordan, A., Allison, C., Zrazhewske, V., Shibistova, O., and Schulze, E.-D., 2002, A trace-gas climatolog above Zotino, central Siberia, *Tellus*, **54B(5):**749-767.

Makhov, G.A., Bazhin, N.M., Efremova, T.T., 1994, Methane emission from bogs of the area between rivers Ob’ and Tom’, *Chemistry in the interest of stable development* **2**:619-622. (in Russia)

Milyukova, I., Kolle, O., Varlagin, A., Vygodskaya, N.N., Schulze, E.-D., and Lloyd, J., 2002, Carbon balance of a southern taiga spruce stand in European Russia. *Tellus*, **54B**(5):429-442

Mortazavi B., and Chanton J. P. 2002, Carbon isotopic discrimination and control of nighttime canopy 18O-CO2 in a pine forest in the southeastern United States, *Global Biogeochem. Cycles* **16**(1):10.10292000GB001390.

Nabuurs, G.J., and Mohren, G.M.J., 1993, Carbon in Dutch forest ecosystems, *Netherlands J. Agricultural Sci.* **41**:309-326.

Nabuurs, G.J., and Mohren, G.M.J., 1995, Modelling analysis of potential carbon sequestration in selected forest types, *Can. J. For. Res.*, **25**(7):1157-1172.

Naumov, A.V., Efremova T.T., Efremov, S.P., 1994, On emission of carbon dioxide and methane from bog soils of Southern Vasyuganie, *Sibirsky Ekologichesky jurnal (Siberian ecological journal),* **1**(3):269-274. (in Russia)

Naumov, A.V., 1997, Plant respiration and carbon dioxide emission in the bog ecosystem, *Sibirsky Ekologichesky jurnal (Siberian ecological journal)*, **4**:385-391.

Nilsson, S., Shvidenko, A.Z., Stolbovoi, et al., 2000, Full Carbon Account for Russia, IIASA, Laxenburg, Austria.

Panikov, N.S., Titlyanova, A.A., Paleyeva, M.V., Semenov, A.M., Mironycheva-Tokareva, N.P., Makarov, V.I., Dubinin, E.V., Efremov, S.P., 1993, Methane emission from bogs of West Siberian south, DAS, **330**(3):388-390. (in Russia)

Peat resources of RSFSR. 1991, Moscow: Torfgeologia (Peat geology), 100 p.

Peylin, P., 1999, ^{18}O isotopic composition in atmospheric CO_2: A new tracerto estimate photosynthesis at global scale. PhD Dissertation, Paris IVUniversity,. 221 pp.

P'yavchenko, N.I., 1985, Peat bogs, their natural and economical importance, Moscow, *Nauka (Science)* 152 p. (in Russia)

Ryan, M.G., Lavigne, L.B., and Gower, S.T., 1997, Annual carbon cost of autotrophic respiration in boreal forest ecosystem in relation to species and climate, *J. Gephys. Research* **102**:28871-28883.

Shibistova, O.B., Lloyd, D., Kolle, O., Arneth, A., Tchebakova, N.M., Zolotukhin, D.A., Zrazhevskaya, G.K., and Schulze, E.D., 2002a, Assessment of CO_2 accumulating by pine stand using the eddy covariance method, DAS, **3**:425-429. (in Russia)

Shibistova, O., Lloyd, J., Zrazhevskaya, G., Arneth, A., Kolle, O., Astrakhantceva, N., Shijneva, I., Knohl, A., and Schmerler, J., 2002b, Ecosystem respiration budget for a Pinus sylvestris stand in Central Siberia, *Tellus* **54B(5)**:568-589.

Shibistova, O., Lloyd, J., Evgrafova, S., Savushkina, N., Zrazhewskaya, G., Arneth, A., Knohl, A., Kolle, O., and Schulze, E.-D., 2002c, Seasonal and spatial variability in soil CO_2 efflux rates for a central Siberian Pinus sylvestris fores. *Tellus* **54B**(5):552-567.

Schulze, E.-D., Lloyd, J., Kelliher, F., Wirth, Ch., Rebmann, C., Luhker, B., Mund., M., Knohl., A., Milyukova., I., Schulze, W., Ziegler, W., Varlagin, A., Sogachev, A., Valentini, R., Dore, S., Grigoriev, S., Kolle, O., Panfyorov, M., Tchebakova, N., and Vygodskaya, N.N., 1999, Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink - a synthesis, *Global Change Biology* **5***(6)*:703-722.

Shvidenko A., Nilsson S. 2003 A synthesis of the impact of Russian forests on global carbon budget for 1961-1998, *Tellus* **55B**:391-415.

Shvidenko, A.Z., Vaganov, E.A., and Nilsson, S., 2003, Biospheric role of Russian forests at the start of the third millenium: carbon balance and Kyoto Protocol, *Sibirsky ekologichesky jurnal (Siberian ecological journal)* **6**:649-658. (in Russia)

Soja, A.J., Sukhinin, A.I., Cahoon, D.R., Shugart, H.H., and P.W., Stackhouse, 2004, AVHRR-derived fire frequency, distribution, and area burned in Siberia, *International Journal of Remote Sensing* **25(**10):1939-1960.

Soja, A.J., Cofer III, W.R., Shugart, H.H., Sukhinin, A.I., Stackhouse, Jr. P.W., McRae, D.J., and Conard, S.G., 2004, Estimating fire emissions and disparities in boreal Siberia (1998 through 2002), *Journal of Geophysical Research* **109**:(D14S06).

Sukhinin, A.I., Ivanov, V.V., Ponomarev, E.I., Slinkina, O.A., Cherepanov, A.V., Pavlichenko, E.A., Romasko, V.Y., and Miskiv, S.I., 2003, The 2002 Fire season in the Asian part of the Russian Federation: A view from space, *Int. Forest Fire News* **28**:18-28.

Sukhinin, A.I., French, N.H.F., Kasischke, E.S., Hewson, J. H., Soja, A.J., Csiszar, I.A., Hyer, E.J., Loboda, T., Conard, S.G., Romasko, V.I., Pavlichenko, E.A., Miskiv, S.I., Slinkina, O.A., 2004, Satellite-based mapping of fires in Russia: New products for fire management and carbon cycle studies, *J. Remote Sensing of Environment* **93**:546-564.

Sukhinin, A.I., 2004, Dynamics of the forest fire situation in the Asian part of Russia during the fire season of 2003 (April- September), *Int. Forest Fire News* **29**:113-118.

Suni T., Berninger, F., Vesala, T., Makkanen, T., Harri, P., Lindroth, A., Arneth, A., Shibistova, O., Lloyd, J., 2003, Air temperature triggers the recovery of evergreen boreal forest photosynthesis in spring, *Global Change Biology* **9**:1410–1426

Tans, P. P., Bakwin, P. S., and Guenther, D. W., 1996, A feasible global carbon cycle: a plan to decipher today’s carbon cycle based on observations, *Global Change Biol.* 2, 309–318.

Tchebakova, N.M., Monserud, R.A., Nazimova, D.I., 1994, A Siberian Vegetation Model Based on Climatic parameters, *Can. J. For. Res.* **24**:1597-1607.

Utkin, A.I., Zamolodchikov, D.G., Chestnykh, O.V., Korovin, G.N., Zukkert, N.V., 2001, Forests of Russia as a reservoir of organic carbon of the biosphere, *Lesovedenie (Forest science)* **5**:8-23. (in Russia)

Vaganov, E.A., Furyaev, V.V., Sukhinin, A.I., 1998, Fires of Siberian taiga, *Priroda (Nature)* **7**:51-62. (in Russia)

Valentini, R., Metteucci, G., Dolman, A.J. et al., 2000, Respiration as the main determinant of carbon balance in European forests, *Nature* **404**:861-865.

Vompersky, S.E., Tsyganova, O.P., Kovalev, A.G., Glukhova, T.V., Valyaeva, N.A., 1999, Bog formation of the Russian area as a factor of fixing atmospheric carbon, carbon turnover on the area of Russia. Selected scientific proceedings on the problem “*Global evolution of the biosphere. Anthropogenic contribution*”, Moscow, 124-145. (in Russia)

Vompersky, S.E., 1994, Role of bogs in carbon cycle, Readings to the memory of the academician V.N.Sukachev. XI: Biogeocenotic peculiarities of bogs and their efficient use. Moscow: *Nauka (Science)* **5-38**. (in Russia)