Forest Ecology and Management 169 (2002) 29–44

Forest Ecology and Management

www.elsevier.com/locate/foreco

Simulated soil organic matter dynamics in forests of the Leningrad administrative area, northwestern Russia

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Abstract

The assessment of carbon balance in forest soils of the Leningrad administrative area (south boreal sub-zone of east European plain) has been carried out using: (1) previous data on carbon pools of forest soils without considering mires area as initial data (organic layer plus 50 cm soil); (2) inventory data on forest stands that has been converted into biomass and data on litter input; (3) meteorological data concerning the mean monthly air temperature and precipitation. The most recent model version of soil organic matter (SOMM) dynamics was applied for a 100-year simulation of carbon dynamics in the 3.22×10^6 ha of forest soils of the Leningrad area considering a constant forest-age structure and climate. The results demonstrate unique carbon dynamics in various soils, and an 8% increase of the total carbon pool of the area's forest soils during the 100-year simulation (from 266 to 286 million tons of carbon). The total carbon input to the soil, in the form of litter carbon, was 8.3 million tons annually, and the carbon emission, in the form of carbon dioxide released from the soils, was 8.1 million tons annually at the end of simulation.

Keywords: Forest soils; Soil organic matter; Soil carbon; SOM dynamics model; Long-term simulation; Northwestern Russia

1. Introduction

It is well known that soils store approximately 2/3 of all the carbon in terrestrial ecosystems (Kobak, 1988). The accumulation of carbon as soil organic matter (SOM) is proposed to be a leading macro-process of soil formation in all natural zones. At the same time, a loss of soil carbon is a dangerous aspect of anthropogenic soil degradation. Previously, a conservative concept of SOM dominated pedological thinking, however, there is now a more deep understanding of SOM's dynamic nature which rapidly reacts with various natural and anthropogenic factors (Chertov and Razumovsky, 1980; Powlson et al., 1996). As a result, the effects of SOM dynamics on atmospheric carbon dioxide concentration in the light of global climate change are now in the forefront of ecological research.

Boreal forests are the most extensive biomic accumulators of carbon in both their living biomass and soil. The forests are intensively used for wood production and are under permanent influence of other anthropogenic impacts including fire, pollution, recreation, and changing land use. Therefore, the clarification of this biome's role in carbon sequestration or its release is of great importance for the biospheric carbon balance as a

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0378-1127/02/$ – see front matter
PII: S0378-1127(02)00295-5

whole. Previously, it has been shown that reforestation and afforestation can play a significant role in carbon sequestration in boreal and temperate forests (Kobak, 1988; Cannell and Milne, 1995; Karjalainen, 1996; Karjalainen et al., 1997, 1999).

Today, there is an interest in estimation of carbon dynamics on a global (Kobak, 1988; Goto et al., 1994; Post et al., 1996), national (Alexeev and Birdsey, 1998; Harrison et al., 1995; Cannell and Milne, 1995; Kolchugina et al., 1995; Rozhkov et al., 1996) and regional scale (Makarevsky, 1991; Homann et al., 1995). It appears that regional assessments are more preferable because they allow a more precise evaluation of soil carbon pool dynamics.

A calculation of carbon balance in forest ecosystems is necessary for a more complete understanding of the problem of global warming. Dynamic (functional) parameterisation of SOM, which accounts for the rate of SOM mineralisation and litter input (Howard et al., 1995), is now discussed. For Russia, the first attempt at calculating the carbon balance was based on the controversial assumption that the net primary production (NPP) is in balance with soil respiration due to SOM decomposition (Kolchugina and Vinson, 1994; Kolchugina et al., 1995). It is thought that the use of simulation models of SOM dynamics is more correct way to assess carbon balance (Powlson et al., 1996).

The aim of this paper is to obtain the functional characteristics of SOM dynamics in the forest soils (3.22×10^6 ha) of the Leningrad administrative area, North-west of the Russian Federation. Peat soils of Scots pine stands and open mires with organic layer more than 30 cm are not considered in the work. This compilation of data from SOM pools, litter input, climate, and SOM dynamics modelling (Chertov and Komarov, 1997) was used to compose a carbon budget of the forest ecosystem on a regional scale. Previously, the estimation of SOM pools in forest soils of drained and poorly drained sites in the Leningrad area have been made by the authors (Chertov and Komarov, in press).

2. Materials and methods

The main methodological approach was to obtain and employ the parameters of SOM mineralisation on regional scale for use in the calculation of carbon release from the forest soils as related to soil carbon sequestration in the total forest litter. There were no mires included in the calculations; only drained and poorly drained mineral soils with an organic layer (forest floor or peat) less than 30 cm in depth were used. No effects of fire, insect attacks, and pollution were considered in the simulations. We mostly operated with the data represented as SOM not as SOC—soil organic carbon.

Calculations were done for stable current climate conditions and current age structure and composition of forests to obtain the parameters of the carbon sources and sinks in existing forest ecosystems. The SOM dynamics were calculated assuming constant age-structure of the stands (with constant proportion of young stands), thereby reflecting the absence of change in the current forest management regime. Young stands were defined as areas with less than 40 years of age for confer species and areas with less than 25 years of age for deciduous species. Model runs in every soil group and stand composition have been carried out for the two fixed age groups, having their specific parameters of area, initial SOM pools, and litter input. A narration of methods and the main input parameter data used to run the model is described below.

2.1. Climatic data

Meteorological (climatic) parameters are necessary to run soil model because the rate of SOM transformation is strongly dependent on soil moisture and temperature. Detailed meteorological information was available for the Leningrad region; however, the absence of spatially distributed soil and stand data for the region made employing the more generalised mean data for all the area more appropriate. The data was obtained by the State Hydrological Institute (St. Petersburg, Russia) and is represented in Table 1. This standard meteorological information was processed by a soil climate generator (Bykhovets and Komarov, in press) which converted the standard data into monthly mean values of soil moisture and soil temperature taking into account the known statistical properties of the regional climate. The generator reproduces about 15% variation of monthly climatic parameters in different years. These values were used as the model's input parameters.

Table 1
Basic climatic data for Leningrad region

Parameters	January	February	March	April	May	June	July	August	September	October	November	December
Mean monthly air temperature, t (°C)	−10.8	−10.3	−5.2	1.4	7.9	13.7	16.3	14.4	9.1	3.1	−2.2	−7.2
Mean monthly soil temperature, t (°C)[a]	0.4	0.1	0.1	1.2	6.1	8.8	12.8	13.2	9.2	6.5	2.9	1.2
Monthly precipitation (mm)	31	25	29	35	45	56	69	81	77	57	47	31

[a] Under grass, 20 cm deep.

For the effectiveness of climate generator, some hydrological and physical properties of the soils have been compiled (Table 2) from Pestriakov (1973).

2.2. Initial SOM pools for model run

The basic database for the calculation of initial SOM pools represents 293 soil profiles studied on temporary sample plots evenly distributed in the forests of Leningrad region (Chertov, 1981). The soil samples for organic horizons and mineral topsoil were composed from 30 individual samples from small pits. The individual samples for B and C layers were taken from a deep pit on every plot. The pools of organic layer were determined directly by taking sample with 25 cm × 25 cm stencil. The soil carbon and nitrogen were determined in the soil samples using Russian standard methods (Arinushkina, 1970, pp. 130–137; Ponomareva and Nikolaeva, 1961; Ponomareva and Plotnikova, 1980). The results were statistically processed as represented in Table 3.

Because lack of statistics on soil units area we used forest inventory data on area of different tree species and forest types. All soils were grouped by the tree species–forest type units. The carbon pools (ton per hectare in organic and 50 cm mineral layers with standard deviation) were calculated in every group. The errors are 15–22% of mean values for well-drained soils and 20–40% for poor drained soils. The carbon data was recalculated then to SOM value as input parameters for the model. The pool of organic layer in young stands was set 20% smaller than the mean values based on experimental data by Orfanitsky and Orfanitskaya (1971) and Chertov (1981). Taking into account the results of previous model test (Chertov et al., 1997) all SOM of organic layer was considered as partially decomposed pool (F) in model input parameters, and a pool of fresh litter (L) was set to zero at first step of simulation.

Additionally, nitrogen pools were estimated using the same database (Chertov, 1981). Because the SOM dynamics are dependent on the quantity and quality of litter, the soil groups have been divided into different sections based on dominating tree species and stand age. All the data is represented in Table 4. The

Table 2
Water and physical properties of the soils

Soil parameters	Raw humus ranker and sandy surface-podsolic soils	Raw humus sandy podsolic soils	Moder and mull podsolic sandy and loamy soils	Raw humus sandy and loamy podsolic soils	Raw humus loamy gley-podsoilc soils	Peaty sandy podsols and loamy gley-podsolic soils	Peaty freshwater (anmoor) gley soils
Soil bulk density (g cm^{-3})	1.4	1.4	1.25	1.4	1.35	1.3	1.0
Wilting point (mm)[a]	15	30	50	50	100	75	100
Full saturation (mm)[a]	100	400	430	430	420	440	600
Initial pool of available water[a]	20	50	90	90	110	250	550
Presence of ground water[b]	0	0	0	0	1	1	1
Presence of permafrost[b]	0	0	0	0	0	0	0

[a] In 100 cm soil layer.
[b] In 100 cm soil layer: 0 means no and 1 means yes.

Table 3
Fragment of primary soil data (mean and S.D.) on SOC content in forest soils of Leningrad region (by Chertov, 1981)

Site and soils	Number of soil pits	A0 (cm)	A1 (A1A2)[a] (cm)	B (cm)	A0 (kg m^{-2})	C (%) in A0	C (%) in A1(A1A2)	Forest type
Well-drained sands								
Raw humus iron podsolic and podzols	14	6.1 (0.32)	2.8 (0.94)	28.2 (2.79)	4.7 (0.50)	35.2 (1.13)	2.2 (0.74)	*Pinetum myrtillosum*
Duff mull (moder) iron podsolic	7	4.4 (0.41)	11.7 (0.39)	60.0 (5.78)	2.6 (n.d.)	29.8 (2.34)	2.2 (0.35)	*Pinetum oxalidosum*
Well-drained moraine loam								
Raw humus podsolic	7	6.0 (0.53)	3.7 (0.89)	52.6 (9.84)	4.0 (0.07)	35.0 (2.60)	2.7 (0.68)	*Piceetum myrtillosum*
Duff mull podsolic	6	3.8 (0.12)	8.0 (0.80)	33.8 (7.44)	3.1 (0.49)	33.1 (2.85)	3.8 (1.05)	*Piceetum oxalidosum*
Moder–mull podsolic	2	1.5 (n.d.)	14.5 (n.d.)	43.0 (n.d.)	1.2 (n.d.)	25.9 (n.d.)	4.6 (n.d.)	*Betuletum oxalidozum*
Weakly drained moraine loam								
Thick raw humus gley-podsolic	5	11.0 (2.10)	5.7 (1.12)	39.8 (10.8)	6.9 (1.50)	39.2 (0.59)	3.8 (1.08)	*Piceetum polytrichosum*

[a] It represents humus-rich topsoil mineral horizons, ‘humus-accumulative’ ones in Russian nomenclature (Ah and AhE).

Table 4
Initial values of SOM and nitrogen pool, 1000 t (organic matter) per all the area, in forest soils of Leningrad region

Forest soil, forest type and its area, 1000 ha	Tree species	Age category	Organic layer		Mineral topsoil	
			SOM	N	SOM	N
Raw humus ranker and sandy surface-podsolic soils; *Cladina* type; 32.8	Scots pine	Young	105.1	1.46	789.4	14.62
		Other	232.4	3.23	2083.3	38.88
	Norway spruce	Young	12.5	0.16	27.3	0.51
		Other	43.6	0.56	95.6	1.77
	Pendula birch	Young	6.2	0.09	13.6	0.32
		Other	51.9	0.79	113.8	2.71
Raw humus sandy podsolic soils; *Vaccinium* type; 294.0	Scots pine	Young	1199.9	16.67	2629.9	45.34
		Other	5233.6	56.0	8840.6	152.42
	Norway spruce	Young	128.8	1.69	459.5	9.99
		Other	387.5	5.10	691.9	15.04
	Pendula birch	Young	28.1	0.47	100.4	2.51
		Other	485.1	7.35	866.2	18.83
	Trembling aspen	Young	7.4	0.12	19.7	0.49
		Other	127.2	1.93	233.8	5.08
Moder and mull podsolic sandy and loamy soils; *Oxalis* type; 894.9	Scots pine	Young	49.6	0.95	635.3	18.69
		Other	1219.6	23.46	5287.8	155.52
	Norway spruce	Young	507.0	9.75	6496.0	191.06
		Other	3573.9	68.73	6237.9	183.47
	Pendula birch	Young	70.5	1.60	1248.3	44.58
		Other	5948.6	129.32	56247.7	2008.85
	Trembling aspen	Young	102.1	2.32	1807.8	64.57
		Other	3479.8	75.65	32903.1	1175.11
Raw humus sandy and loamy podsolic soils; *Myrtillus* type; 796.8	Scots pine	Young	1008.3	15.75	3468.0	69.36
		Other	15491.6	227.82	30961.4	619.23
	Pendula birch	Young	747.3	12.88	3208.4	80.21
		Other	15873.5	273.68	35432.0	885.80
Raw humus loamy gley-podsoilc soils; *Myrtillus* type; 577.0	Norway spruce	Young	4050.8	65.34	19810.0	396.20
		Other	16186.8	261.08	41226.2	824.52
	Trembling aspen	Young	260.8	4.50	1403.7	35.09
		Other	3481.7	60.03	10013.4	250.34
Peaty sandy podsols and loamy gley-podsolic soils; *Politrichum* type; 323.3	Scots pine	Young	1651.1	22.93	3556.8	77.32
		Other	5812.9	81.84	15944.8	346.63
	Norway spruce	Young	3040.4	46.07	5086.8	115.61
		Other	6283.6	95.21	12615.9	286.72
	Pendula birch	Young	994.9	16.58	1664.5	41.61
		Other	5229.9	87.16	10500.3	262.51
	Trembling aspen	Young	70.6	1.18	35.5	0.89
		Other	282.3	4.70	142.2	3.55
Peaty freshwater (anmoor) gley soils; *Herbo-philipendulosum* type; 301.8	Norway spruce	Young	3437.2	74.72	6389.2	228.19
		Other	3701.6	80.47	6880.7	245.74
	Pendula birch	Young	978.3	21.27	1818.5	64.94
		Other	18356.0	399.04	34121.0	1218.61
	Trembling aspen	Young	1480.6	52.88	2752.3	98.30
		Other	11950.9	259.80	22214.9	793.39

methodology of SOM pools estimation is described in detail by Chertov and Komarov (in press).

2.3. Calculation of litter input

Litter input calculations were made using forest inventory data for every simulated soil unit (soil–forest species–age category). The data of the inventory was converted to biomass using the latest conversion factors (Alexeev and Birdsey, 1998).

Annual litter pools, as a proportion of total forest biomass, were calculated based on comprehensive biological productivity data of boreal forests (Kazimirov and Morozova, 1973; Kazimirov et al., 1977, 1978), thereby yielding the following portions of annual litter: (a) in young stands of Scots pine 0.08 ± 0.018, in Norway spruce 0.03 ± 0.005, in deciduous stands (birch and aspen) 0.07 ± 0.028; (b) in all other stands (mean aged and old growth ones) the portions are 0.05 ± 0.009, 0.02 ± 0.003 and 0.035 ± 0.045 correspondingly. The total annual litter input (as total litter including leaf/needle, root and branch cohorts) was calculated for every simulated soil unit.

This litter input represents amounts produced by trees only, and we used them for the majority of soil groups where a role of ground vegetation litter is negligible. However, in wet sites a proportion of ground vegetation litter is high, and the data was partially corrected for two soil groups. In peaty sandy podsols and loamy gley-podsolic soils (*Politrichum* forest type), it was increased 15% due to significant role of moss litter because a moss productivity and litter reaches here 15–20% of the tree litter (Kazimirov et al., 1977, p. 93). In peaty freshwater (anmoor) gley soils (*Herbo-philipendulosum* forest type), aboveground herb and grass litter reaches 20–30% of the tree litter (Kazimirov and Morozova, 1973, pp. 39–40; Kazimirov et al., 1978, p. 130). Taking into account that dead roots reach 80% of total grass litter (Rodin and Bazilevich, 1965; Poniatovskaya, 1978; Bazilevich, 1993) the litter input was doubled in this soil group compared to earlier SOMM test (Chertov et al., 1997). No separate pool of coarse wood litter was considered in this simulation.

Because nitrogen and ash content influence the rate of SOM decomposition, the model must also take into consideration these parameters (Kazimirov and Morozova, 1973; Kazimirov et al., 1977, 1978). The values were treated as the weighed mean of leaf, root, and branch litter masses. Litter input data is represented in Table 5. It should be additionally mentioned that a factor of 0.50 was used to recalculate SOM values to soil carbon in boreal forest soils instead of standard factor 0.58 according to previous experimental data (Ponomareva and Plotnikova, 1980).

2.4. The model

The soil model, SOMM (Chertov and Komarov, 1997), used in this study, is a mathematical formulisation of the ‘‘humus form’’ concept, which has existed in Forest Science since the 19th century. SOMM describes organic matter dynamics and nitrogen release in two compartments of the organic layer (forest floor) and in one of the mineral topsoil. In the model, SOM of mineral profile is treated as a fraction of stable humus; no easily decomposed fraction (labile humus) is considered in mineral horizons. The model has six processes: three processes of full mineralisation of every compartment and three processes of organic matter transformation by three different organism–destructor complexes which are responsible for the formation of the three main humus forms. It is a complex of soil fungi with microfauna (raw humus formation), soil *Arthropoda* with bacteria (moder development), and finally, earthworms with two previous groups (mull formation). The first complex is responsible for development of organic layer, two other groups incorporate humified material into mineral soil. The model calculates the transformation (humification and mineralisation) of three SOM compartments (two of organic layer and one of mineral soil), the gross carbon dioxide flow from the soil due to SOM mineralisation and the nitrogen available for plant growth. The model has been evaluated against experimental long-term observations, and has provided satisfactory results for actual forest data sets (Chertov et al., 1997). The model therefore fits well with an aggregated individual-based forest ecosystem model (Chertov et al., 1999).

2.5. Model runs

Model runs were performed in every soil unit (soil–forest species–age category) for a duration of 100

Table 5
Parameters of annual litter input and its nitrogen and ash content in Leningrad region

Forest soil and forest type	Tree species	Age category	Litter input, 1000 t per year	Nitrogen content of litter (%)	Ash content of litter (%)
Raw humus ranker and sandy surface-podsolic soils; *Cladina* type	Scots pine	Young	22.7	0.6	2.0
		Other	73.6	0.6	2.0
	Norway spruce	Young	1.3	0.7	2.5
		Other	9.0	0.7	2.5
	Pendula birch	Young	0.4	1.0	3.0
		Other	14.7	1.0	3.0
Raw humus sandy podsolic soils; *Vaccinium* type	Scots pine	Young	252.6	0.6	2.0
		Other	285.7	0.6	2.0
	Norway spruce	Young	14.1	0.7	2.5
		Other	47.3	0.7	2.5
	Pendula birch	Young	3.5	1.0	3.0
		Other	19.3	1.0	3.0
	Trembling aspen	Young	1.1	0.9	3.5
		Other	18.5	0.9	3.5
Moder and mull podsolic sandy and loamy soils; *Oxalis* type	Scots pine	Young	34.3	0.8	2.5
		Other	428.8	0.8	2.5
	Norway spruce	Young	115.0	0.85	3.0
		Other	693.3	0.85	3.0
	Pendula birch	Young	23.0	1.1	3.5
		Other	2217.8	1.1	3.5
	Trembling aspen	Young	35.4	1.0	4.0
		Other	1036.3	1.0	4.0
Raw humus sandy and loamy podsolic soils; *Myrtillus* type	Scots pine	Young	261.3	0.6	2.0
		Other	2775.1	0.6	2.0
	Pendula birch	Young	87.3	1.0	3.0
		Other	2265.0	1.0	3.0
Raw humus loamy gley-podsoilc soils; *Myrtillus* type	Norway spruce	Young	413.9	0.7	2.5
		Other	1790.4	0.7	2.5
	Trembling aspen	Young	10.0	0.9	3.5
		Other	376.2	0.9	3.5
Peaty sandy podsols and loamy gley-podsolic soils; *Politrichum* type	Scots pine	Young	82.5	0.6	2.0
		Other	651.7	0.6	2.0
	Norway spruce	Young	52.2	0.7	2.5
		Other	286.8	0.7	2.5
	Pendula birch	Young	1.3	1.0	3.0
		Other	305.7	1.0	3.0
	Trembling aspen	Young	1.0	0.9	3.5
		Other	8.5	0.9	3.5
Peaty freshwater (anmoor) gley soils; *Herbo-philipendulosum* type	Norway spruce	Young	92.8	0.85	3.0
		Other	175.1	0.85	3.0
	Pendula birch	Young	59.1	1.1	3.5
		Other	1244.3	1.1	3.5
	Trembling aspen	Young	32.4	1.0	4.0
		Other	535.9	1.0	4.0

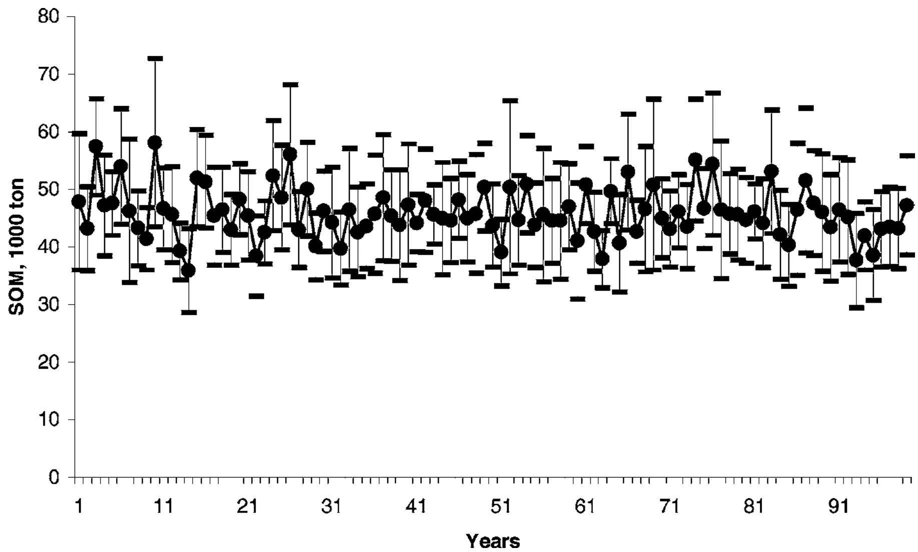

Fig. 1. Standard representation of simulation output data as mean values and standard deviation of simulated SOM pool. Here it is a time series of fresh litter pool in raw humus ranker and sandy podsolic soils (in 1000 t) for an area of 32.8×10^3 ha.

years. In each simulation, 10 Monte Carlo runs were performed with the calculation of mean values and standard deviations of the SOM parameters for every simulated year in every simulated soil unit. Area of soil units can be found from Table 4. The 15% variation of climatic parameters and litter input was carried out at Monte Carlo simulation. Examples of output data are represented in Fig. 1. Generally, the deviation values were very small (for total SOM pools, it is about 5% of mean values), and are not represented in the results of the simulation discussed below. These basic results were then processed in relation to the summation of the data for every soil group and different stand compositions within those soil groups.

3. Results

3.1. SOM dynamics on different soils and total regional SOM dynamics

There are some remarkable changes of SOM pools in the different forest soil groups during the 100-year simulation. Markedly different tendencies of SOM change were found in various soil groups (Table 6). Dry poor rankers and sandy podsolic soils of Scots pine stands demonstrated significant accumulation of raw humus (forest floor) in the first 50 years of the simulation. At the same time, there was only a 14% increase of the SOM pool in the mineral topsoil (Fig. 2).

In well-drained site conditions with soils of different productivity (various podsolic soils) the results of the model show that the forest floor (organic layer) pool demonstrates no significant changes during the 100 years of simulation. In the mineral topsoil, one can see a consistent accumulation of SOM to a level of 30% (Table 6, Fig. 3). Generally these results reflect the maintenance of the existing types of SOM such as raw humus or moder humus types.

Other tendencies in SOM pool dynamics have been observed in the simulation of poorly drained forest sites with thick raw humus or shallow peat on gley-podsolic or gley forest soils. In this case, a decrease of the SOM pool in the organic layer was clearly detected, reflecting some degradation of the organic layer. This demonstrates a weak SOM accumulation and sometimes even a reduction of SOM in the mineral horizons (Table 5, Fig. 4).

These opposed tendencies of simulated SOM changes in different soils were significantly smoothed when a calculation of the total regional trends of SOM dynamics in forest soils of the whole Leningrad region, 3.22×10^6 ha, was made (Table 6, Fig. 5).

Table 6
SOM dynamics, 1000 t (organic matter) per all the area, at the beginning and end of 100-year simulation

Soil and forest type, area in 1000 ha	Year of simulation	SOM of organic layer	SOM of 0–50 cm of mineral topsoil	Total SOM
Raw humus ranker and sandy surface-podsolic	1	503	3124	3627
soils; *Cladina* type, 32.8	100	2705	3571	6276
Raw humus sandy podsolic soils;	1	7104	13891	20995
Vaccinium type, 294.0	100	6246	16325	22571
Moder and mull podsolic sandy and	1	15462	111393	126855
loamy soils; *Oxalis* type, 894.9	100	14934	144372	159306
Raw humus sandy and loamy podsolic	1	32353	73602	105955
soils; *Myrtillus* type, 796.8	100	33997	106990	140987
Raw humus loamy gley-podsoilc	1	22593	72788	95381
soils; *Myrtillus* type, 577.0	100	13514	82077	95591
Peaty sandy podsols and loamy gley-podsolic	1	21625	49693	71318
soils; *Politrichum* type, 323.3	100	10484	45741	56225
Peaty freshwater (anmoor) gley soils;	1	30172	76899	107071
Herbo-philipendulosum type, 301.8	100	5672	85968	91640
Total in Leningrad region, 3220.6	1	129812	401390	531202
	100	87553	485044	572597

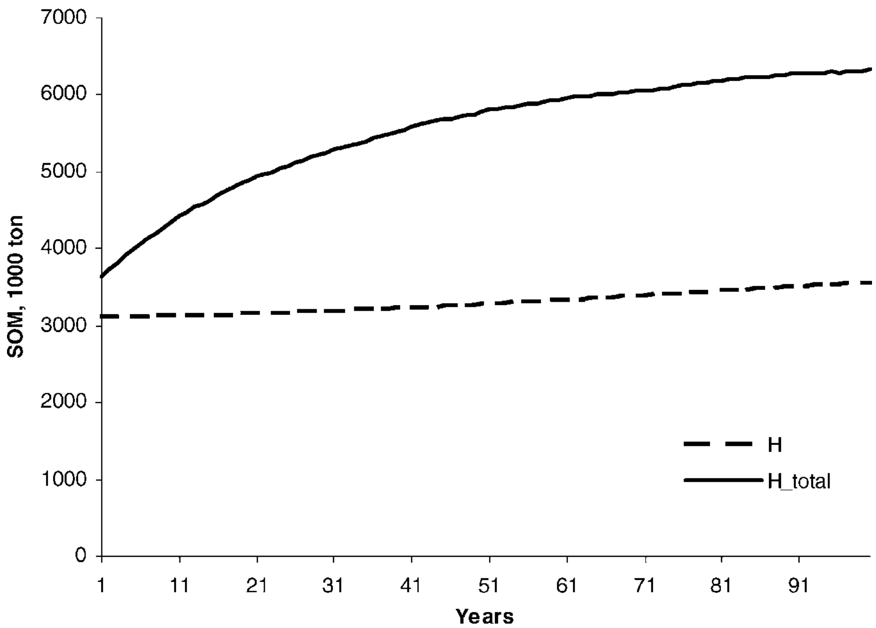

Fig. 2. Total SOM pool dynamics in raw humus ranker and sandy podsolic soils of dry Scots pine stands (32.8×10^3 ha); H—SOM pool in mineral topsoil; H_total—total SOM pool. The difference between SOM of total and mineral topsoil pools represents SOM pool in organic layer (forest floor or peat).

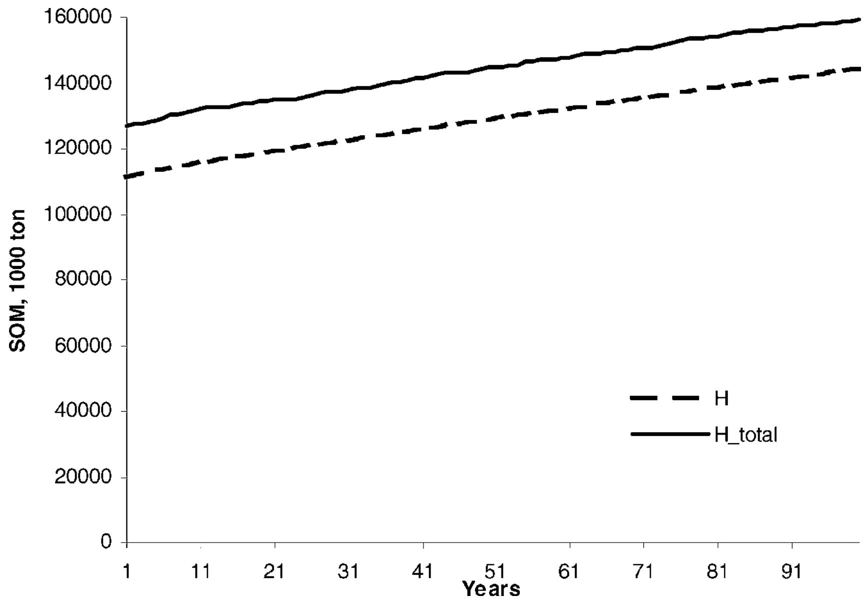

Fig. 3. Total SOM pool dynamics in moder and mull podsolic soils of various stands of *Oxalis* type (894.9 × 10^3 ha). See explanation to Fig. 2.

A 30% decrease in the SOM pool in organic layers and a 20% increase in the SOM pool in mineral topsoil was found; however, total changes of SOM in forest soils of the Leningrad region show only a 7.8% increase during the 100-year simulation. Total carbon pool changes were calculated using this SOM dynamics data. Carbon pools in the forest soils of the Leningrad region (50 cm layer plus organic horizon) increased during the

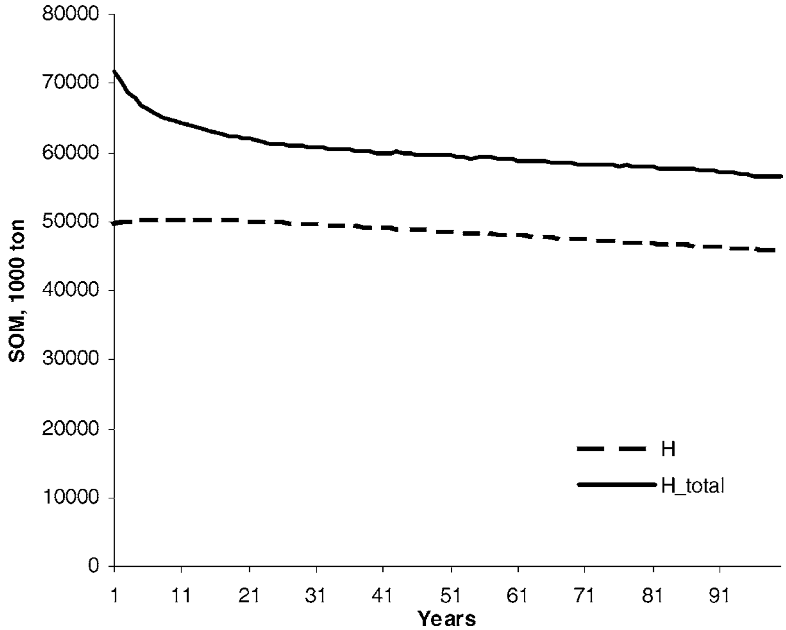

Fig. 4. Total SOM pool dynamics in shallow peaty podsoils and gley-podsolic soils of various stands of *Polytrichum* type (323.3 × 10^3 ha). See explanation to Fig. 2.

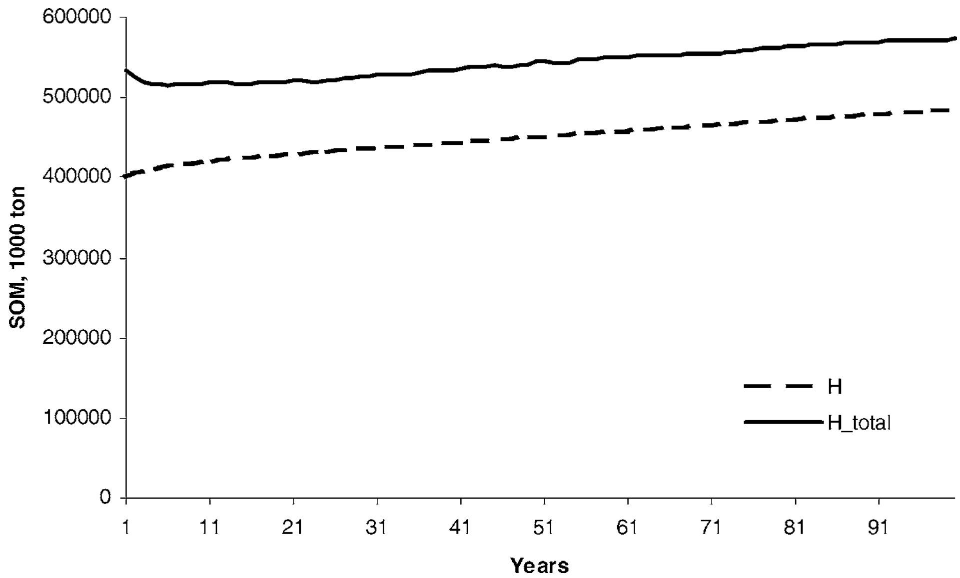

Fig. 5. Total SOM pool dynamics in forest soils of Leningrad region (3.22×10^6 ha). See explanation to Fig. 2.

100 years from 265.6×10^6 to 286.3×10^6 t. Generally, a gross of 20.7×10^6 t increase of the carbon pool in the forest soils under existing climatic conditions and forest land-use for 1 century was obtained, i.e. 0.207×10^6 t C per year or 0.064 t C ha^{-1} per year.

3.2. SOM dynamics under different tree species

In all soil groups, the identical response of SOM changes to stand composition has been observed during the simulation as demonstrated in Table 7. The consistent accumulation of SOM pool in the raw humus forest floor was found under all Scots pine stands. Under Norway spruce and deciduous stands, the SOM pool of the organic layer was approximately the same or decreased weakly by the end of the simulation. The SOM pool in mineral topsoil was mostly increased under all stands of well-drained forest soils.

3.3. Carbon fluxes and balance of carbon in Leningrad area forests

The simulation data allows for the calculation of the total carbon balance in forest soils of the Leningrad

Table 7
Soil organic mater dynamics, amounts as 1000 t (organic matter) per all the area, in Moder and Mull podsolic sandy and loamy soils of *Oxalis* type under stands of different composition at the beginning and end of 100-year simulation

Stand composition, area of 1000 ha	Year of simulation	SOM of organic layer	SOM of 0–50 cm of mineral topsoil	Total SOM
Scots pine stands, 49.0	1	1422	5947	7369
	100	2059	8558	10617
Norway spruce stands, 115.9	1	4022	12839	16861
	100	3221	18057	21278
Pendula birch stands, 455.5	1	6379	57756	64135
	100	6444	76377	82821
Aspen stands, 274.5	1	3641	34852	38493
	100	3210	41379	44589

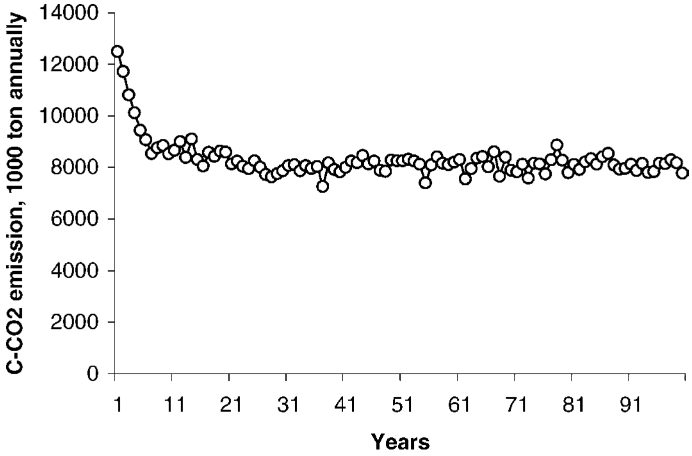

Fig. 6. Total carbon emission from the soils (as carbon dioxide) due to SOM mineralization in forest soils of Leningrad region (3.22×10^6 ha).

region. On the basis of litter data input (Table 5), the total carbon input to the soil was estimated as $8312 \times 10^3 \pm 1246.8 \times 10^3$ t annually. On the basis of carbon dioxide output data of the simulation (Fig. 6), the carbon emission being produced annually after full SOM mineralisation was evaluated as $8071 \times 10^3 \pm 205.6 \times 10^3$ t for the last 50 years of the simulation. This clearly indicates that forest soils of the region have a balanced carbon budget at the end of the simulation. However, there is a gross of 20.7×10^6 t increase of the soil carbon pool (i.e. 41.4×10^6 t of whole SOM) in the forest soils (Table 6 and Fig. 5) due to slow, consistent accumulation in the mineral horizons. This corresponds to a 0.08% annual total SOM or carbon increase in the forest soils over the 100 years simulation period.

4. Discussion and conclusion

Underlying question arises when we analyse the outcome of this simulation: how realistic are the results obtained? Are they reflect truly the natural processes or it is a 'fantasy world' (Parton, 1996)? This question can be divided into following parts: (a) what is the accuracy of the simulation? and (b) how to interpret the simulated trends of SOM dynamics?

One source of simulation errors can be the model structure. As we mentioned before, there is no division of SOM in mineral horizon into fractions of labile and stable organic matter. However, this fact does not influence the accuracy of simulation because the rate of mineralisation of this fraction reflects decomposition of whole SOM of mineral topsoil (Chertov and Komarov, 1997). We should point out that the coefficients of the SOMM model equations are evaluated against laboratory experiments in controlled conditions and are treated as dependent on litter quality, temperature and moisture. This methodological feature is strongly different of other SOM models compiled mostly on the basis of field experiments (Smith et al., 1997). These models obviously reflect the accuracy of litter cohort measurement and mostly miss the effect of fine root litter. However, the sensitivity of the SOMM model is not very high in relation to random modifications of its coefficients. Simultaneous random change of all coefficients within the interval with 50% variation leads to changes in main output variables of about 10%. So we think that the model structure is not a serious source of errors in this simulation.

The estimation of initial SOM pools can be a source of simulation uncertainty. There is a lot of soil information for Leningrad area reviewed by Pestriakov (1973), but the data was collected for a half-century period with different methodology of field sampling and without proper description of the vegetation. The consistent database used in this study (Chertov, 1981) supposes to be the best available source of information for SOM pools estimation in forests of Leningrad area.

The other sources of data uncertainty affecting the results of modelling are simulation scenarios: (i) underestimation of total SOM pools because only the top 50 cm soil layer was considered; (ii) errors of estimation of litter input and climatic scenario; (iii) coarse wood litter was not incorporated in the simulation; (iv) forest fires of dry sites and impact of other disturbances were also not considered. These factors can influence the results of simulation and we consider them below discussing dynamics in soil groups.

The total quantitative evaluation of the uncertainty is basically a difficult speculative problem because the comprehensive information on soil initial parameters and functional characteristics (initial SOM pools and litter input) is always incomplete even in more detailed databases (Smith et al., 1997). It should be pointed out that procedure of Monte Carlo simulation was done to address the data uncertainty. In this case we can give the following conclusion. Considering the standard deviation of initial soil data and litter input scenario (Tables 3 and 5), and also the results of Monte Carlo simulation we can roughly assess that the total simulated SOM pools have standard deviation of 20–30% of the SOM values.

We should accentuate that the uncertainty of simulation scenarios stays high even in a case of detailed data of field experiments, and a modeller always has to solve inverse problems to specify poorly estimated or absent input data or parameters (Parton, 1996; Smith et al., 1997). Generally, we can conclude that the problem of data uncertainty, adequacy of model structure and accuracy of input parameters are common for all regional and global applications of ecological models (Goto et al., 1994; Post et al., 1996; Powlson et al., 1996; Liski et al., 1998). However, this fact is not a reason to reject this approach because the results of any simulation are 'an approximation' reflecting current state of the art in the science. The exploring of the mechanisms influencing dynamics of the system can be more important than a simple quantitative prediction.

There are two answers on the other key question how to interpret the simulated SOM trends: (a) changes in the SOM pools during the simulation period are a results of an imbalance between the initial SOM contents and equilibrium ones according to the values of model driving variables (rate of processes); (b) the simulated SOM changes are the results of natural forest soil dynamics. Actually, the imbalance of litter input, initial SOM pools and model structure is visible in Figs. 2–5. However, these figures, and especially Fig. 6 with carbon emission from SOM, show clearly that the balance is reached in 15–20 years. In any case, if we accept this assumption as a main reason for simulated dynamics then the results of simulation demonstrate quite good correspondence of initial SOM pools, litter input and climatic scenario. The 10% change in the total soil carbon during the century is within the accuracy of soil parameters' measurements and the simulation. So this reason cannot explain 100-year trends in simulated SOM dynamics.

In relation to natural SOM dynamics we affirm that the soils of the region are now far of a quasi-stable state in climax-mosaic of absolutely uneven-aged coniferous and mixed 'virgin, native, untouched, pristine forests'. Because of three centuries intensive exploitation, mostly harvesting and fires, the current SOM content in the soils is lower than the theoretically expected level (Chertov, 1981). It can explain a trend of slow consistent growth of humus pool in mineral horizons in some soils and the entire region if we exclude one disturbance factor (forest fire in our scenario). Below we specify this explanation for main soil groups.

The simulated trends of SOM dynamics in the group of rankers, and sandy podsolic soils of dry forest sites correspond to experimentally observed trends of soil development in post-fire secondary succession without regular damage by forest fires. There are clear evidence of post-fire origin of this forests and soils as reported in the comprehensive review of Korchagin (1954). Moreover, there is data on the regular burning of these sites by local population in north Russia to regenerate lichens cover for grazing (Razumovsky, 1981). The soils in these forests have clear signs of post-fire origin (Chertov, 1973), and natural dynamics of this ecosystems without fires leads to transformation of forests from *Cladina* to *Vaccinum* types with an accumulation of thick forest floor (Chertov and Razumovsky, 1980; Chertov, 1981). In this case soil fungi and microfauna is absolutely dominating complex of organisms–destructors explaining slow mineralization of litter, accumulation of raw humus and low increase of SOM in mineral horizons. This specific pattern of SOM transformation is reflected in the simulation, and strong accumulation of forest floor reflects the transition of the *Cladina* forests to *Vaccinium* stands without impact of forest fires.

In well-drained sites with various podsolic soils, the dynamics of the SOM pool, under the stable conditions of the simulation also fully correspond to the observed tendencies of soil development in the region (see citation above). In this case, qualitative changes of humus types are not observed in the simulation. The pool of organic layer stays stable for 100-year simulation. Instead, the smooth accumulation of SOM in the mineral topsoil takes place here. It reflects a continuous process of ecogenetical (primary) succession in forest ecosystems with intensive work of soil *Arthropoda* and also earthworms transporting humified material from the organic layer to the mineral soil.

Quite specific simulated SOM dynamics in poorly drained forest soils (gley-podsolic and gley soils) with consistent degradation of organic layer also corresponds to the observed data, if forests are not regularly disturbed and secondary peat formation does not take place (Chertov, 1981; Morozova, 1991). The intensification of mineralization in organic and mineral soil here can be explained by soil moisture regime. The decrease of SOM pool in this group can also reflect the imbalance of litter input and climatic scenarios.

The simulated SOM dynamics under different tree species likewise generally correspond to existing concepts in the forest soil sciences (Wilde, 1958; Duchaufour, 1961; Chertov, 1981; Morozova, 1991). The observed SOM dynamics show accumulation of raw humus surface pool in conifer forests (in our case it concerns mostly Scots pine stands) and the formation of more productive soils with a moder humus type and an accumulation of SOM in the mineral topsoil under deciduous stands. It reflects activity of different groups of organisms–destructors incorporated in the model: the dominance of fungi and microfauna under coniferous forests, and the active role of soil *Arthropoda* and earthworms under deciduous species.

The results of this simulation demonstrate that the forest soils of the region represent, as first approximation, a very weak sink of atmospheric carbon under existing climatic conditions, stand structure, composition, and current silvicultural regime. These results are important for understanding the role of this region in national and continental carbon budget.

It can be concluded that this 100-year simulation reflects the relative stability of SOM pools in the forest soils of the region under the existing climate, stand structure, and forest management. Generally and unexpectedly, the model shows a good correspondence of the measured and simulated SOM pools. This argues that the input data of this simulation (initial SOM and nitrogen pools and parameters of litter input) which displays a satisfactory fitness with the SOM dynamics of the simulation model is quite realistic.

It should be clearly understood that the ideal situation for regional assessment of SOM, soil carbon pools, and their dynamics should use regular local soil databases as has been stated previously (Homann et al., 1995). However, in Russia, such national soil database does not exist. All the numerous soil databases are dissipated in local research bodies and paper files of old, unpublished project reports. Fortunately, there is an abundance of regional publications that may be used as a source of regional SOM information. This explains the presence of some comprehensive works on national soil carbon assessment in Russia (Kolchugina et al., 1995; Rozhkov et al., 1996; Alexeev and Birdsey, 1998), and the lack of soil carbon evaluations on a regional scale (Makarevsky, 1991).

The combined methodology described herein of regional SOM, soil carbon pools, and dynamics assessment, using local soil information, forest inventory data and a simulation model of SOM dynamics, is proposed to be a more feasibly realistic approach for regional assessment of SOM dynamics in Russian boreal forests. The following phases are proposed for the realisation of this approach: (i) to apply this methodology in the regional assessment of soil carbon pools and dynamics in Russian forests using local published soil data, forest inventory information, and suitable simulation models of SOM dynamics; (ii) to use the approach for climate change predictions; (iii) to develop different scenarios reflecting the combined effects of climate changes, various silvicultural practices, and other environmental impact factors. The use of forest ecosystem models with a SOM dynamics compartment (Bossel et al., 1991; Friend et al., 1997; Chertov et al., 1999) seems to be a more precise tool than the usage of a single SOM model with a fixed or separately simulated litter input.

Acknowledgements

This work was supported by Oregon State University, Corvallis, USA (Project "Comparison of Carbon Pools in Forest Ecosystems of US Pacific Northwest and Russian European Northwest"), European Forest Institute, Joensuu, Finland (Project 619 "Modelling of mixed stand/soil system in European boreal forests") and by EU INTAS programme (97-30255 Project FORMOD). We are grateful for the English editing performed by William Horgan, ICBM, Carl von Ossietzky University of Oldenburg, Germany. The authors would like to express their gratitude to the reviewers for their comprehensive consideration of the manuscript.

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