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SOIL CARBON IN THE FORESTS OF RUSSIA

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Abstract. The 50% variation in the estimates of carbon (C) content in the forest soils of Russia at present is caused by confusion of terms and ignorance of the soil geographical representativeness in forests. The GIS-based analysis closes the gap to the estimate published earlier by Alexeyev and Birdsey (1994, p. 170). The average soil carbon density (SCD) for the 0.3 meter (m) layer of the forest soils in Russia is about 8.1 kg C m^{-2}; the 1 m layer captures some 11.4 kg C m^{-2}; and the 2 m layer holds nearly 12.3 kg C m^{-2}. The mass of C is about 61.6 Pg C concentrated in the 0.3 m layer of forest soils; the 1 m layer accumulates 87.6 Pg C and the 2 m layer holds about 94.1 Pg C. The C content in soils of the forest zone is much higher for Russia. The SCD is 18.8 kg C m^{-2} and the soil C pool (SCP) is 223.6 Pg C in 1 m layer. Peat soils contribute a considerable portion of C to the forest zone of the country. The cold climate, permafrost and vegetation residues that are rich in recalcitrant compounds support a high accumulation rate of organic matter and associated nutrients in soils. This conservation is a mechanism to keep the production potential of the boreal ecosystems high in spite of their relatively low actual productivity in present environments.

Keywords: boreal forest, carbon, soil

1. Introduction

About 90% of forests in Russia are located in the boreal forest region. The latter comprises nearly 65% (0.77×10^9 hectares (ha), FSFMRF 1999) of the world's boreal forests, which are thought as playing a key role in the global C cycle. The Russian boreal forest occupies about 8% (1.37×10^9 ha) of the earth's vegetation and holds nearly 25% (559 Pg (petagrams; 1 Pg = 10^{15} g) of global terrestrial C stocks (LULUCF 2000). From this amount some 88 Pg C (20%) is captured by phytomass; the rest, 471 Pg C (80%), is allocated in soils. Over the last decade, major efforts of foresters in the country have been centered on estimating the C density and pools in phytomass. The results finally agree, e.g., 4.5 kg C m^{-2} (Isaev et al. 1995) and 4.4 kg C m^{-2} (Nilsson et al. 2000). However, soils were not the focus of these studies. The reported estimates of C content in forest soils remain controversial and uncertain. The variation in the estimates reaches 50%, e.g., 11.3 kg C m^{-2} (Alexeyev and Birdsey 1994) and 17.0 kg C m^{-2} in the 1m layer (Shvidenko and Nilsson 1998). The discrepancy of 5.7 kg C m^{-2} considerably exceeds the above-mentioned average C content in forest biomass. This gap makes most considerations on the C cycle and predictions of climate and human-induced changes in the forest biome for Russia speculative. Clearly, there is a need to improve the estimate results.

However, the latter can be done in a scientifically sound fashion if the causes of the above-mentioned variation are well understood.

By and large, a few general reasons contribute to the uncertainty of C estimates in soils: (1) insufficiency of soil knowledge; (2) variability of soil parameters involved in the computation; (3) inconsistency between the methods and concepts behind the calculation routine (Stolbovoi 2000). Some of these reasons can be avoided as far as Russia's forest soils are concerned. Indeed, Russia is rich in soil data. The systematic study of forest soils is rooted in the XIX century when Dokuchaev developed the fundamentals of soil science. Since then, numerous in-depth investigations have been carried out to overview diversity and specific pedogenetic features of forest soils, examine their fertility, ecological functions, etc. (Zonn 1964; Remezov and Pogrebnyak 1965; Karpachevski 1981). The major findings have been summarized by national soil classification (Classification... 1977) and applied for soil mapping at different scales. At the national level, the forest soils of Russia are mapped at scales of 1:2.5 million and 1:1 million. The administrative districts of the country have soil maps at scales 1:100 000 and 1:300 000. The forest enterprises carry out soil inventory at scales 1:25 000 and 1:50 000. In other words, the lack of reliable data on forest soils cannot be posed as a reason for the above-mentioned variation in the C estimates.

Estimating the C content in soils involves a set of parameters, e.g., C content, thickness, bulk density, and stone content (Stolbovoi 2002). The variability of the soil parameters are of natural and technical origin. Regarding Russia's soils, it is easy to estimate that with a 25–30% variability of the independent soil characteristics, the variation of the estimate would be within 15%. This consideration leads us to conclude that the variability of the soil parameters cannot explain the 50% variation in the C estimates in the forest soils.

Thus, we logically come to the conclusion that the inconsistency in the methods and concepts behind the calculation routine might be the major source of the observed variability between different C estimates. In fact, there is not a common accounting methodology for the C content in soils by different spatial units, e.g., natural zones, tree species, administrative regions, etc. Our special research has shown that different authors report the area of the tundra zone to be from 204 to 345 million ha for Russia (Stolbovoi 2000). Numerous studies in the country take zonal soil as being representative of the natural zone. It has been shown that Podzols, which are zonal for the taiga and mixed-coniferous-deciduous forests, occupy only 11% of the zone area and far beyond being an "average" for the zone (Stolbovoi and Sheremet 1997). The examples mentioned illustrate the need for considerable efforts to set up a common method to make the estimates of the C content in forest soils comparable.

The overall objective of this paper is to contribute to a better knowledge of C in the forest soils of Russia. The study specifically intends to demonstrate a transparent methodology of the C estimate in forest soils and reports the C density and pools in soils of the forest zone, forests and different tree species, and land use patterns.

2. Materials and Methods

The potentially forested territory in Russia, named the forest vegetation zone, covers approximately 1,050 million ha or 63% of the country (Stolbovoi and McCallum 2002). The Official State Forest Account operates with the "forest fund" and was about 1,181 million ha in 1990 (FSFMRF 1999). Nearly 763 million ha (70% of the forest fund) are forests. The rest includes non-forested territories that are under the authority of the Federal Forest Service, e.g., tundra pastures, meadows and bogs. Data on the forest fund mainly describes forests and is provided by administrative units. It does not contain information on natural characteristics (climate, vegetation zones, soils) and has limited details on other land use classes (cropland, grassland, wetland). Therefore, to come up with a comprehensive analysis of the C content in forest soils a diversity of different sources have to be processed. Most of the data used in the study is available on the newly established georeferenced database on the land resources of Russia (Stolbovoi and McCallum 2002). This source provides spatially explicit data relevant to the geographical scale of 1:4 million. The following databases have been used:

1. Dominant forests tree species of Russia (Figure 1a). The latter have been distinguished by selecting 49 forest communities from the vegetation map of Russia. This source reports data on potential vegetation, which is the status of the latter at the pre-industrial stage of development, e.g., the map shows forests that occurred before establishing cropland. The vegetation database allows for the forest to be aggregated by dominant species and natural zones.
2. Land use of Russia. This database has been applied to distinguish a present-day distribution of forests. It is also used to overview forests together with other land cover patterns of the country.
3. Soil map of Russia (Figure 1b). This database has been used to define spatially explicit C content in soils.

The overall methodology stems from a GIS-based analysis and includes the overlay of vegetation, land-use and soil digital maps to generate spatial accounting units and carry out spatially explicit calculations. Due to the divergence of natural boundaries the overlay might generate polygons with non-existing combination of vegetation, soils and land use. To distinguish the proper match between forests and soils, the map overlay was accompanied by adjustment rules to exclude soils that are not met in forests. The latter is attributed to Peat soils having a peat thickness of more than 0.3 m. This thickness is a criterion to distinguish forests from bogs in the State Forest Service of Russia (FSFMRF 1995). The average for the polygon C content in soils was taken to compensate the loss of C due to removing Peat soils and keeping the area balance of the polygon. Soils with a peat

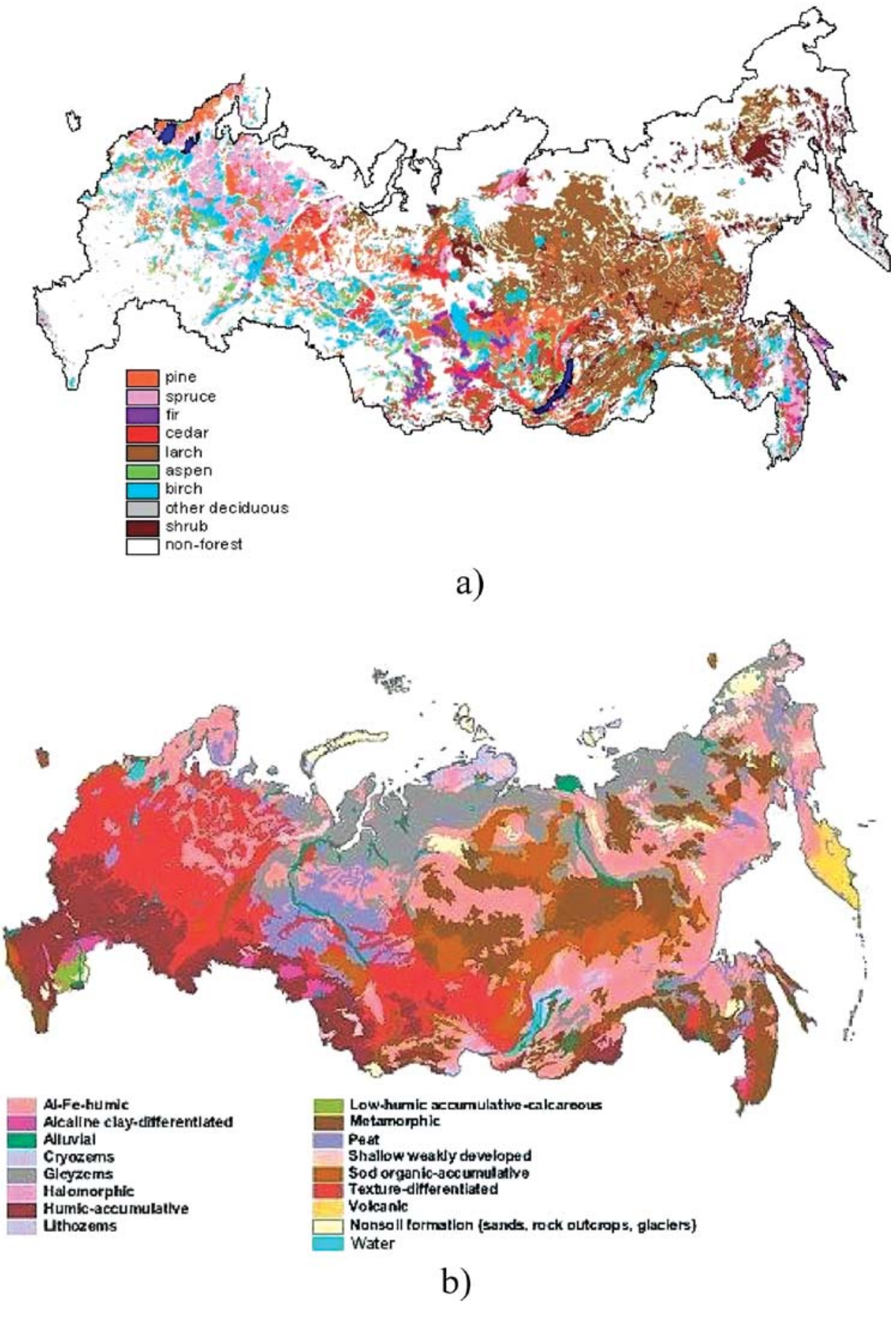

Figure 1. Distribution of tree species (a) and soils (b) in Russia (derived from: Stolbovoi and McCallum, 2002).

thickness less than 0.3 m are common for swampy forests and are included in the estimate.

The analysis exploits about 130 soil classes of the soil map legend that have different taxonomic levels. In order to make the discussion easy the calculated numbers generated by soil classes have been aggregated by 12 Soil Divisions, which are the second highest level of the classification hierarchy in Russia (Fridland 1982). This taxon distinguishes dominant pedogenetic features posed by the major characteristics of the soil profile resulting from leading soil-forming processes (for a soil description of Russia see Stolbovoi 2000). Special attention is paid to organic transformation and translocation that make Soil Divisions easily applicable to the study. A collection of 231 reference soil profiles characterizes forest soils of Russia in the study. This sampling population does not meet the statistical standard. It has been designed to describe all variety of soils occurring in the forest. To provide representativeness, the collection of soil profiles has been selected from widely cited publications describing the particular soil types. This expert-based representativeness can be used if statistically sound analysis is not applicable. Main definitions, laboratory and calculation routines on the C content in soils were discussed before (Stolbovoi 2002).

3. Results

3.1. FOREST AND SOILS OF RUSSIA

Forests penetrate the Arctic coast of European Russia, the tundra zone of Siberia and along river valleys in the Far East (Figure 1a). The majority of Russia's rivers flow from south to north. A mass of this water carries a huge amount of heat and warms surrounding areas in high latitudes. This explains the northward invasion of forests along river valleys. The tree line reaches 71°30′ N in the Khatanga River valley in the north of Krasnoyarskiy Krai, which is the northernmost point of forest appearance in the world. River valleys and sandy soils are the sites of the forest invasion to the south. Fir and pine forests with considerable areas of early succession of birch and aspen forests are found in European Russia. Dark coniferous forests of Siberian spruce, cedar and fir extend to the Ural Mountains and West Siberia. Light coniferous pine and larch forests on the north of Enisey River comprise vast territories of northern taiga. Fir and spruce forests occupy the mountains of South Siberia and the Far East. Forests in the Altai and Sayan mountains are dominated by Siberian spruce, cedar, and Siberian fir. The unique cedar-broad-leaved forests, spruce, and firs occur in the Amur region and to the south of Amur River. Stone birch forests and Siberian dwarf-pine woods in combination with sub-alpine vegetation of herbs and shrubs often occupy upper mountain forest belts in East Siberia, Zabaikalie and the Northeast.

Figure 1b shows the soil distribution across the country. The soil area, the correlation with internationally used soil classifications and the characteristic of soil sampling population used in the analysis are presented in Table I. This data demonstrate that Russia is dominated by Al-Fe-Humic (Podzols, Cryosols)[1] soils that occupy more than 365 million ha or 23% of the country's area. These soils are found in the northern part of the East European plain, in the middle part of West Siberia, in the central and southern parts of East Siberia and in the Far East. Gleyzems (Gleysols, Cryosols) are the second most extended soils in Russia. These soils occupy some 249.9 million ha or 15% of the country and are widespread in the north of the East European plain, in West Siberia, north of East Siberia and the Far East. Texture-differentiated (Albeluvisols) soils cover about the same area, 248.6 million ha or

TABLE I

Soil reserves, correlation and reference soil profiles

Soil Divisions (adapted from Fridland 1982)	Correlation with Reference Soil Groups (WRB 1998, p. 88)	Correlation with the USDA Soil Taxonomy (1999, p. 869)	Area of soil divisions		Number of forest soil profiles
			1×10^6 ha	% of total	
Al-Fe-Humic	Podzols, Cryosols	Spodosols, Gelisols	364.8	22	18
Gleyzems	Gleysols, Cryosols	Inceptisols, Gelisols	249.9	15	17
Texture-differentiated	Albeluvisols	Alfisols, Mollisols	248.6	15	41
Metamorphic	Cambisols, Umbrisols, Cryosols	Inceptisols, Gelisols	212.6	13	14
Humic-accumulative	Cheronozems, Phaeozems, Kastanozems, Planosols	Mollisols, Entisols, Aridisols	163.5	10	23
Peat	Histosols	Histosols	116.2	7	15
Sod organic-accumulative	Rendzic Leptosols, Umbrisols, Cryosols	Mollisols, Inseptisols, Gelisols	92.4	6	20
Alluvial	Fluvisols	Inceptisols	54.2	3	13
Shallow weakly-developed	Leptosols, Arenosols	Inceptisols	34.5	2	20
Volcanic	Andosols, Cryosols	Andisols, Gelisols	14.5	1	5
Alkaline clay-differentiated	Solonetz, Planosols	Aridisols, Alfesols, Mollisols	12.5	1	
Cryozems	Cryosols (also includes soil from other soil divisions)	Gelisols	9.4	1	27
Lithozems	Leptosols	Inceptisols	7.2	<1	18
Low-humic accumulative-calcareous	Calcisols	Aridisols	4.4	<1	n.f.
Halomorphic	Solonchaks, Fluvisols (Marsh)	Aridisols, Inceptisols	2.0	<1	n.f
Non-soil formations	Rock outcrops, glaciers, sands		40.3	2	n.f
Total			*1,627.0*	*100*	*231*

n.f. = non-forest soil

15% of the territory, as Gleyzems. These soils are widespread in the central part of the East European plain, in some parts of central West Siberia and the southern part of East Siberia. Metamorphic (Cambisols, Umbrisols, Cryosols) soils occupy about 212.6 million ha or 12%. These soils are found in the northern Caucasus, Ural, the central and northern parts of East Siberia and the Far East. Peat[2] (Histosols) soils amount to about 116 million ha or 7% of soil cover. The biggest extent of these soils is observed in the central part of West Siberia. All soils mentioned above are a product of cold and humid climates that cover about 80% of the country area. Soil-formation in warm semi-arid climate, e.g., Humic-accumulative soils (Chernozems, Phaeozems, Kastanozems, Planosols), is very limited in Russia (about 164 million ha or 10%). In particular, a small area in a hot arid climate is occupied by, e.g., Alcaline clay differentiated soils (Solonetz, Planosols) amounting to some 12.5 million ha or 1%, Low- humic accumulative calcareous soils (Calcisols) about 4 million ha or less than 1%, and Halomorphic soils [Solonchaks, Fluvisols (Marsh)] amounting to 2 million ha or less than 1%.

3.2. FOREST SOILS

The overlap of forest, land use and soil maps, as described in the methods section, results in a spectrum of forest soils (Figure 2). This figure shows that forests are selective to soil conditions. The most widespread in the forests of Russia are Al-Fe-humic soils. They are common for coniferous forests and derived from coarse-textured siliceous parent material. Texture-differentiated soils are the second most common forest soils. They develop under coniferous and/or mixed forests and are formed from medium or fine-textured loess-like and glacial till deposits. Metamorphic soils have the same extent in the forests as the Texture-differentiated

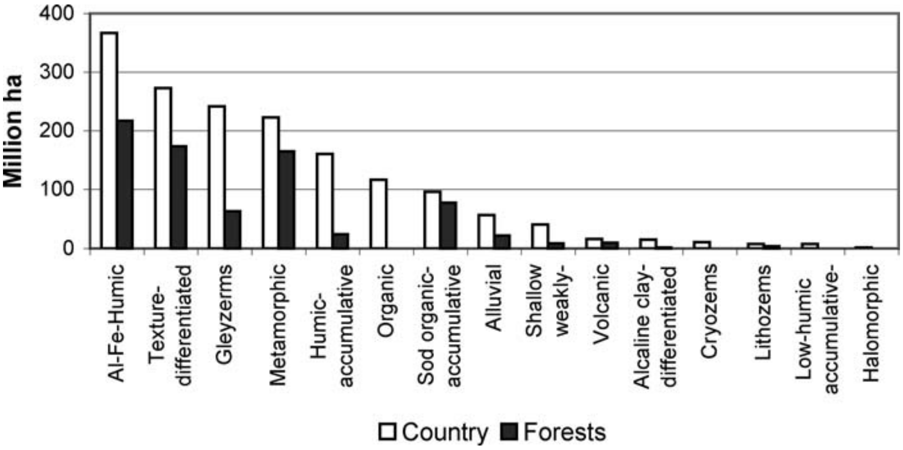

Figure 2. Forest in soil reserve of Russia.

soils. Sod organic-accumulative soils are common for the southern taiga and temperate forests that have abundant on-ground grasses and well-developed rhizosphere. Gleyzems are found in swampy forests that are common for poorly drained interfluves or depressions with shallow groundwater. Figure 2 shows the limited extent of Gleyzems in the forests of Russia. This fact illustrates that forests fail to grow on waterlogged soils in which development of a root system is constrained by poor oxygen, stagnant water and anoxic conditions (Persson 1992). Humus-accumulative, Alluvial and other soils are seldom found in the forests of Russia. These soils occur in treeless southern natural zones. As mentioned above, forests do not appear in both cold-polar and hot-subtropical semi-deserts and deserts in the country. Consequently, soils of these natural zones are not found in the forest soil spectrum.

Most forest soils have a profound accumulation of under decomposed organic litter on the topsoil, which is driven by specific C turnover, quality of the organic input into soils and allocation of the nutrient uptake by fine roots in the decaying litter (Persson 1992). About 93–94% of litter is utilized on the soil surface with the release of carbon dioxide (CO_2) as a final product (Glazovskaya 1996). The rest comes to soil solution and leaches supporting overall eluviation prevailing over enrichment in the forest soils.

The average concentration of dissolved organic substances is about 30–80 mg L^{-1}, which is detected by soil lizymeters in the forests (Dyakonova 1972). Part of this C is absorbed by deep soil. Another part is transported by rivers to seas or deeply leaked (Artemyev 1996).

It is widely reported that low temperature limits microbiological activity and slows down decay rate in the boreal forests (Raich 1995; Kudeyarov et al. 1996; Stolbovoi 2003). Nearly 90% of the forests in Russia have a negative annual air temperature (Stolbovoi 1999), which relates to permafrost (FAO 1998). Permafrost soils are unfavorable for soil fauna and are lacking zooturbation and mechanical mixing of organic matter that are common for the soils of the warmer climates. The abundant on-ground mosses, lichens, and evergreen leaves are rich in lignin and other recalcitrant organic compounds and have a low decomposition rate (Bazilevitch and Rodin 1971; Grishina 1986; Hobbie et al. 2000). Swampy forests formed due to excessive atmospheric precipitation have *Sphagnum spp.*, which produce antimicrobial substances favoring conservation of vegetation residues.

3.3. CARBON DENSITY AND PROFILES IN THE FOREST SOILS

The accumulation of under decomposed vegetation residues on the topsoil correlates with a high C content (Table II). It can be calculated that the 0.3 m layer contains more than 70% of C of the 2 m layer for the majority of forest soils. The concentration of C in the topsoil of Metamorphic soils is 12.2 kg C m^{-2} (0.3m) that roughly accounts for about 80% of C captured by the 2 m layer (15.7 kg C m^{-2}). The exception is for soils formed under a specific lithogenic regime, such as volcanic

TABLE II

Area-weighted average C density in forest soils of Russia (layers in m)

	Organic (kg C m^{-2})			
Soil division	0–0.3	0–0.5	0–1.0	0–2.0
Metamorphic	12.2	13.6	15.2	15.7
Humic-accumulative	11.7	16.2	20.2	22.4
Gleyzems[a]	10.7	12.5	13.7	14.9
Sod organic-accumulative	10.3	11.9	13.9	15.1
Volcanic	7.0	10.1	18.2	22.3
Texture-differentiated	7.0	9.3	10.8	11.9
Lithozems	6.8	n.d.	n.d.	n.d.
Al-Fe-Humic	6.7	8.3	9.7	10.0
Alluvial	6.2	9.2	14.1	18.0
Shallow weakly developed	3.1	4.0	n.d.	n.d.

[a] Glezems with thickness of peat horizon more than 30 cm excluded.
n.d.–not distinguished for shallow soils.

and alluvial soils, where pedogenesis co-exists with sedimentogenesis. These soils have profiles with numerous buried organic horizons and the distribution of C with depth is smooth.

Figure 3 illustrates major types of C profiles in the forest soils of Russia. The lowest C content is found for Al-Fe-Humic soils that have limited absorption capacity due to coarse texture. Fine textured Texture-differentiated soils have a higher rate of absorption, which coincides with the larger C concentration. Metamorphic soils and Gleyzems are rich in C topsoil that sharply declines with depth. This C profile corresponds to the intensive surface accumulation of the litter. Sod organic-accumulative

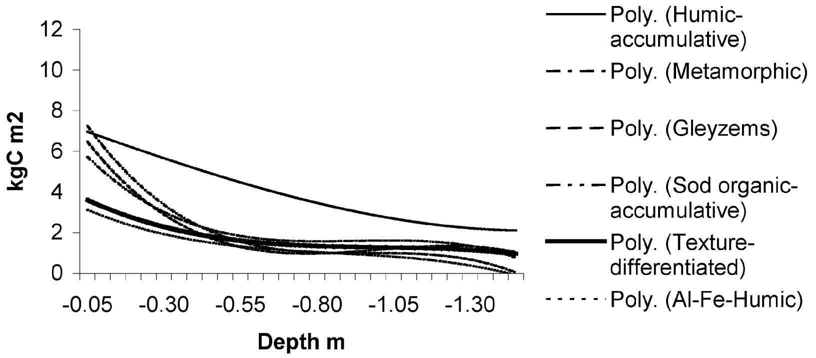

Figure 3. Distribution of C density with depth for major forest soils of Russia (3rd order polynomial trend lines).

soils have a similar C profile. However, these soils occur in the south taiga with abundant grasses and have sod-humus topsoil. Humic-accumulative soils have a C profile different from that of other forest soils. These soils are rich in C topsoil and contain a considerable amount of C in deep soil. The latter is common for the steppe grassland having a well-developed rhyzosphere that favors humus formation.

The SCD varies by four times (from 3.1 to 12.2 kg C m^{-2}) in the forest soils of Russia (Table II). This range is considerably less than that of the complete spectrum of soils in the country, e.g., from 1.7 to 20.9 kg C m^{-2} for 0.3 m (Stolbovoi 2002). The narrower range in the SCD is explained by a limited variety of ecological controls in the forest for biomass production, litter fall, decay, humification and translocation into the litho- and hydrosphere.

The highest SCD is found in the topsoil (0.3m) of Metamorphic soils (12.2 kg C m^{-2}), which are common for the permafrost-affected soils of Siberia having a thick litter horizon formed from moss, lichen and coniferous leaves. The lowest SCD (3.1 kg C m^{-2}) is manifested by shallow weakly developed soils. These two values identify thresholds of SCD for the forests soils in Russia. Within this range, Humic-accumulative soils have 11.7 kg C m^{-2} and Gleysols and Sod organic-accumulative soils accumulate 10.3 kg C m^{-2} and 10.7 kg C m^{-2}, respectively. Other Soil Divisions fall into the intermediate group holding from 6.2 to 7.0 kg C m^{-2}. The SCD values match well those reported for soils of Russia (Turin 1965; Orlov et al. 1996).

3.4. CARBON CONTENT IN SOILS BY DOMINANT FORESTS SPECIES

Forest species have different preferences for soil conditions (Figure 4). As can be seen in this figure, pine, larch and cedar coniferous and soft deciduous forests

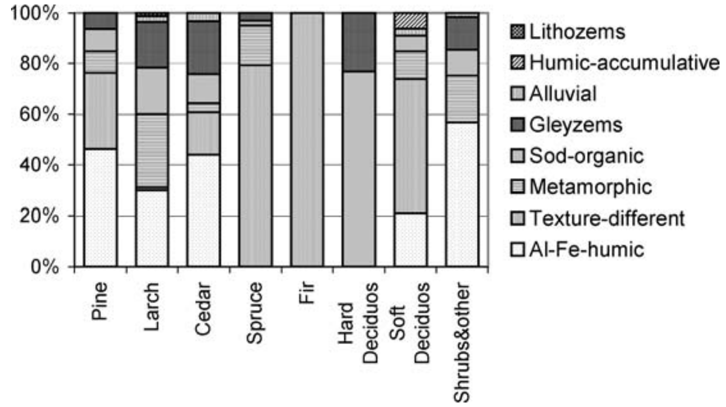

Figure 4. Soil Spectra (% of area) by dominant forest species in Russia.

and shrubs are eurytolerant to soil conditions. These forests have a wide range (spectrum) of soils varied from well aerated coarse-textured Al-Fe-humic to poorly drained fine textured Gleyzems. Spruce forests prefer a variety of fine textured soils. Hard deciduous and fir in particular are more selective to soil conditions. These forest species occupy sites with fine textured soils that might have features of redoximorphism.

The observation of the soil variety under different forest species clearly illustrates a lack of any single soil to be representative for all forests. Moreover, different forests can be identified only by entire soil diversity or forest specific spectra of soils occurring in this forest. This finding can be drawn as a common rule stating that only spectra of soils or region specific fractional composition of soils provide a geographically sound soil characterization of any territory, e.g., natural zone, administrative region, forest, etc. Thus, all spatially explicit calculations have to operate with area-weighted soil values. This approach is applied in our study.

The highest (hereafter area-weighted) SCD (10.2 kg C m^{-2}) is found in the topsoil under larch forests (Table III). This is explained by a relatively low decomposition rate of vegetation residues in these forests. In fact, larch occupies the coldest thermal niche among all forests in Russia. Mean annual air temperature for larch forests varies from -8.4°C in the middle taiga to -12.2°C in the forest-tundra zone (Stolbovoi 1999). The low decomposition is also supported by the highest lignin content and lowest nutrient concentrations in larch leaves (Bazilevitch and Rodin 1971; Mitrofanov 1977). Soils under fir and spruce forests have practically the same C content, i.e., 7.3 kg C m^{-2} and 7.2 kg C m^{-2}, respectively. Soils under coniferous forests have a sharp C decline with depth, which is common for soil having a thick litter and peaty-muck topsoil. The content of C in soils of deciduous forests varies

TABLE III

Carbon mean area weighted densities and pools in soils under different tree species (layers in m)

		0–0.3		0–0.5		0–1.0		0–2.0	
Forests	Area ha 10^6	kg C m^{-2}	Pg C	kg C m^{-2}	Pg C	kg C m^{-2}	Pg C	kg C m^{-2}	Pg C
Pine	127.7	6.5	8.3	8.2	10.5	9.3	11.9	10.1	12.9
Spruce	84.6	7.2	6.0	9.5	8.0	10.8	9.1	11.7	9.9
Larch	264.1	10.2	27.0	12.4	32.7	13.7	36.3	14.7	38.9
Cedar	43.2	7.0	3.0	8.9	3.8	10.0	4.3	10.7	4.6
Fir	15.9	7.3	1.2	8.6	1.4	10.0	1.6	11.1	1.8
Coniferous	540.5	8.4	45.5	10.5	56.5	11.7	63.1	12.6	68.0
Hard deciduous	19.5	7.9	1.6	10.0	2.0	13.1	2.6	15.2	3.0
Soft deciduous	133.5	6.9	9.2	8.5	11.4	9.9	13.2	10.8	14.5
Shrubs & other	70.0	8.9	6.2	10.7	7.5	12.1	8.4	13.0	9.1
Total country	763.5	8.2	62.4	10.2	77.3	11.5	87.3	12.5	94.5

from 6.9 kg C m^{-2} (soft deciduous) to 7.9 kg C m^{-2} (hard deciduous). These forests have the warmest mean annual temperature, around 0°C and better decomposable litter due to relatively low lignin content and relatively high concentrations of nutrients in leaves. Hard deciduous forests have a well-developed rhizosphere that supports humus formation leading to the highest C content (15.2 kg C m^{-2}) in the 2 m soil layer.

The SCP for dominant forests species is defined by area weighted composition of soil occurring in this forest (Table III). The larch forest has both the highest SCD and the largest area and holds the biggest SCP, e.g., 27 Pg C in the 0.3 m layer and about 39 Pg C in the 2 m layer. This amount comprises nearly 70% of total accumulation of C in the soils under coniferous forests. Opposite, the fir forest occupies the smallest area and has considerably lower SCP that is about 1 Pg C and 2 Pg C in 0.3 m and 2 m layers, respectively.

3.5. CARBON CONTENT IN THE FOREST SOILS BY NATURAL ZONES

Table IV illustrates that C mass in the 0.3 m soil layer tends to concentrate in the tundra, pre-tundra and northern taiga, middle taiga and south taiga zones. This pattern is common for Russia (Orlov et al. 1996; Stolbovoi 2002) and supports the above-mentioned observation on specific C turnover in forest ecosystems. The average SCD for the forest zones is higher than that of the forest species (Table III). The latter shows that Peat soils are another important component that influences the C content in the topsoil of the forest zone (Figure 5).

TABLE IV

Organic C Content[a] in Soil by Vegetation Zones (layers in m)

	Area		0–0.3			0.3–1.0			0–1.0		
			Pool			Pool			Pool		
Zone	10^6 ha	% of total	Pg	% of total	Density, kg Cm^{-2}	Pg	% of total	Density, kg Cm^{-2}	Pg	% of total	Density, kg Cm^{-2}
Polar desert	0.7	0	0	0	2.9	0	0	0	<0.1	0	2.9
Tundra	266.9	16	30.9	18	11.6	13.4	10	5	44.3	15	16.6
Forests, including											
Forest-tundra & northern taiga	233	14	31.1	19	13.3	31.5	24	13.5	62.6	21	26.9
Middle taiga	683.6	42	64.4	38	9.4	47	36	6.9	111.4	37	16.3
Southern taiga	211.5	13	18.4	11	8.7	22.4	17	10.6	40.8	14	19.3
Temperate forest	60.4	4	5.5	3	9	3.3	3	5.4	8.8	3	14.5
Total forest zone	1188.5	73	119.4	71	10.0	104.2	80	8.8	223.6	75	18.8
Steppe	148.8	9	15.6	9	10.5	11.6	9	7.8	27.2	9	18.3
Semi-desert & desert	25.4	2	1.5	1	5.9	0.9	1	3.6	2.4	1	9.5
Total Russia	1,629.80	100	167.4	100	10.3	130.1	100	8	297.5	100	18.3

[a] Anthropogenic impact is not accounted.

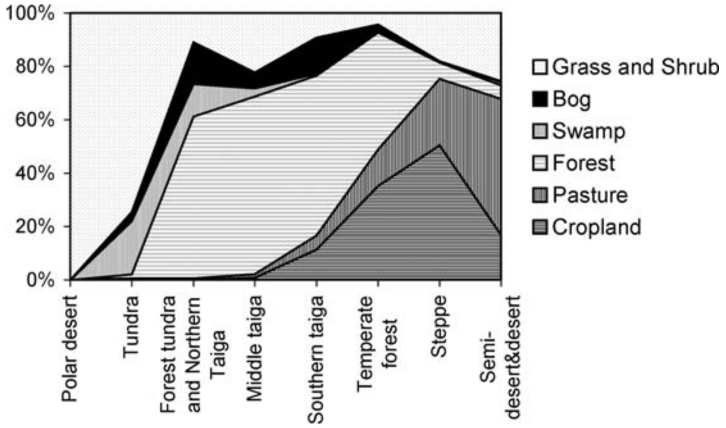

Figure 5. Land-cover of Russia (Source: Stolbovoi 2002).

The 0.3–1 m layer shows a picture different from that of the topsoil (Table IV). The tundra soils contain less C than can be expected from the proportion of the zone area. Due to a high permafrost table this zone is dominated by Gleyzems with shallow peat (Vomperski et al. 1998; Stolbovoi 2002). The soils of the forest-tundra, northern and southern taiga have considerable area of deep peat, which results in the highest C content in deep soil (Figure 5). Thus, the content of C in deep soils of the forest zone is substantially driven by the distribution of Peat soils. The latter is conditioned by hydrological regime, redoximorphic features in soils and low decay of mosses and vascular plants tissues. Processes of polludification in the tundra and Siberian forests are also supported by shallow permafrost along with poorly drained relief (Stolbovoi 2002).

The content of C in the 1 m soil layer reaches 297.5 Pg, which corresponds to 18.3 kg C m^{-2} mean SCD for the country. The largest SCP is observed for the middle taiga zone (111.4 Pg C) due to its huge area. The highest SCD (26.9 kg C m^{-2}) is found for the forest-tundra and the northern taiga zones, which, as mentioned above, is caused by considerable area of Peat soils. The forest zone of Russia holds 223.5 Pg C, which is 75% of the country total. This amount corresponds to the mean SCD for the forest zone that is close to 18.8 kg C m^{-2}.

3.6. CARBON CONTENT IN THE FOREST SOILS BY LAND USE PATTERNS

As can be seen in Figure 5 forests are an essential element of land cover mosaic of all natural zones in the country except the polar and southern deserts. The tundra contains small fragments of forests (2%), which occupy the warmest river valleys. Forests cover about 64% of the forest-tundra and northern taiga, 67% of the middle taiga and 62% of the southern taiga. They occupy nearly 42% of the temperate zone and about 4% of the steppe zone.

Various land use covers (LUC) are different by C content in soils (Table V). This is caused by selective use of soils in line with natural conditions and different land management practices. The table illustrates that soil C profiles of LUC patterns principally follow that of natural soils. The major regularities found for the natural zones are kept. This is caused by the limited extent of agriculture, about 13% of the country's area and, the traditional C-saving land management containing crop rotation with legumes, fallows, etc.

The content of C in the topsoil of forest soils is less than that of cropland, which is explained by the dehumification of cultivated soils and causes the loss of about 20% of the native C content (Stolbovoi 2002). However, deep soil horizons of cultivated soils are about two times richer in C compared to forest soils. The prevailing Humic-accumulative soils in cropland explain this. The concentration of C in forest soils is higher than that in the soils of pastures, grasses and shrubs. Forest soils have less C than swamps and bogs, which is widely reported (Orlov et al. 1996; Vomperski et al. 1998; Stolbovoi 2002).

The distribution of the SCP correlates with the LUC area (Table V). Forest soils capture less C than their area, e.g., they hold about 38% of the SCP in the 0.3 m and occupy about 45% of the country. This disproportion is in line with less SCD in the forest soils compared with that of other LUC patterns. The gap under consideration increases with depth and the 0.3–1 m layer of forest soils captures only 20% of the C of the country. This decline is also observed by soils under pastures, grasses and shrubs. The picture is different for swamps and bogs. Occupying about 13% of the territory together, these soils capture 32% of the organic C accumulated by the 0.3 m layer and nearly 61% of C stocked by the 0.3–1 m layer.

TABLE V

Organic C Content[a] by Land Use (layers in m)

	Area		0–0.3			0.3–1.0			0–1.0		
			Pool			Pool			Pool		
Land-use	1×10^6 ha	% of total	Pg	% of total	Density, kg C m^{-2}	Pg	% of total	Density, kg C m^{-2}	Pg	% of total	Density, kg C m^{-2}
Cropland	130	8	10.8	7	8.2	8.2	6	6.3	19	6	14.6
Pasture	81	5	5.9	4	7.3	3	2	3.7	8.9	3	11.0
Forest	764	45	61.6	38	8.1	25.7	20	3.4	87.3	30	11.4
Swamps[b]	116	7	28.4	17	24.5	9.2	7	7.9	37.6	13	32.4
Bogs[c]	105	6	24.3	15	23.1	70	54	60.3	94.3	32	89.8
Grasses & Shrubs	433	25	33	20	7.6	12.5	10	2.9	45.5	16	10.5
Bare land	79.8	5	0	0	0	0	0	0	0	0	0.0
Total country	1, 709.6	100	164	100	10.1	128.6	100	7.9	292.6	100	18.0

[a] Human-induced dehumification is included; [b] Thickness of peat is 0.3–0.5m;
[c] Thickness of peat >0.5m.

The analysis of the C content for the 1 m layer illustrates that soils under forests hold about 87 Pg C or nearly 30% of the country total. The average SCD (11.4 kg C m^{-2}) is higher than in pastures (11.0 kg C m^{-2}) and grasses and shrubs (10.5 kg C m^{-2}). The SCD in cropland is about 25% higher than that of the forests. The average SCD and SCP for the country calculated by land use patterns is less than that of the natural zones (Table V). This is explained by dehumufication of the agricultural soils caused by cultivation (Stolbovoi 2002).

4. Discussion

Alexeyev and Birdsey (1994, p. 170) report the average SCD for the 1 m layer to be about 11.3 kg C m^{-2}, which is practically the same as the result of this study 11.4 kg C m^{-2} (Table III). Chestnykh et al. (1999, p. 13–21) calculate the SCD for 1 m layer to be about 14.8 kg C m^{-2}, which is 25% higher than the result of this study. Stemming from tabular-based sources, both cited studies have insufficient cartographic background to enable sound geographical analysis of soil distribution to be carried out. To characterize the soils of the administrative regions and forests, these studies applied average C content arrived from available soil sampling. However, these averages address only the sampling population itself and have little in common with the geographical representativeness of the soil collection. In other words, the key question on how this sampling population meets soil diversity of the particular forest or region remains out of consideration. As illustrated above, the SCD is varied greatly from one soil to another. A fractional composition of soils (soil spectra) defines the amount of soil C in any spatial unit (forest zone, forest species, administrative region, etc.). We hypothesize that the discrepancy in the geographical representation of soils is the reason for the inconsistency between the two cited estimates above. The highest C content in the forest soils published by Chestnykh et al. (1999, p. 13–21) are taken from the sampling population containing occasionally richer C soils.

The highest SCD (17.0 kg C m^{-2}) reported by Shvidenko and Nilsson (1998, p. 25) addresses the soil of the forest zone and is taken from Rozhkov et al. (1996, p 44). However, Rozhkov et al. applied misgiving correction coefficients to adjust incomplete C recovery of Turin's method, which vary from 1.18–1.36 for different soils in the country. This correction made the results incompatible with any other in Russia. Nevertheless, if we use an average for soil of Russia coefficient 1.28 to make the estimate of Shvidenko and Nilsson (1998, p. 25) compatible, we will come up with 13.3 kg C m^{-2}, which is somewhere between the results of Alexeyev and Birdsey and Chestnykh et al. In the latest publication Shvidenko and Nilsson (2003, p. 391–415) reported SCD (15.6 kg C m^{-2}) for 1 m soil layer of Russia's forests. This publication does not indicate which soil database was used and if it was Rozhkov et al. (1996, p. 44) it is not clear why the result is different from the earlier one. Lastly, both above-mentioned publications by Shvidenko and Nilsson do not contain explanations of the origin of the estimates, e.g., description of soils and databases, methods of calculations, etc. For example, it is unclear, which soil organic horizons have been included in 1 m soil layer and how the authors separate litter from surface soil organic matter, etc.

Our observation above shows that two reasons cause a big variation in estimating the C content in the forest soils of Russia: (1) a confusion of terms, especially "soils under forest or forest soils" and "soils of the forest zone or soil of the region where forest occur", and (2) ignorance of geographical representativeness of the soils. In spite of this finding, the criteria of the "true" estimate are unclear. In this context, the consideration of the C content in the forest soils in relation to other LUC patterns might be of specific interest. We assume that forest-limited analysis of the land cover mosaic is partial and insufficient for justifying the result. Our study shows that the result well matches the most comprehensive estimate of the C reserves for the country, e.g., 296 Pg C (Orlov et al. 1996) and 292.6 Pg C (Table V) for the 1 m layer. As far as other LUC patterns are concerned, we found previously (Stolbovoi 2002) a good agreement (6–7%) with data reported by the countrywide soil survey for cropland (Krylatov 1996) and high confidence with the independent estimate of the C content in wetlands (Vomperski et al. 1998).

Our result meets the global SCD average for the 1 m layer of the boreal forest soils, 11.6 kg C m^{-2} (Post et al. 1982). This is in the order of magnitude of SCD in the boreal forests of Canada (about 9.2 kg C m^{-2}), which is the sum of C in the forest floor and mineral soils (Bhatti and Apps 2000). Tarnocai (1998, p. 81–93) reports the SCD for the 0.3 m layer of the boreal zone of Canada being about 11.8 kg C m^{-2}, which is in the range of C content in the boreal zone of Russia (from 8.7 to 13.3 kg C m^{-2}). This author found SCD for the 1 m layer two times higher (50.5 kg C m^{-2}) in Canada than that in Russia (19–27 kg C m^{-2}). The laboratory routines in both countries (Walkley-Black method in Canada and Turin method in Russia) give compatible results (Kogut and Frid 1993). We suggest that the difference originates from a discrepancy in the field measurements. Clearly, a harmonization of the sampling techniques has to be done in the future for the soils of the circumpolar boreal zone. Our result coincides with the average SCD in the 1 m of the forest soils in Minnesota, Wisconsin, and Michigan (10.5 kg C m^{-2}) (Grigal and Ohman 1992) and in Finland (4.0 to 11.9 kg C m^{-2})(Liski and Westman 1995).

Soils of the boreal forest zone in Russia accumulate some 223.6 Pg C in the upper 1 m layer, which comprises about 40% of that captured by the global boreal biome (470 Pg C, LULUCF 2000). This is nearly 25% less than can be expected from the proportion of the country in the biome area (some 65%). As shown above, the C content in forest soils is compatible with that of other boreal regions. Thus, the inconsistency in question comes mostly from the difference in the C concentration in Peat soils.

The productivity of boreal forests and consequently input of vegetation residues into soils of Russia is about 20% less than that of other boreal regions (Nilsson et al. 2000). Following the basic rule describing C equilibrium in soils (Orlov 1990; Stevenson 1994), the low input of organic matter should result in the lower C content in soils. However, our study does not support this rule, which means that the intensity of C accumulation in soils of Russia is relatively high. The major reasons for the latter have been considered above and explained by the specific features of the C cycle in the boreal forests of Russia, e.g., deteriorated microbiological activity favoring organic conservation, accumulation of about 70–80% of total C content on the soil surface, abundant content of recalcitrant compounds in soil litter, etc.

The high accumulation of organic matter and associated essential nutrients in the soils of boreal forests keeps production potential of the boreal ecosystems high in spite of their relatively low productivity in present natural conditions. Without conservation of organic matter in soils forest ecosystems will lose unutilized nutrients due to intensive leaching. To investigate the mechanisms and regulatory role of soils in maintaining nutrient resources and productivity of the boreal ecosystems are great challenges for future research.

5. Conclusions

The confusion of terms and ignorance of the soil geographical representativeness for forests are major causes of high variation between present-day estimates of C content in the forest soils of Russia.

The average SCD for the 0.3 m layer of the forest soils in Russia is about 8.1 kg C m^{-2}; the 1 m layer captures some 11.4 kg C m^{-2}; and the 2 m layer holds nearly 12.3 kg C m^{-2}. Larch forests have the highest C concentration in the topsoil due to the coldest temperature thereby slowing down biological activity in soils and specific chemical composition of the vegetation residues that are abundant in recalcitrant compounds content, e.g., rich in lignin and poor in nutrients content mosses, lichen and vascular plants, etc. The intensive downward migration of dissolved organic substances is another important feature of the C biogeochemistry of the forest soils.

The mass of C is about 61.6 Pg C concentrated in the 0.3 m layer of forest soils. The 1 m layer accumulates 87.6 Pg C and the 2 m layer holds about 94.1 Pg C.

The C content in the forest zone is much higher for Russia. The SCD is 18.8 kg C $m^{-2}$and SCP is 223.6 Pg C. Peat soils contribute a considerable portion of C to the forest zone of the country.

The cold climate, permafrost and vegetation residues that are rich in recalcitrant compounds support a relatively high rate of accumulation of organic matter and associated nutrients in soils. This conservation keeps the production potential of the boreal ecosystems high in spite of their relatively low productivity in present environments.

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Notes

1. Hereafter the FAO (1998, p.88) terms are given in brackets.
2. The thickness of the peat horizon exceeds 0.5 m.

References

Alexeyev, V.A. and Birdsey R.A. (eds.): 1994, *Carbon in Ecosystems of Forests and Wetlands of Russia,* Krasnoyarsk, Russia, Publ. Sukachev Institute of Forest Research, p. 170 (in Russian).

Artemyev, V.E.: 1996, *Geochemistry of Organic Matter in River-Sea Systems*, Dordrecht, Netherlands, Kluwer Academic Publishers, p. 204.

Bazilevitch, N.I. and Rodin, L.E.: 1971, ‘Production and elements turnover in native and used phytocoenosises’, in ‘Biological Productivity and Elements Turnover in Vegetation Communities’, Nauka, Leningrad, Russia, pp. 5–32 (in Russian).

Bhatti, J.S. and Apps, M.: 2000, *Carbon and Nitrogen Storage in Upland Boreal Forests*, *Advances in Soil Science* Lewis Publishers, USA, p. 79–78.

Chestnykh, O.V., Zamolodchikov, D.G., Utkin, A.I. and Korovin, G.N.: 1999, ‘Distribution of organic carbon stock in forest soils of Russia’, *Lesovedenje* **2**, 13–21 (in Russian).

Classification and diagnostic of soils of the USSR: 1977, Moscow, Russia, Publ. Kolos, p. 221 (in Russian).

Dyakonova, K.V.: 1972, ‘Organic and mineral substances in the lysimeter solution from some soil types and their role in modern soil-forming processes’, in *Organic Substances of Native and Managed Soils*, Moscow, Russia, Nauka, p. 183–223 (in Russian).

FAO: 1998, World Reference Base for Soil Resources. *World Soil Resources Report* Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, **84**, p. 88.

Fridland, V.M.: 1982, *Main Principles and Elements of Basic Soil Classification and Program for Development*, Moscow, Russia, All Union Academy of Agricultural Science, p. 149 (in Russian).

FSFMRF: 1995, *Manual on Forest Inventory and Planning in Forest Fund of Russia*, Federal Service of Forest Management of the Russian Federation (FSFMRF), Moscow, Part I, p. 175; Part II, p. 112 (in Russian).

FSFMRF: 1999, *Forest Fund of Russia* (State by 1 January 1998), Federal Service of Forest Management of the Russian Federation (FSFMRF), Moscow, p. 650 (in Russian).

Glazovskaya, M.A.: 1996, ‘Role and functions of the pedosphere in geochemical carbon cycles’, *Pochvovedenje* Nauka, Russia, **2**, 174–186 (in Russian).

Grigal, D.F. and Ohman, L.F.: 1992, ‘Carbon storage in upland forest of the Lake States’, *Soil Science Society of American Journal* **56**, 935.

Grishina, L.A.: 1986, *Humus Formation and Humus Status of Soils*, Russia, Publication of Moscow State University, p. 244 (in Russian).

Hobbie, S., Schimel, J.P., Trumbore, S.E. and Randerson, J.R.: 2000, ‘Controls over carbon storage and turnover in high-latitude soils’, *Global Change Biology* **6** (Suppl. 1), 196–210.

Isaev, A., Korovin, G., Zamolodchikov, D., Utkin, A. and Pryashnikov, A.: 1995, ‘Carbon stock and deposition in phytomass of the Russian forests’, *Water, Air and Soil Pollution* **82**, 207–256.

Karpachevski, L.O.: 1981, *Forests and Forest Soils. Forest Industry*, Moscow, Russia, p. 262 (in Russian).

Kogut, B. and Frid, A.: 1993, Comparative evaluation of methods of determining humus concentration in soils. *Pochvovedenie*, 9, Nauka, Moscow, Russia, pp. 119–123 (in Russian).

Krylatov, A.K.: 1996, *Physical-Chemical Characteristics of Agricultural Land and Humus Balance of Cropland of Russian Federation*, Russlit, Moscow, p. 392, (in Russian).

Kudeyarov, V.N., Hakimov, F.I., Deyeva, N.F., Il’ina, A.A., Kuznetzova, T.V. and Timchenko, A.V.: 1996, ‘Evaluation of respiration of Russian soils’, *Eurasian Soil Science* **28**, 20–34.

Liski, J. and Westman, C.J.: 1995, ‘Density of organic carbon in soil at coniferous forest sites in southern Finland’, *Biogeochemistry* **29**, 183–197.

LULUCF: 2000, ‘Land use, land-use change, and forestry’, in R. Watson, N. Ravindranath, I. Noble, D.J. Verardo, B. Bolin and D.J. Dokken, (eds.), *A special Report of the IPCC*, Cambridge University Press, Cambridge, UK, p. 377.

Mitrofanov, D.P.: 1977, *Chemical Composition of the Forest Vegetation in Siberia*, Russia, Publications of Nauka Siberian Branch, Novosibirsk, p. 120 (in Russian).

Nilsson, S., Shvidenko, A., Stolbovoi, V., Gluck, M., Jonas, M. and Obersteiner, M.: 2000, *Full Carbon Account for Russia*, Interim Report IR-00-021, International Institute for Applied Systems Analysis, Laxenburg, Austria, p. 180.

Orlov, D.S.: 1990, *Humic Acids in Soils and General Theory of Humification*, Moscow, Publications of Moscow State University, p. 325.

Orlov, D.S., Biryukova, O.N. and Sakhanova, N.I.: 1996, *Soil Organic Matter of Russia*, Nauka, ISBN 5-02-003643-9, Moscow, Russia, p. 256 (in Russian).

Persson, H.: 1992, *Factors Affecting Fine Root Dynamics of Trees*, in SUO Maries and peat, Vol. 43, 4–5, Helsinki, Finland, p. 163–172.

Post, W.M., Emanuel,W.R, Zinke, O.J. and Stangerberger, A.G.: 1982, ‘Soil carbon pools and live zones’, *Nature*, **298**, 156–159.

Raich, J.W. and Potter, C.S.: 1995, ‘Global patterns of carbon dioxide emissions from soils’, *Global Biogeochemical Cycles* **9**, 23–36.

Remezov, N.P. and Pogrebnyak, P.S.: 1965, *Forest Pedology*, Forest Industry, Moscow, Russia, p. 324 (in Russian).

Rozhkov, V.A., Wagner, V.B., Kogut, B.M., Konyushkov, D.E., Nilson, S., Sheremet, V.B. and Shvidenko, A.Z.: 1996, *Soil Carbon Estimates and Soil Carbon Map for Russia*, Working Paper WP-96-60, International Institute for Applied Systems Analysis, Laxenburg, Austria, p. 44.

Shvidenko, A. and Nilsson, S.: 1998, *Phytomass, Increment, Mortality and Carbon Budget of Russian Forests*, Interim Report IR-98-105, International Institute for Applied Systems Analysis, Laxenburg, Austria, p. 25.

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

Stevenson, F.J.: 1994, *Humus Chemistry: Genesis, Composition, Reactions*, Wiley, New York, USA, p. 281.

Stolbovoi, V.: 1999, ‘Classification of Russia’s boreal forest in relation to global climate warming’, in S. Woxhott (ed.), *Proceedings of the ninth IBFRA Conference*, Oslo, September 21–23, 1998, Aktuelt, 4, North institute for skogforskning, pp. 60–69.

Stolbovoi, V.: 2000, *Carbon Pools in Tundra Soils of Russia: Improving Data Reliability. Advances in Soil Science*, Lewis Publishers, USA, pp. 39–58.

Stolbovoi, V.: 2000, *Soils of Russia: Correlated with the Revised Legend of the FAO Soil Map of the World and World Reference Base for Soil Resources*, Research Report RR-00-13, International Institute for Applied Systems Analysis, Laxenburg, Austria, p. 112.

Stolbovoi, V.: 2002, 'Carbon in Russian soils', *Climatic Change* **55**(1–2), 131–156.

Stolbovoi, V.: 2003, Soil respiration and its role in Russia's terrestrial C flux balance for the Kyoto baseline year', *Tellus* **55B**, 258–269.

Stolbovoi, V. and Sheremet, B.: 1997, 'On the soil fund of Russia', *Eurasian Soil Science* **30**(12), 1278–1286.

Stolbovoi, V. and McCallum, I.: 2002, *Land Resources of Russia*, CD-ROM, International Institute for Applied Systems Analysis, Laxenburg, Austria and the Russian Academy of Sciences, Moscow. Available on the Internet: http://www.iiasa.ac.at/Research/FOR/Russia_cd/index.htm.

Tarnocai, C.: 1998, 'The amount of organic carbon in various soil orders and ecological provinces in Canada. Soil processes and the carbon cycle', in R. Lal, J. Kimble, R. Follet, B. Stewart (eds.), *Soil Processes and the Carbon Cycle*, Advances in Soil Science, CRC Press, Boca Raton, Fla, USA, pp. 81–93.

Turin, I.V.: 1965, *Soil Organic Matter and Its Role in the Soil Fertility*, Nauka, Moscow, USSR, p. 319 (in Russian).

Vomperski, S.E., Tciganova, O.P., Kovalev, A.V., Gluhova, T.V. and Valiaeva, N.A.: 1998, 'Over-moisturing of Russia territory as a factor of carbon sequestration from atmosphere', in G.A. Zavarzin (ed.), *Carbon Turnover on Russia Territory*, Moscow branch of SSRC WGD Ministry of Education of Russia, Moscow, Russia, pp. 233–270 (in Russian).

Zonn, S.V.: 1964, *Soils, as a Component of Forest Biogeocenoese*, Fundamental of forest biocenology. Moscow, Russia, p. 574 (in Russian).