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Assessment of the Average Annual Methane Flux from the Soils of Russia

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FOREWORD

During the last decade greenhouse gas exchange between soil and atmosphere has been considered to be one of the most important problems of biogeochemistry. An accurate estimation of methane emissions is important for the future control of global climate change. In this context there is a high importance in estimating the contribution of methane in the territory of Russia, where vast areas are occupied by wetlands (e.g. West-Siberian Lowland). Wetlands are the most significant sources of methane emissions among natural ecosystems. However automorphic, and not over-moistened, territories are known to be sinks of methane. The extent of automorphic territories is quite considerable in Russia. Thus the net impact on the methane fluxes of the Russian territory has to be evaluated.

IIASA, the Russian Academy of Sciences and Russian governmental organizations initiated the Siberian Forest Study in 1992, with the overall objective of the Study to be:

- identification of possible future sustainable development options of the Siberian forest sector (assess the biospheric role of Siberian Forests, and identify suitable strategies for sustainable development of forest resources, the industry, the infrastructure and the society);
- identification of policies for the different options to be implemented by Russian and international agencies.

The first Phase of the Study was to build relevant and consistent databases for the upcoming analyses of the Siberian forest sector (Phase II). Nine cornerstone areas have been identified for the assessment analyses, namely further development of the databases, greenhouse gas balances, forest resources and forest utilization, biodiversity and landscapes, non-wood functions, environmental status, forest industry and markets, transportation infrastructure, and socio-economics.

An important component of the greenhouse gas balances' cornerstone is the emissions of methane. Thus, the work presented in this paper deals with analyses of the net annual average fluxes between soils and the atmosphere of the territory of Russia. This report was carried out by V.V. Zelenev from the Institute of Microbiology of the Russian Academy of Sciences in Moscow during his stay at IIASA in 1995.

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ASSESSMENT OF THE AVERAGE ANNUAL METHANE FLUX FROM THE SOILS OF RUSSIA

V.V. Zelenev

1. INTRODUCTION

Methane emissions from soils to the atmosphere is a very important problem of biogeochemistry (Andreae and Shimel 1989; Bouwman 1990). Methane is involved in many chemical reactions connected with atmospheric gases (interactions with hydroxyl radicals and stratospheric chlorine, formation of troposphere ozone and carbon monoxide), and through its infrared properties, methane also has an influence on the Earth's energy balance (the greenhouse effect). Moreover, each molecule of methane (CH_4) is 21 times more radiatively active than one of carbon dioxide (CO_2) (WMO/UNEP 1990).

The methane atmospheric concentration has increased from a relatively stable level of 0.7 ppm to 1.7 ppm during the last 300 years. The rate of increase has accelerated during the last 100 years (Craig and Chou 1982; Stauffer et al. 1985). The concentration in the northern hemisphere has recently decreased from an average of 11.6±0.2 parts per billion by volume (ppbv) yr^{-1} during 1983-1991 to 1.8±1.6 ppbv yr^{-1} in 1992 (Dlugokencky et al. 1994). This decrease remains unexplained and emphasizes the need for further refinement of our understanding of the CH_4 budget.

The total annual flux of methane to the atmosphere is estimated to be between 374-714 Tg (Stewart et al. 1989). There has been an average increase in the atmospheric CH_4 concentration of 1% per year, according to tropospheric measurements available for the last 30 years (Cicerone and Oremland 1988; Blake and Rowland 1988; Khalil et al. 1989). However, there has been a decrease in the concentration during the last 5 years of this longer period (Blake and Rowland 1988; Dlugokencky 1994; Khalil et al. 1989).

The latest assessment of the annual CH_4 flux to the atmosphere is 540 Tg of which 115 Tg (21%) stems from natural wetlands (Cicerone and Oremland 1988) and 35 Tg originated from wetlands and tundra north of the 50° N parallel (Fung et al. 1991). The contribution of CH_4 from northern wetland ecosystems and tundra soils to the global emission to the atmosphere, as calculated on the basis of the world mire distribution, is estimated to be 18-22% (Matthews and Fung 1987; Aselmann and Crutzen 1989). On the same basis, Bartlett and Harriss (1993) estimated the global flux from northern, temperate and tropical wetlands to be 109 Tg yr^{-1}. Crutzen (1991) estimated the total flux from natural wetlands and rice fields to 215±50 Tg yr^{-1}.

The removal of CH_4 from the atmosphere through the reaction with hydroxyl radicals is estimated to be the largest CH_4 sink (420±80 Tg yr^{-1}; Crutzen 1991). Soil microbial oxidation (methane uptake) is estimated to account for 5 to 20% of the total global CH_4 removal (Bender and Conrad 1993; Cicerone and Oremland 1988; Koschorreck and Conrad 1993) or 10% (Duxbury and Mosier 1993) to 15% (Born et al. 1990). The rates of the CH_4 uptake by soils have been estimated in a wide range of environments including swamps (Amaral and Knowles 1994; Harriss et al. 1982), peat soils (Yavitt et al. 1990; Panikov et al. 1993), boreal forest soils (Whalen et al. 1992), temperate forest (Adamsen and King 1993; Crill 1991; Born et al. 1990; Steudler et al. 1989), temperate grassland (Mosier et al. 1991), agricultural soils (Mosier and Schimel 1991; Goulding et al. 1995). Soil is an important source of CH_4 emissions under anaerobic conditions, such as in natural wetlands or flooded lands but aerobic soil is an important sink where CH_4 is oxidized to CO_2. To a large extent, the methane emission rates to the atmosphere are a function of the balance between methane production and consumption in the soil profile. Up to 90% of the methane produced in the anaerobic zone can be oxidized before it reaches the atmosphere (e.g. Fechner and Hemond 1992; King et al. 1990).

The rates of methanogenesis and methane emissions from the soils to the atmosphere are controlled by several factors: type and amount and quality of organic material in the soils (Kelly and Chynoweth 1981; Harriss and Sebacher 1981), status of the water table (defines the anaerobic conditions), the variable decomposition pathways occurring in different chemical environments (Bartlett et al. 1987), transport of CH_4 within plant tissues, soil temperature (Bartlett et al. 1987; Moore and Knowles 1987), vegetation (Sebacher et al. 1985), net ecosystem productivity (Whiting and Chanton 1993), and populations of methanogens and methanotrophs.

There are great uncertainties regarding the magnitude of CH_4 emissions from wetlands. Recent direct measurements undertaken mainly in the USA and Canada (Roulet et al. 1992; Harriss et al. 1993) revealed rather low intensity of CH_4 emissions from boreal and sub-Arctic wetlands. A global extrapolation of these flux studies provides a global flux of wetlands in the range of 10-35 Tg yr^{-1}, which is one order of magnitude lower than previous estimates of 100-200 Tg yr^{-1} (Houghton et al. 1992). Attempts to provide a reliable estimate of the methane emissions from wetlands are limited by the high variability within and among sites and the diverse nature of wetlands.

To date, modeling efforts have mainly focused on single variables without fully integrating all the ecological aspects of the CH_4 dynamics. It is recommended that future attempts at predictive modeling should incorporate simple correlative approaches which use variables such as water table, temperature and the net ecosystem productivity (Bubier and Moore 1994). This modeling effort should not only concentrate on the relationship between CH_4 fluxes and environmental factors, but also on the separate processes of methane formation and consumption.

Whalen and Reeburgh (1988, 1992) demonstrated the strong control that microtopography can exert on methane emissions in the Alaskan tundra for scales of <1 m. For the Russian territory and particularly Siberia, where the greatest wetland areas of the Earth are situated, there are strong needs for similar investigations. According to recent results (Panikov et al. 1995) CH_4 emissions from wetlands of West Siberia varied from -20 to 240 mg CH_4/m^2/day, depending on the environmental factors. A positive relationship was found between emission rates and soil temperature, ground water level and soil acidity. The highest methane emissions (average 234, with a standard deviation of 326 mg CH_4/m^2/day) was observed in Vasyugan Lowland (West Siberia). These estimates are one order of magnitude higher than that reported for natural wetlands of Canada and Europe. Extrapolation of the regional results from West Siberia results in a conclusion that the West Siberian territory is to be regarded as a significant source of methane even at the global scale.

There are also large areas of automorphic soils in Russia, which have a methane-consuming ability as noted above. Thus, to avoid overestimation and reach a more precise evaluation of the total methane fluxes from the territory of Russia, the differences between soils in respect to methane emissions have to be carefully considered.

To understand the variability in the fluxes at regional scales is crucial for extrapolations of in situ measurements to the global scale. So far no studies have examined the patterns of methane emissions at these intermediate scales. To solve this problem more reliable and complete data on sources and sinks of methane are necessary. There is an urgent need for collection and systematization of available information concerning CH_4 fluxes from different sites measured by the chamber method, a micrometeorological and/or aircraft technique connected with corresponding environmental parameters.

Quantitative estimations of the methane fluxes from the soils of Russia to the atmosphere also require additional research because

a) there is a lack of data on the methane fluxes directly measured on the territory of Russia, and
b) the estimates published are based on various assumptions and approaches, and the results differ substantially.

Harriss et al. (1993) estimated the total CH_4 emissions from the European part of Russia, the wetlands of Fenno-Scandia and the West-Siberian lowland to 11.4 Tg yr^{-1}. Andronova and Karol (1993) estimated 11 Tg yr^{-1} as the maximum emission from the wetlands of the former USSR.

An attempt to estimate the total methane fluxes from the natural lands of Russia was undertaken by Rozanov (1995). Wetlands and overmoistened ecosystems were related to soil units represented on the FAO/UNESCO (1974) *Soil Map of the World*. Each methane producing soil unit was specified with assigned methane fluxes. Estimation of the specific fluxes was made according to directly measured values of emission rates from sites corresponding to certain soil units. The methane emission rate from a certain soil unit was only linked to the length of the period of the biological activity (PBA) in a simple way, namely: permafrost or non-permafrost areas. It was assumed that the emission of methane could only take place during a period with biological activity. According to this approach, the total methane fluxes from the natural lands of Russia was found to be 39 Tg yr^{-1}, which corresponds to some 35% of the total average global methane emission from wetlands. However, no consumption of methane by automorphic soils was considered.

The work presented in this paper was dedicated to assess the annual methane fluxes between soils and atmosphere for the territory of Russia. The *Soil Map of the World* (FAO/UNESCO 1974), in the scale of 1:5 million, was used as the cartographic base for the calculations. The legend of the map consists of 106 soil units (SU) and was considered to be a comparatively comprehensive set of separate objects for characterizing methane fluxes. A generalization of all available data on methane fluxes--obtained by direct measurements on the territory of Russia, the territories of Europe and North America--was made in order to estimate the fluxes for the different soil units.

An additional objective of this work was to assess the annual methane fluxes from the soils of Russia to the atmosphere on a basis of more precise estimation of the specific methane fluxes for different soil units, by taking into account their geographical location and specific environmental conditions. This was not done in the work by Rozanov (1995).

In this work an attempt was made to assess not only the size of the methane emissions, but also the magnitude of the methane consumption by the different soils of Russia.

This work has been carried out according to five distinct steps:

1) Information concerning soil types, areas and geographical coordinates of soil units was extracted from the FAO/UNESCO (1974) *Soil Map of the World*;
2) A database containing methane fluxes and corresponding environmental parameters collected from available literature was generated;
3) Representative methane fluxes for the majority of the temperate, boreal and tundra soil units were calculated using the database;
4) The period of biological activity (PBA) for the mapped units was estimated based on their geographical coordinates; and
5) The assessment of the total annual methane fluxes from the soils of Russia was based on the different soils’ capacities to produce or consume methane.

2. DESCRIPTION OF THE METHANE FLUXES DATABASE

The generation of a methane fluxes database (MFDB) was encouraged by the existence of a great number of literature sources reporting numerous methane fluxes measurements from different terrestrial ecosystems. The number of measurements has progressively increased during the last years. In the literature, various ecosystems (predominantly wetlands) are characterized by methane flux rates accompanied by environmental parameters. Abundance, complexity, and high variability of data require a systematization of the available data. There is also a need to estimate the methane fluxes from ecosystems with no or poorly-determined data. In this approximation a database is of high value.

So far no MFDB has been developed where a sufficient set of data, representing the diversity of ecosystems accompanied by specific methane fluxes, is stored. The "Emission Database for Global Atmospheric Research" (Olivier et al. 1994) was developed for atmospheric chemistry and climate modeling, and does not even deal with methane emissions from the terrestrial ecosystems (soils).

Thus, the aim of MFDB generation was, besides the collection of methane flux data from different sites of temperate, boreal, and tundra zones, to combine methane fluxes with specific environmental conditions. This structure provides a possibility to deal with the variations of the CH_4 emissions rates as dependent of the ecological properties of the local environment. The developed MFDB may also be used for model development as a source of experimental data for problem identification and model verification.

The MFDB developed contains more than 500 records describing methane emission rates from various soil and ecosystem types accompanied by a set of environmental parameters. The data represents field site measurements carried out in Alaska, Canada, USA, UK, Sweden, Finland, Germany and Russia. More than 40 different original sources have been used for the database. All available information concerning methane fluxes from soils directly measured on the territory of Russia is represented in the database. Sites of the measurements are situated in the European part (south boreal and tundra belts), West-Siberian and Kolyma lowlands, and Central Yakutia. The extent of the data obtained for Russia constitutes about 30% of the total database.

In relation to previous research (Rozanov 1995), we tried in this case to include not only methane emissions from wetlands, which are considered to be the main methane source among terrestrial ecosystems, but also consumption of methane by forests, grasslands and other automorphic soils. One of the goals for the MFDB generation was to characterize as many soil units as possible with respect to methane fluxes to the atmosphere.

In Table 1, the main fields of the database and their descriptions are listed. This set of fields was the basis for our further calculations. The complete list of the fields represented in the database is provided in Appendix 1. The database contains methane fluxes as well as various information characterizing not only the ecosystem or sampling site, but also its state and environmental conditions. Unfortunately, there are great differences between different sources in the sets of parameters represented, which leads to information gaps and empty fields for numerous records. Methane fluxes are given in every record, but they refer to different periods of measurements, which are reflected in special fields. The variation in the measurement period is up to several years in the database.

Table 1. List of the main fields of the methane fluxes database.

NN	FIELD NAME	FIELD TYPE	FIELD DESCRIPTION
1.	ID-N	Numeric	Record number
2.	COUNTRY	Character	Country code
3.	LOCATION	Character	Administrative region name
4.	PLACE	Character	Local name of the sampling site
5.	SITUATION	Character	Mezorelief element of the sampling site
6.	SITE	Character	Ecosystem type of the sampling site
7.	SUBFORM	Character	Ecosystem subformation of the sampling site
8.	PHYSGNMC-GROUP	Character	Upper level vegetation characteristics
9.	TYPE	Character	Mineral nutrition level of ecosystem
10.	MICRORELIEF	Character	Microrelief characteristics
11.	COMMNTS	Character	Peculiar site properties
12.	POSITION	Character	Microrelief element of the sampling site
13.	VEGETATION	Character	Type of vegetation and/or dominant species
14.	PERMAFROST	Logical	Indicator of permafrost presence
15.	LATITUDE	Numeric	Geographical latitude of the sampling site [degrees.minutes]
16.	LONGITUDE	Numeric	Geographical longitude of the sampling site [degrees.minutes]
17.	SOIL-UNIT	Character	Sampling site Soil Unit index according to the Legend of the FAO/UNESCO (1974) Soil Map of the World
18.	ORG-S-U	Character	Sampling site original soil name as indicated in source of information according to classification used
19.	DATE	Date	Date of measurement
20.	START-DATE	Date	Initial date of the series of measurements
21.	END-DATE	Date	Final date of the series of measurements
22.	MG-D-L	Numeric	Minimal methane flux registered in the series of measurements [mg CH_4/m^2/day]
23.	MG-D-H	Numeric	Maximal methane flux registered in the series of measurements [mg CH_4/m^2/day]
24.	MG-D-AV	Numeric	Mean methane flux in the series of measurements [mg CH_4/m^2/day]
25.	OBS-N	Numeric	Number of data in series
26.	CITATION	Character	Reference to the source of information

Each site represented in the MFDB is related to one of 106 soil units given in the legend of the FAO/UNESCO (1974) *Soil Map of the World* (SMW) according to the following:

a) original soil unit (SU) stored in ORG-SU field of the database, if directly indicated in a source;
b) in accordance with Table 2, listed for site properties in the database fields: ZONE, SITUATION, SITE, SUBFORM, PHYSGNMC-GROUP, TYPE, MICRORELIEF, COMMNTS, POSITION, VEGETATION, PERMAFROST;
c) the SU is listed for a SMW polygon based on the site's geographical coordinates (the fields LATITUDE and LONGITUDE).

The latter approach (item c) seems to be fruitful to determine the site's linkage to a mapping unit of the SMW.

The result of the MFDB generation is presented in Tables 3 and 4. Weighted minimum, mean and maximum methane fluxes for each of the SUs, separated for permafrost and non-permafrost soils, were calculated for the individual SUs throughout the MFDB. For SUs identified as containing a specific major soil grouping and only indexed by a capital letter, the specific methane fluxes were calculated as weighted values among all the MFDB records matching the major soil grouping.

The weights used in the calculation were the following:

a) the number of site flux measurements contained in the MFDB field OBS-N for a given record;
b) the period of measurements expressed in days as contained in the MFDB fields END-DATE and START-DATE.

In order to validate the resulting numbers of records used for the calculations, each individual SU flux is presented as well as the sum of the observations. It should be noted that the less records forming the SU flux, the less reliable is the flux estimate.

Tables 3 and 4 show that 17 permafrost SUs and 31 non-permafrost SUs out of 75 SUs actually represent soils on the territory of Russia with specified methane fluxes. The majority of wet and overmoistened soils, which are considered to be the main sources of methane, were specified with methane fluxes. These soils are fluvisols, histosols, gleysols, and gleyic soil units of various Major Soil Groupings.

The methane-consuming SUs are specified in less extent with regard to fluxes due to a comparatively limited number of publications reporting soil methane consumption data. Investigations carried out in recent times are mostly in regions with sufficient moisture: forests and wetlands of temperate, boreal and tundra zones. There is a lack of similar data for the arid and semiarid regions of deserts, semi-deserts and steppes. However, all of these SUs with non-specified methane fluxes represent predominantly automorphic or dry soils which probably constitute methane-consuming properties or produce insignificant methane fluxes.

Table 2. Principal scheme for cross-references between sites and FAO/UNESCO (1974) soil units (after Rozanov 1995).

SITE	SUBFORM	PHYSIOGNOMIC GROUP	MOISTURE	ZONE/BELT	SOIL UNIT
Alluvial					J , Je
Bog	Forested				Od, Gd
Bog	Open				Od
Bog				Permafrost	Ox
Fen	Forested				Oe, Ge
Fen	Open				Oe
Fen				Permafrost	Ox
Forest		Coniferous	Wet	Taiga	Pg
Forest		Coniferous		Taiga	Po, Ph
Forest		Mixed	Wet	Taiga	Lg, Dg
Forest		Mixed		Taiga	Dd, De, Pl
Forest		Mixed		Temperate	Bd
Forest		Deciduous	Wet	Temperate	Bg, Mg
Forest		Broadleaf		Temperate	Be
Marsh	Salt				Zg, Sg
Meadow		Sedge			Gm
Swamp		Coniferous			Gh
Tundra			Moist	Permafrost	Gx
Tundra			Well-drained	Permafrost	Rx, Bx, I, U, E

Table 3. Methane fluxes from non-permafrost soils of Russia based on calculations from the methane fluxes database.

NN	MAJOR SOIL GROUPINGS	SOIL UNITS	SPECIFIC METHANE FLUX mg CH_4/m^2/day MEAN	MIN	MAX	NUMBER* OF RECORDS	NUMBER** OF OBSERVATIONS
1	CAMBISOLS	B	0.51	-2.04	14.81	46	628
2		Bd	-2.08	-5.36	-0.48	7	7
3		Be	-0.38	-0.81	-0.03	5	6
4		Bg	0.66	-1.85	15.70	34	615
5	PODZOLUVISOLS	D	0.02	0.02	0.02	5	5
6		Dd	0.00	0.00	0.00	2	2
7		De	0.00	0.00	0.00	2	2
8		Dg	4.80	4.80	4.80	1	1
9	GLEYSOLS	G	21.87	9.40	97.31	122	4525
10		Gd	2.15	-1.34	20.59	20	467
11		Ge	27.42	20.11	36.54	19	2150
12		Gh	17.54	-0.12	100.26	17	1310
13		Gm	28.37	0.02	379.15	11	543
14		Gx	15.09	15.09	15.09	55	55
15	FLUVISOLS	J	27.67	12.71	44.40	15	284
16		Je	27.67	12.71	44.40	15	284
17	LUVISOLS	L	-0.49	-0.94	-0.04	17	30
18		Lo	-0.49	-0.94	-0.04	17	30
19	GREYZEMS	M	2.20	0.00	4.40	4	8
20		Mo	2.20	0.00	4.40	4	8
21	HISTOSOLS	O	28.63	17.78	106.81	122	8116
22		Od	24.63	12.85	70.78	64	3940
23		Oe	32.62	22.61	142.15	49	4167
24		Ox	1.24	1.24	1.24	9	9
25	PODZOLS	P	1.10	-0.34	55.04	51	599
26		Pg	1.73	-0.13	59.00	5	553
27		Ph	-0.32	-1.28	0.00	1	1
28		Pl	-2.85	-3.37	0.18	20	20
29		Po	-3.02	-4.07	-2.88	25	25
30	REGOSOLS	R	-0.48	-0.67	-0.30	9	1366
31		Re	-0.48	-0.67	-0.30	9	1366

* Number of database records used for the flux calculations

** Number of methane flux measurements taken into account for the flux calculations

Table 4. Methane fluxes from permafrost soils of Russia based on calculations from the methane fluxes database.

NN	MAJOR SOIL GROUPINGS	SOIL UNITS	SPECIFIC METHANE FLUX mg CH_4/m^2/day MEAN	MIN	MAX	NUMBER* OF RECORDS	NUMBER** OF OBSERVATIONS
32	GLEYSOLS	G	60.22	5.52	213.19	103	1850
33		Gd	-0.49	-1.38	0.00	4	133
34		Gh	54.47	7.96	262.80	26	451
35		Gm	123.05	-8.03	454.41	22	493
36		Gx	27.96	13.00	46.96	51	773
37	LITHOSOLS	I	10.13	-0.05	123.41	13	724
38	FLUVISOLS	J	0.56	-0.31	0.87	4	96
39		Jd	36.12	32.03	42.94	2	6
40		Je	-0.17	-0.98	0.00	2	90
41	HISTOSOLS	O	71.50	15.61	171.22	46	272
42		Od	11.73	0.40	29.13	19	170
43		Oe	356.88	92.97	906.26	21	60
44		Ox	63.02	9.71	108.61	6	42
45	PODZOLS	P	4.60	-0.30	67.00	1	18
46		Pg	4.60	-0.30	67.00	1	18
47	REGOSOLS	R	119.00	34.00	266.00	1	44
48		Rx	119.00	34.00	266.00	1	44

* Number of database records used for the flux calculations

** Number of methane flux measurements taken into account for the flux calculations

Table 3 shows that among the non-permafrost SUs, the histosols and fluvisols have the highest methane-generating ability with methane fluxes of about 30 mg CH_4/m^2 and day. Non-permafrost gleysols are characterized by average fluxes with more than 20 mg CH_4/m^2 and day. Methane emissions from the examined gleyic units of cambisols, podzoluvisols, and podzols did not exceed 5 mg CH_4/m^2 and day. The other SUs of cambisols, podzoluvisols, luvisols, podzols and regosols have methane-consuming properties in the range of -5 to 0 mg CH_4/m^2 and day. Table 4 indicates that the methane fluxes for permafrost SUs are significantly higher than for non-permafrost SUs. The variability of methane fluxes between individual SUs of the same Major Soil Grouping is also higher for the permafrost SUs. The mean flux of permafrost gleysols varies between -0.5 to 123 mg CH_4/m^2 per day. For permafrost histosols the range is wider: 11-357 mg CH_4/m^2 and day. Very few data are available for permafrost fluvisols, podzols and regosols and show a significant variation in the fluxes between SUs of the Major Soil Groupings. It can also be concluded that more data are available for the non-permafrost regions than for the permafrost region.

3. ASSUMPTIONS AND CALCULATIONS

Estimation of the total methane flux from the territory of Russia is based on a conventional approach, namely the integration of methane fluxes throughout the whole territory depending on an area with specific fluxes and the period of biological activity. Rozanov (1995) used the following expression:

$$Em = \sum_{i=1}^{n} a_i \cdot \int_{t_1}^{t_2} r_{i(t)} dt \qquad \textbf{(1)}$$

where

Em = accumulated methane flux;
a_i = area of the i-th mapping unit component;
n = number of mapping units;
t = time;
$r_{i(t)}$ = specific methane flux from i-th mapping unit component depending on time;
t_1, t_2 = initial respectively final points of time, which are boundaries for the period of biological activity.

In fact this equation can be reduced to:

$$FLUX = \sum_{i,j} (A_{ij} * F_i * T_j) \qquad \textbf{(2)}$$

where

FLUX = total annual methane flux;
i = accumulation index that takes the values from all SUs with specified methane fluxes (i.e. EXAMINED SU);
j = accumulation index that takes the values from all mapping units (polygons), where the i-th SU is represented;
A_{ij} = area occupied by the i-th SU within the j-th mapping unit;
F_i = specified methane flux for the i-th SU;
T_j = period of time during a year, while soils of the j-th mapping unit are active in terms of methane fluxes (the period of biological activity).

Expression (2) was used to estimate annual methane fluxes to the atmosphere from the soils of Russia.

The following assumptions were made for the calculations:

a) permafrost and non-permafrost soils represented by the same SU were considered as different soil types;
b) duration of a period of biological activity was uniform for all locations (i.e. SU) within a specific mapping unit (polygon); and
c) the specific methane fluxes of each SU were uniform during the PBA for all mapping units, where the SU was represented.

Thus, in the calculations there was a need to assess values of three variables in expression (2): i) set of areas; ii) specific methane fluxes; iii) duration of the period of biological activity.

The set of areas was taken from the FAO/UNESCO (1974) SMW. After the map processing, the areas were calculated for 80 soil and land units of the territory of Russia. These areas are presented in Appendix 2 together with their cumulative methane fluxes. For a number of SUs the specific methane fluxes are presented in Tables 3 and 4.

Finally, it was necessary to estimate values for PBA. In earlier work the length of the methane-production season was roughly supposed to be equal to 100 days for high latitudes and 150 days for middle latitudes (Matthews and Fung 1987), and the same values were also relevant to permafrost and non-permafrost territories respectively (Rozanov 1995).

For the non-methane production season, the methane fluxes from soils were set to zero. In spite of the fact, significant winter fluxes have been identified (Dise 1992). In global and regional calculations these fluxes were considered to be negligible in relation to the overall estimation errors. The majority of the methane flux measurements have been carried out during the spring-autumn period. Therefore the use of the methane production season allows us to extrapolate the experimental data for a whole year and by that receive annual estimates.

Thus, an attempt was made to carry out more realistic approximations of PBA than in earlier work. All of the territory of Russia has negative temperatures during the winter. Therefore the estimate on the average long-term duration of the frostless period was based on the geographical coordinates of a certain mapping unit. The definition of a frostless period is the period from the last frost in the spring to the first one in the autumn. Data on the frostless period duration for different places in Russia and adjacent countries were taken from the directory "Principal data on the climate of the USSR" (Osnovnye dannye po klimatu SSSR 1976). Based on the geographical coordinates, specific frostless periods were calculated for each of the 355 mapping units identified within the territory of Russia on the FAO/UNESCO (1974) SMW. Data for the interpolation of the frostless period for the SUs is presented in Appendix 3.

4. ESTIMATION OF THE TOTAL METHANE FLUX FROM NATURAL LANDS OF RUSSIA

The main goal of this study was to make assessments of the total methane flux from Russia’s territory to the atmosphere. There are a number of reasons for updating the estimates by Rozanov (1995). First, additional data dealing with the specific methane fluxes from certain soil units are now available. In this study an attempt was made to detect the consumption of methane by various automorphic soils from the total fluxes generated by the wetlands. This attempt was made in order to estimate net fluxes. In this work a more refined approach to the PBA estimation was used. However, calculations were also made using the simple approach of distributing the daily fluxes over a year according to the period of biological activity as demonstrated by Matthews and Fung (1987) and Rozanov (1995).

Aggregated results for the methane fluxes estimations are presented in Table 5 for non-permafrost and permafrost soils, and for the total area of Russia. In this table the fluxes are related to the Major Soil Groupings and corresponding areas.

The distribution of the methane-generating and methane-consuming areas of the soils of the Russian territory (Tables 6, 7, 8, and 9) was calculated in the following way:

Table 5.1. Distribution of soils over areas and examined methane fluxes within the non-permafrost territory of Russia.

SOIL GROUP / LAND UNIT	SOIL GROUP / LAND UNIT CODE	UNEXAMINED AREA km^2	EXAMINED AREA km^2	EXAMINED METHANE FLUX Tg yr^{-1}	TOTAL AREA km^2
ACRISOLS	A	672.1			672.1
CAMBISOLS	B	26765.9	226865.5	-0.032	253631.4
CHERNOZEMS	C	886121.1			886121.1
PODZOLUVISOLS	D		1519186.7	0.057	1519186.7
RENDZINAS	E	12427.1			12427.1
GLEYSOLS	G	18861.3	786080.3	1.420	804941.6
PHAEOZEMS	H	12997.1			12997.1
LITHOSOLS	I	515508.8			515508.8
FLUVISOLS	J	39168.8	184041.2	0.648	223210.0
KASTANOZEMS	K	347646.1			347646.1
LUVISOLS	L	214438.1	191319.1	-0.014	405757.2
GREYZEMS	M	60881.6	235792.9	0.068	296674.5
HISTOSOLS	O		688965.2	2.036	688965.2
PODZOLS	P		731196.9	-0.048	731196.9
SOLONETZ	S	178909.5			178909.5
ANDOSOLS	T	115116.8			115116.8
RANKERS	U	11781.0			11781.0
PLANOSOLS	W	17218.1			17218.1
XEROSOLS	X	50791.4			50791.4
SOLONCHAKS	Z	23927.8			23927.8
TOTAL AREA of SOILS:		2606879.4	4575760.5	4.134	7182639.9
DUNES, SHIFTING SANDS	DS	32158.2			32158.2
GLASIER	GL	6355.6			6355.6
ROCKS	RK	20222.0			20222.0
WATER	WR	186959.7			186959.7
NO DATA	ND	237.6			237.6
TOTAL AREA of MISCELLANEOUS LAND UNITS:		245933.1			245933.1
TOTAL AREA:		2852812.5	4575760.5	4.134	7428573.0

Table 5.2. Distribution of soils over areas and examined methane fluxes within the permafrost territory of Russia.

SOIL GROUP / LAND UNIT	SOIL GROUP / LAND UNIT CODE	UNEXAMINED AREA km^2	EXAMINED AREA km^2	EXAMINED METHANE FLUX Tg yr^{-1}	TOTAL AREA km^2
ACRISOLS	A				
CAMBISOLS	B	2297357.7			2297357.7
CHERNOZEMS	C	47330.8			47330.8
PODZOLUVISOLS	D	1191854.0			1191854.0
RENDZINAS	E				
GLEYSOLS	G	25992.3	1796534.6	3.106	1822526.9
PHAEOZEMS	H				
LITHOSOLS	I		1574543.6	1.501	1574543.6
FLUVISOLS	J		92980.3	0.067	92980.3
KASTANOZEMS	K	5978.6			5978.6
LUVISOLS	L	103.0			103.0
GREYZEMS	M	23012.5			23012.5
HISTOSOLS	O		1079363.9	7.315	1079363.9
PODZOLS	P	44666.9	70187.0	0.028	114853.9
REGOSOLS	R	193419.2	871719.6	7.912	1065138.8
ANDOSOLS	T	14413.9			14413.9
RANKERS	U	179.5			179.5
PLANOSOLS	W	33671.5			33671.5
XEROSOLS	X				
SOLONCHAKS	Z	769.7			769.7
TOTAL AREA of SOILS:		3888981.5	5485329.0	19.928	9374310.5
DUNES, SHIFTING SANDS	DS				
GLASIER	GL				
ROCKS	RK	35149.3			35149.3
WATER	WR				
NO DATA	ND				
TOTAL AREA of MISCELLANEOUS LAND UNITS:		35149.3			35149.3
TOTAL AREA:		3924130.8	5485329.0	19.928	9409459.8

Table 5.3. Distribution of soils over areas and examined methane fluxes for the total territory of Russia.

SOIL GROUP / LAND UNIT	SOIL GROUP / LAND UNIT CODE	UNEXAMINED AREA km^2	EXAMINED AREA km^2	EXAMINED METHANE FLUX $Tg\ yr^{-1}$	TOTAL AREA km^2
ACRISOLS	A	672.1			672.1
CAMBISOLS	B	2324123.6	226865.5	-0.03	2550989.1
CHERNOZEMS	C	933451.9			933451.9
PODZOLUVISOLS	D	1191854.0	1519186.7	0.06	2711040.7
RENDZINAS	E	12427.1			12427.1
GLEYSOLS	G	44853.6	2582614.9	4.53	2627468.5
PHAEOZEMS	H	12997.1			12997.1
LITHOSOLS	I	515508.8	1574543.6	1.50	2090052.4
FLUVISOLS	J	39168.8	277021.5	0.71	316190.3
KASTANOZEMS	K	353624.7			353624.7
LUVISOLS	L	214541.1	191319.1	-0.01	405860.2
GREYZEMS	M	83894.1	235792.9	0.07	319687.0
HISTOSOLS	O		1768329.1	9.35	1768329.1
PODZOLS	P	44666.9	801383.9	-0.02	846050.8
REGOSOLS	R	267066.0	884032.3	7.91	1151098.3
ANDOSOLS	T	129530.7			129530.7
RANKERS	U	11960.5			11960.5
PLANOSOLS	W	50889.6			50889.6
XEROSOLS	X	50791.4			50791.4
SOLONCHAKS	Z	24697.5			24697.5
TOTAL AREA of SOILS:		6495860.9	10061089.5	24.06	16556950.4
DUNES, SHIFTING SANDS	DS	32158.2			32158.2
GLASIER	GL	6355.6			6355.6
ROCKS	RK	55371.3			55371.3
WATER	WR	186959.7			186959.7
NO DATA	ND	237.6			237.6
TOTAL AREA of MISCELLANEOUS LAND UNITS:		281082.4			281082.4
TOTAL AREA:		6776943.3	10061089.5	24.06	16838032.8

Table 6. Areas of methane-generating soils of Russia.

SOIL GROUPS	PROBABLE METHANE-GENERATING AREAS			EXAMINED AREAS			TOTAL AREA
	NON-PERMAFROST km^2	PERMAFROST km^2	TOTAL km^2	NON-PERMAFROST km^2	PERMAFROST km^2	TOTAL km^2	km^2
HISTOSOLS				688965.2	1079363.9	1768329.1	1768329.1
FLUVISOLS	39168.8		39168.8	184041.2	34184.1	218225.3	257394.1
GLEYSOLS	18861.3	25992.3	44853.6	786080.3	1507426.7	2293507.0	2338360.6
GLEYIC UNITS*	276648.0	173702.4	450350.4	395846.0	67971.3	463817.3	914167.7
OTHER UNITS**	46187.5	2057623.0	2103810.5	303878.8	2448478.9	2752357.7	4856168.2
TOTAL AREA of SOILS:	380865.6	2257317.7	2638183.3	2358811.5	5137424.9	7496236.4	10134419.7
WATER	186959.7		186959.7				186959.7
TOTAL AREA:	567825.3	2257317.7	2825143.0	2358811.5	5137424.9	7496236.4	10321379.4

* NON-PERMAFROST PROBABLE METHANE-GENERATING GLEYIC UNITS of Phaeozems, Luvisols, Greyzems, Solonetz, Solonchaks;
PERMAFROST PROBABLE METHANE-GENERATING GLEYIC UNITS of Cambisols, Podzoluvisols, Greyzems, Solonetz;
NON-PERMAFROST EXAMINED GLEYIC UNITS of Cambisols, Podzoluvisols, Podzols;
PERMAFROST EXAMINED GLEYIC UNITS of Podzols.

** NON-PERMAFROST PROBABLE METHANE-GENERATING SOIL UNITS of Gelic Cambisols, Gelic Regosols;
PERMAFROST PROBABLE METHANE-GENERATING SOIL UNITS of Gelic Cambisols;
NON-PERMAFROST EXAMINED SOIL UNITS of Cambisols, Orthic Greyzems, Podzols;
PERMAFROST EXAMINED SOIL UNITS of Lithosols, Podzols, Gelic Regosols.

Table 7. Fractions of areas of methane-generating soils of the total area of Russia.

SOIL GROUPS	PROBABLE METHANE-GENERATING AREAS			EXAMINED AREAS			TOTAL AREA
	NON-PERMAFROST %	PERMAFROST %	TOTAL %	NON-PERMAFROST %	PERMAFROST %	TOTAL %	%
HISTOSOLS				4.09	6.41	10.50	10.50
FLUVISOLS	0.23		0.23	1.09	0.20	1.30	1.53
GLEYSOLS	0.11	0.15	0.27	4.67	8.95	13.62	13.89
GLEYIC UNITS*	1.64	1.03	2.67	2.35	0.40	2.75	5.43
OTHER UNITS**	0.27	12.22	12.49	1.80	14.54	16.35	28.84
TOTAL AREA of SOILS:	2.26	13.41	15.67	14.01	30.51	44.52	60.19
WATER	1.11		1.11				1.11
TOTAL AREA:	3.37	13.41	16.78	14.01	30.51	44.52	61.30

* NON-PERMAFROST PROBABLE METHANE-GENERATING GLEYIC UNITS of Phaeozems, Luvisols, Greyzems, Solonetz, Solonchaks;
PERMAFROST PROBABLE METHANE-GENERATING GLEYIC UNITS of Cambisols, Podzoluvisols, Greyzems, Solonetz;
NON-PERMAFROST EXAMINED GLEYIC UNITS of Cambisols, Podzoluvisols, Podzols;
PERMAFROST EXAMINED GLEYIC UNITS of Podzols.

** NON-PERMAFROST PROBABLE METHANE-GENERATING SOIL UNITS of Gelic Cambisols, Gelic Regosols;
PERMAFROST PROBABLE METHANE-GENERATING SOIL UNITS of Gelic Cambisols;
NON-PERMAFROST EXAMINED SOIL UNITS of Cambisols, Orthic Greyzems, Podzols;
PERMAFROST EXAMINED SOIL UNITS of Lithosols, Podzols, Gelic Regosols.

Table 8. Area of methane-consuming soils of Russia.

SOIL GROUPS	PROBABLE METHANE-CONSUMING AREAS			EXAMINED AREAS			TOTAL AREA
	NON-PERMAFROST km^2	PERMAFROST km^2	TOTAL km^2	NON-PERMAFROST km^2	PERMAFROST km^2	TOTAL km^2	km^2
ACRISOLS	672.1		672.1				672.1
CAMBISOLS	20716.3	164170.0	184886.3	169551.8		169551.8	354438.1
CHERNOZEMS	886121.1	47330.8	933451.9				933451.9
PODZOLUVISOLS		1119332.5	1119332.5	1413804.2		1413804.2	2533136.7
RENDZINAS	12427.1		12427.1				12427.1
GLEYSOLS					289107.9	289107.9	289107.9
PHAEOZEMS	12974.2		12974.2				12974.2
LITHOSOLS	515508.8		515508.8				515508.8
FLUVISOLS					58796.2	58796.2	58796.2
KASTANOZEMS	347646.1	5978.6	353624.7				353624.7
LUVISOLS	27173.3	103.0	27276.3	191319.1		191319.1	218595.4
GREYZEMS		7628.2	7628.2				7628.2
HISTOSOLS							
PODZOLS		44666.9	44666.9	429961.2		429961.2	474628.1
REGOSOLS	33508.9	193419.2	226928.1	12312.7		12312.7	239240.8
SOLONETZ	152799.0		152799.0				152799.0
ANDOSOLS	115116.8	14413.9	129530.7				129530.7
RANKERS	11781.0	179.5	11960.5				11960.5
PLANOSOLS	17218.1	33671.5	50889.6				50889.6
XEROSOLS	50791.4		50791.4				50791.4
SOLONCHAKS	21559.6	769.7	22329.3				22329.3
TOTAL AREA of SOILS:	2226013.8	1631663.8	3857677.6	2216949.0	347904.1	2564853.1	6422530.7
DUNES, SHIFTING SANDS	32158.2		32158.2				32158.2
GLASIER	6355.6		6355.6				6355.6
ROCKS	20222.0	35149.3	55371.3				55371.3
NO DATA	237.6		237.6				237.6
TOTAL AREA of MISC. LAND UNITS:	58973.4	35149.3	94122.7				94122.7
TOTAL AREA:	2284987.2	1666813.1	3951800.3	2216949.0	347904.1	2564853.1	6516653.4

Table 9. Fractions of areas of methane-consuming soils of the total area of Russia.

SOIL GROUPS	PROBABLE METHANE-CONSUMING AREAS			EXAMINED AREAS			TOTAL AREA
	NON-PERMAFROST %	PERMAFROST %	TOTAL %	NON-PERMAFROST %	PERMAFROST %	TOTAL %	%
ACRISOLS	0.004		0.004				0.004
CAMBISOLS	0.123	0.975	1.098	1.007		1.007	2.105
CHERNOZEMS	5.263	0.281	5.544				5.544
PODZOLUVISOLS		6.648	6.648	8.396		8.396	15.044
RENDZINAS	0.074		0.074				0.074
GLEYSOLS					1.717	1.717	1.717
PHAEOZEMS	0.077		0.077				0.077
LITHOSOLS	3.062		3.062				3.062
FLUVISOLS					0.349	0.349	0.349
KASTANOZEMS	2.065	0.036	2.100				2.100
LUVISOLS	0.161	0.001	0.162	1.136		1.136	1.298
GREYZEMS		0.045	0.045				0.045
PODZOLS		0.265	0.265	2.554		2.554	2.819
REGOSOLS	0.199	1.149	1.348	0.073		0.073	1.421
SOLONETZ	0.907		0.907				0.907
ANDOSOLS	0.684	0.086	0.769				0.769
RANKERS	0.070	0.001	0.071				0.071
PLANOSOLS	0.102	0.200	0.302				0.302
XEROSOLS	0.302		0.302				0.302
SOLONCHAKS	0.128	0.005	0.133				0.133
TOTAL AREA of SOILS:	13.220	9.690	22.911	13.166	2.066	15.232	38.143
DUNES, SHIFTING SANDS	0.191		0.191				0.191
GLASIER	0.038		0.038				0.038
ROCKS	0.120	0.209	0.329				0.329
NO DATA	0.001		0.001				0.001
TOTAL AREA of MISC. LAND UNITS:	0.350	0.209	0.559				0.559
TOTAL AREA:	13.570	9.899	23.469	13.166	2.066	15.232	38.702

a) If a certain SU was specified with positive or negative methane fluxes the area occupied by the SU was related as methane-generating, respectively methane-consuming. Thus, in Tables 6 and 7, areas occupied by methane-generating SUs were unified in the section Examined Areas as areas of histosols, fluvisols, gleysols, gleyic units of Major Soil Groupings, or other units. The gleyic units and other units are listed as footnotes to the tables.

b) For SUs not specified with any methane fluxes the areas occupied by SUs belonging to histosols, fluvisols, gleysols or gleyic units of Major Soil Groupings were allocated to the section Probable Methane-Generating Areas. Areas occupied by other SUs with unknown methane fluxes were allocated to the section Probable Methane-Consuming Areas.

An attempt was also made to estimate the range of the total annual methane fluxes based on the minimum and maximum methane fluxes for individual SUs (Tables 3 and 4) and the corresponding duration of the period of biological activity.

In order to estimate an extreme lower limit for the total annual methane fluxes the following algorithm was used:

$$\begin{aligned} &F_i = \min(F_i); \\ &T_j = \min(T_j), \ \text{if} \ \min(F_i) > 0; \\ &T_j = \max(T_j), \ \text{if} \ \min(F_i) < 0; \end{aligned} \tag{3}$$

where F_i is the minimum value of the methane flux for the i-th SU, but the selection of the PBA value (T_j) depends on the sign of $\min(F_i)$ in order to come up with a minimal estimate.

A similar approach was taken for estimation of the extreme upper limit of total annual methane fluxes:

$$\begin{aligned} &F_i = \max(F_i); \\ &T_j = \max(T_j), \ \text{if} \ \max(F_i) > 0; \\ &T_j = \min(T_j), \ \text{if} \ \max(F_i) < 0. \end{aligned} \tag{4}$$

Aggregated lower and upper estimation results are presented in Tables 10 and 11.

The estimated total net annual methane flux from the soils of Russia to the atmosphere are in the range of 5-110 Tg yr^{-1}. However, this range should be considered as very coarse, because the minimum and maximum values for the methane fluxes for various SUs differ greatly. In some cases minimum and maximum estimates have different signs, meaning that the same SU plays opposite roles in the two extreme estimates: methane-generating or methane-consuming.

Table 10. Lower estimate of the annual methane fluxes from the soils of Russia.

		NON-PERMAFROST		PERMAFROST		TOTAL	
		FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2
CONSUMPTION		-0.33	3289679.3	-0.09	2043971.8	-0.42	5333651.1
EMISSION		1.49	1286081.2	4.40	3441357.2	5.88	4727438.4
TOTAL EXAMINED		1.16	4575760.5	4.30	5485329.0	5.46	10061089.5
UNEXAMINED AREA			2852812.5		3924130.8		6776943.3
TOTAL AREA			7428573.0		9409459.8		16838032.8
CONSUMING AREA (%)	of EXAMINED AREA		71.89		37.26		53.01
EMITTING AREA (%)			28.11		62.74		46.99
CONSUMING AREA (%)	of TOTAL AREA		44.28		21.72		31.68
EMITTING AREA (%)			17.31		36.57		28.08
EXAMINED AREA of TOTAL AREA (%)			61.60		58.30		59.75

Table 11. Upper estimate of the annual methane fluxes from the soils of Russia.

	NON-PERMAFROST		PERMAFROST		TOTAL	
	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2
CONSUMPTION	-0.11	2207894.9	0.00	347904.1	-0.11	2555799.0
EMISSION	22.49	2367865.6	87.35	5137424.9	109.84	7505290.5
TOTAL EXAMINED	22.37	4575760.5	87.35	5485329.0	109.72	10061089.5
UNEXAMINED AREA		2852812.5		3924130.8		6776943.3
TOTAL AREA		7428573.0		9409459.8		16838032.8
CONSUMING AREA (%) of EXAMINED AREA		48.25		6.34		25.40
EMITTING AREA (%)		51.75		93.66		74.60
CONSUMING AREA (%) of TOTAL AREA		29.72		3.70		15.18
EMITTING AREA (%)		31.88		54.60		44.57
EXAMINED AREA of TOTAL AREA (%)		61.60		58.30		59.75

The mean net annual methane flux from some 60% of the area of Russia (Tables 12-14) is estimated at 24 Tg yr^{-1}, which corresponds to previous estimates. It is in the middle of the reported range of 11 Tg yr^{-1} (Andronova and Karol 1993; Harriss et al. 1993) and 39 Tg yr^{-1} (Rozanov 1995). Moreover, it is in accordance with the estimates of 25-65 Tg yr^{-1} for territories to the north of the 45° N parallel (Matthews and Fung 1987; Aselmann and Crutzen 1989; Harriss et al. 1993; Fung et al. 1991; Bartlett and Harriss 1993). Nevertheless, the mean estimate of 24 Tg yr^{-1} may be a high estimate due to the fact that some of the site-specific methane fluxes used in the calculations are very high. For example, the methane fluxes calculated for permafrost of eutric histosols (Oe) and gelic regosols (Rx) are equal to 357 respectively 119 mg CH_4/m^2/day (Tables 3 and 4). These values are considerably higher than the methane fluxes for the majority of the other SUs. The fluxes from the rest of the 40% of Russia's territory do not seem to change the presented estimates significantly. However, the extent of the unexamined automorphic soils constitutes 23.5% of Russia's territory, which is more than half of the total unexamined territory. These soils are likely to have a methane consumption ability of approximately 1 mg/m^2/day, which may reduce the total methane fluxes by at least 0.6 Tg yr^{-1}.

Some 15% of the area of Russia is estimated to have an average methane consumption of -0.17 Tg yr^{-1}. The lower and upper limits of the negative fluxes for these soils are estimated to be -0.11 Tg yr^{-1} and -0.42 Tg yr^{-1} respectively. The examined area of methane-consuming soils is less than half of the area of probable methane-consuming soils of Russia (Table 9). This is the reason for a possible underestimate of the annual methane consumption.

Estimations of the specific methane fluxes for some SUs appear to be uncertain (calculated on the basis of less than 3 records of MFDB). After elimination of these SUs with likely uncertain specific methane fluxes, new mean, lower and upper estimates were calculated for the reduced SU list (Tables 15, 16, and 17). The extent of the examined area dropped from 60% to 44% by this deduction. In this case, the mean annual estimate of the total net methane flux is 16 Tg yr^{-1}. The lower and upper limits for the total net methane fluxes for 44% of the Russian territory are reduced to 3 Tg yr^{-1} and 87 Tg yr^{-1}.

To illustrate the importance of an exact estimation of the PBA a calculation was made with a simple approximation of PBA according to Matthews and Fung (1987) and Rozanov (1995) (Table 18). In this case the mean total net annual methane fluxes from 60% of the area of Russia is estimated to be 33 Tg yr^{-1}. This is close to the Rozanov (1995) estimate of 39 Tg yr^{-1}, based on a similar assumption concerning the PBA estimation. The difference between the two estimates can probably be explained by the differences in the SU specific methane fluxes estimates derived from the data set employed in the current report.

The comparison of the results based on different approaches shows the importance of an accurate estimate of the length of the season for methane production and its influence on the total methane fluxes estimate. Thus, for 60% of the territory of Russia, our calculations show a net flux of methane of 24 Tg yr^{1} if a more detailed PBA estimate is used. The net flux estimate becomes almost 50% higher if a simplified PBA approach is used.

Table 12. Assessment of average annual methane emission from examined soils of Russia.

SOIL GROUPS	NON-PERMAFROST		PERMAFROST		ALL TERRITORY OF RUSSIA	
	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}
HISTOSOLS	688965.2	2.036	1079363.9	7.315	1768329.1	9.351
FLUVISOLS	184041.2	0.648	34184.1	0.068	218225.3	0.716
GLEYSOLS	786080.3	1.420	1507426.7	3.118	2293507.0	4.538
GLEYIC UNITS*	395846.0	0.105	67971.3	0.027	463817.3	0.132
OTHER UNITS**	303878.8	0.077	2448478.9	9.413	2752357.7	9.490
TOTAL AREA:	2358811.5	4.286	5137424.9	19.941	7496236.4	24.227

* NON-PERMAFROST GLEYIC UNITS of Cambisols, Podzoluvisols, Podzols;
PERMAFROST GLEYIC UNITS of Podzols.

** NON-PERMAFROST Cambisols, Orthic Greyzems, Podzols;
PERMAFROST Lithosols, Podzols, Gelic Regosols.

Table 13. Assessment of average annual methane consumption by examined soils of Russia.

SOIL GROUPS	NON-PERMAFROST		PERMAFROST		ALL TERRITORY OF RUSSIA	
	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}
CAMBISOLS	169551.8	-0.037			169551.8	-0.037
PODZOLUVISOLS	1413804.2	0.000			1413804.2	0.000
GLEYSOLS			289107.9	-0.012	289107.9	-0.012
FLUVISOLS			58796.2	-0.001	58796.2	-0.001
LUVISOLS	191319.1	-0.014			191319.1	-0.014
PODZOLS	429961.2	-0.101			429961.2	-0.101
REGOSOLS	12312.7	-0.001			12312.7	-0.001
TOTAL AREA:	2216949.0	-0.152	347904.1	-0.013	2564853.1	-0.166

Table 14. Estimate of the mean annual methane fluxes from the soils of Russia.

		NON-PERMAFROST		PERMAFROST		TOTAL	
		FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2
CONSUMPTION		-0.15	2216949.0	-0.01	347904.1	-0.17	2564853.1
EMISSION		4.29	2358811.5	19.94	5137424.9	24.23	7496236.4
TOTAL EXAMINED		4.13	4575760.5	19.93	5485329.0	24.06	10061089.5
UNEXAMINED AREA			2852812.5		3924130.8		6776943.3
TOTAL AREA			7428573.0		9409459.8		16838032.8
CONSUMING AREA (%)	of EXAMINED AREA		48.45		6.34		25.49
EMITTING AREA (%)			51.55		93.66		74.51
CONSUMING AREA (%)	of TOTAL AREA		29.84		3.70		15.23
EMITTING AREA (%)			31.75		54.60		44.52
EXAMINED AREA of TOTAL AREA (%)			61.60		58.30		59.75

Table 15. Estimate of the mean annual methane fluxes from the soils of Russia (for reduced set of soil units with specified methane flux).

		NON-PERMAFROST		PERMAFROST		TOTAL	
		FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2
CONSUMPTION		-0.15	654692.5	-0.01	289107.9	-0.16	943800.4
EMISSION		4.23	2253429.0	11.93	4169257.3	16.16	6422686.3
TOTAL EXAMINED		4.08	2908121.5	11.92	4458365.2	16.00	7366486.7
UNEXAMINED AREA			4520451.5		4951094.6		9471546.1
TOTAL AREA			7428573.0		9409459.8		16838032.8
CONSUMING AREA (%)	of EXAMINED AREA		22.51		6.48		12.81
EMITTING AREA (%)			77.49		93.52		87.19
CONSUMING AREA (%)	of TOTAL AREA		8.81		3.07		5.61
EMITTING AREA (%)			30.33		44.31		38.14
EXAMINED AREA of TOTAL AREA (%)			39.15		47.38		43.75

Table 16. Lower estimate of the annual methane fluxes from the soils of Russia (for reduced set of soil units with specified methane flux).

		NON-PERMAFROST		PERMAFROST		TOTAL	
		FLUX $Tg\ yr^{-1}$	AREA km^2	FLUX $Tg\ yr^{-1}$	AREA km^2	FLUX $Tg\ yr^{-1}$	AREA km^2
CONSUMPTION		-0.30	1727422.8	-0.09	1914988.6	-0.39	3642411.4
EMISSION		1.43	1180698.7	2.59	2543376.6	4.02	3724075.3
TOTAL EXAMINED		1.13	2908121.5	2.50	4458365.2	3.63	7366486.7
UNEXAMINED AREA			4520451.5		4951094.6		9471546.1
TOTAL AREA			7428573.0		9409459.8		16838032.8
CONSUMING AREA (%)	of EXAMINED AREA		59.40		42.95		49.45
EMITTING AREA (%)			40.60		57.05		50.55
CONSUMING AREA (%)	of TOTAL AREA		23.25		20.35		21.63
EMITTING AREA (%)			15.89		27.03		22.12
EXAMINED AREA of TOTAL AREA (%)			39.15		47.38		43.75

Table 17. Upper estimate of the annual methane fluxes from the soils of Russia (for reduced set of soil units with specified methane flux).

		NON-PERMAFROST		PERMAFROST		TOTAL	
		FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2
CONSUMPTION		-0.11	645638.4	0.00	289107.9	-0.11	934746.3
EMISSION		22.43	2262483.1	61.63	4169257.3	84.06	6431740.4
TOTAL EXAMINED		22.32	2908121.5	61.63	4458365.2	83.94	7366486.7
UNEXAMINED AREA			4520451.5		4951094.6		9471546.1
TOTAL AREA			7428573.0		9409459.8		16838032.8
CONSUMING AREA (%)	of EXAMINED AREA		22.20		6.48		12.69
EMITTING AREA (%)			77.80		93.52		87.31
CONSUMING AREA (%)	of TOTAL AREA		8.69		3.07		5.55
EMITTING AREA (%)			30.46		44.31		38.20
EXAMINED AREA of TOTAL AREA (%)			39.15		47.38		43.75

Table 18. Estimate of the mean annual methane fluxes from the soils of Russia (for simple approximation of the period of biological activity).

		NON-PERMAFROST		PERMAFROST		TOTAL	
		FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2
CONSUMPTION		-0.19	2216949.0	-0.02	347904.1	-0.21	2564853.1
EMISSION		5.44	2358811.5	27.87	5137424.9	33.31	7496236.4
TOTAL EXAMINED		5.24	4575760.5	27.86	5485329.0	33.10	10061089.5
UNEXAMINED AREA			2852812.5		3924130.8		6776943.3
TOTAL AREA			7428573.0		9409459.8		16838032.8
CONSUMING AREA (%)	of EXAMINED AREA		48.45		6.34		25.49
EMITTING AREA (%)			51.55		93.66		74.51
CONSUMING AREA (%)	of TOTAL AREA		29.84		3.70		15.23
EMITTING AREA (%)			31.75		54.60		44.52
EXAMINED AREA of TOTAL AREA (%)			61.60		58.30		59.75

5. SUMMARY

In order to assess the methane fluxes from the Russian soils to the atmosphere the following steps have been taken:

1) Information concerning soil types, areas, and coordinates for the soils of Russia was collected from the FAO/UNESCO (1974) *Soil Map of the World.*
2) A database, based on experiments described in the literature, was generated concerning methane fluxes and environmental parameters influencing the fluxes.
3) Representative methane fluxes for the majority of the temperate, boreal and tundra soils were calculated based on the database.
4) The period of biological activity (PBA) for the different soils was estimated based on their geographical location.
5) Based on the above information the total annual methane fluxes are estimated based on the different soil's capacities to produce or consume methane.

It can be concluded that there are still big uncertainties connected with the methane flux estimates for Russia due to the lack of data. The basic analyses carried out are based on site and soil type specific methane fluxes corresponding to some 60% of the land of Russia (44% methane-generating and 15% methane-consuming). However, the remaining unexamined 40% of the land of Russia, with missing site and soil type specific methane fluxes is constituted by soils of which 17% are methane-generating (of which 43% are significant sources) and 23% are probably methane-consuming soils. These soils will probably not significantly influence the presented overall estimate in the fluxes. Extreme lower and extreme upper estimates are produced for the 60% of the land with available site and soil specific methane fluxes. The estimated range is 5-110 Tg yr^{-1}. The mean net annual methane flux based on the same area is 24 Tg yr^{-1}, which is in the middle of earlier published estimates. Andronova and Karol (1993) and Harriss et al. (1993) estimated a net flux of 11 Tg yr^{-1} and Rozanov (1995) estimated a flux of 39 Tg yr^{-1}. The 24 Tg yr^{-1} estimate is including methane fluxes for some of the soil types with a limited number of direct site specific methane flux measurements. If these measurements are deleted from the analyses the mean net annual methane flux in Russia is reduced to 16 Tg yr-1.

The estimation of the length of the period of biological activity (PBA) is crucial for the estimates of the total fluxes. In the above estimate, based on 60% of the land area with site and soil type specific fluxes and a detailed estimate of the PBA based on the geographical coordinates of the different soil types, a mean net annual flux of 24 Tg yr^{-1} is achieved. But if we employ PBA estimates on the more simple method used by Matthews and Fung (1987) and Rozanov (1995) the mean net annual flux estimate is 33 Tg yr^{-1}.

In spite of numerous attempts to find correlations between methane fluxes and ecological characteristics of different biomes the problem of regional extrapolation of sporadic field measurements still exists.

There are very few regions and ecosystems investigated by field measurements in comparison with the natural diversity. Thus, many soil units are not characterized by any measurements of the methane fluxes. The majority of the soil units with measurements represent automorphic soils and wetlands and wet soils are not sufficiently represented.

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APPENDIX 1. List of fields in the methane fluxes database.

NN	FIELD NAME	FIELD TYPE	FIELD DESCRIPTION
1.	ID-N	Numeric	Record number
2.	ORIG-NUM	Character	Site code as identified in source of information
3.	COUNTRY	Character	Country code
4.	LOCATION	Character	Administrative region name
5.	ZONE	Character	Natural zone/belt name
6.	PLACE	Character	Local name of the sampling site
7.	SITUATION	Character	Mezorelief element of the sampling site
8.	SITE	Character	Ecosystem type of the sampling site
9.	SUBFORM	Character	Ecosystem subformation of the sampling site
10.	PHYSGNMC-GROUP	Character	Upper level vegetation characteristics
11.	TYPE	Character	Mineral nutrition level of ecosystem
12.	MICRORELIEF	Character	Microrelief characteristics
13.	COMMNTS	Character	Peculiar site properties
14.	POSITION	Character	Microrelief element of the sampling site
15.	VEGETATION	Character	Type of vegetation and/or dominant species
16.	PERMAFROST	Logical	Indicator of permafrost presence
17.	PERDEPTH	Numeric	Mean thickness of thawed layer for the period of measurements [cm] (for sites on permafrost)
18.	LATITUDE	Numeric	Geographical latitude of the sampling site [degrees.minutes]
19.	LONGITUDE	Numeric	Geographical longitude of the sampling site [degrees.minutes]
20.	ANN-PRCPTN	Numeric	Annual precipitation [mm]
21.	ANN-EVPTRPN	Numeric	Annual evaporation [mm]
22.	FROST-FREE	Numeric	Duration of the frostless period [d]
23.	SOIL-UNIT	Character	Sampling site Soil Unit index according to the Legend of the FAO/UNESCO (1974) Soil Map of the World
24.	ORG-S-U	Character	Sampling site original soil name as indicated in source of information according to classification used
25.	DATE	Date	Date of measurement
26.	START-DATE	Date	Initial date of the series of measurements
27.	END-DATE	Date	Final date of the series of measurements
28.	T-AIR	Numeric	Mean air temperature for the period of measurements [Celsius degrees]
29.	PH	Numeric	pH of the soil
30.	EH	Numeric	Eh of the soil [mV]

Appendix 1. (continued)

NN	FIELD NAME	FIELD TYPE	FIELD DESCRIPTION
31.	T-SOIL	Numeric	Mean soil temperature for the period of measurements [Celsius degrees]
32.	T-S-DEPTH	Numeric	Depth of soil temperature measurement [cm]
33.	T-S-LOW	Numeric	Minimal soil temperature registered for the period of measurements [Celsius degrees]
34.	T-S-HIGH	Numeric	Maximal soil temperature registered for the period of measurements [Celsius degrees]
35.	SOIL-MOIST	Numeric	Moisture of the soil [% of oven dried soil]
36.	GR-W-DEPTH	Numeric	Depth of the ground water level [cm]
37.	SOIL-DEPTH	Numeric	Thickness of the soil profile [cm]
38.	MG-H-L	Numeric	Minimum methane flux registered in the series of measurements [mg CH_4/m^2/hour]
39.	mgC-h-l	Numeric	Minimum carbon flux registered in the series of measurements [mg C/m^2/hour]
40.	MG-H-H	Numeric	Maximum methane flux registered in the series of measurements [mg CH_4/m^2/hour]
41.	mgC-h-h	Numeric	Maximum carbon flux registered in the series of measurements [mg C/m^2/hour]
42.	MG-H-AV	Numeric	Mean methane flux in the series of measurements [mg CH_4/m^2/day]
43.	mgC-h-av	Numeric	Mean carbon flux in the series of measurements [mg C/m^2/day]
44.	MG-H-STD	Numeric	Standard deviation of methane flux [mg CH_4/m^2/day]
45.	mgC-h-std	Numeric	Standard deviation of carbon flux [mg C/m^2/day]
46.	MG-D-L	Numeric	Minimum methane flux registered in the series of measurements [mg CH_4/m^2/day]
47.	mgC-d-l	Numeric	Minimum carbon flux registered in the series of measurements [mg C/m^2/day]
48.	MG-D-H	Numeric	Maximum methane flux registered in the series of measurements [mg CH_4/m^2/day]
49.	mgC-d-h	Numeric	Maximum carbon flux registered in the series of measurements [mg C/m^2/day]
50.	MG-D-AV	Numeric	Mean methane flux in the series of measurements [mg CH_4/m^2/day]
51.	MG-D-SE	Numeric	Mean error of methane flux [mg CH_4/m^2/day]
52.	mgC-d-av	Numeric	Mean value of carbon flux [mg C/m^2/day]
53.	MG-D-STD	Numeric	Standard deviation of methane flux [mg CH_4/m^2/day]
54.	mgC-d-std	Numeric	Standard deviation of carbon flux [mg C/m^2/day]

Appendix 1. (continued)

NN	FIELD NAME	FIELD TYPE	FIELD DESCRIPTION
55.	MG-D-MED	Numeric	Median value of the series of measurements [mg CH_4/m^2/day]
56.	mgC-d-med	Numeric	Median value of the series of measurements [mg C/m^2/day]
57.	G-YR	Numeric	Mean value of methane flux [g CH_4/m^2/yr]
58.	gC-yr	Numeric	Mean value of carbon flux [g C/m^2/yr]
59.	G-YR-STD	Numeric	Standard deviation of methane flux [g CH_4/m^2/yr]
60.	gC-yr-std	Numeric	Standard deviation of carbon flux [g C/m^2/yr]
61.	OBS-N	Numeric	Number of data in series
62.	COMMENTS	Character	Record comments
63.	CITATION	Character	Reference to the source of information

COMMENTS:

There are many fields in the database which represent the same parameters expressed in different units of measurement; it was made to store original values of parameters as given in a source of information in order to avoid errors during input and for consequent control of the data; for further calculations similar parameters were reduced to the uniform units of measurement.

APPENDIX 2. Estimate of the mean annual methane fluxes from the soils of Russia to the atmosphere.

NN	SOIL GROUP/UNIT (FAO/UNESCO, 1974)	SOIL GROUP/UNIT CODE	NON-PERMAFROST		PERMAFROST		TOTAL TERRITORY OF RUSSIA	
			AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}
1	Orthic Acrisols	Ao	672.1				672.1	
2	CAMBISOLS	B	65.3	0.000			65.3	0.000
3	Chromic Cambisols	Bc	2384.0				2384.0	
4	Dystric Cambisols	Bd	130157.2	-0.035	110338.0		240495.2	-0.035
5	Eutric Cambisols	Be	39394.6	-0.002			39394.6	-0.002
6	Gleyic Cambisols	Bg	57248.4	0.004	75564.7		132813.1	0.004
7	Humic Cambisols	Bh	18332.3		179.5		18511.8	
8	Calcic Cambisols	Bk	0.0		53652.5		53652.5	
9	Gelic Cambisols	Bx	6049.6		2057623.0		2063672.6	
10	CHERNOZEMS	C	141650.7		16602.9		158253.6	
11	Glossic Chernozems	Cg	26782.4		18977.6		45760.0	
12	Haplic Chernozems	Ch	293123.4		8809.4		301932.8	
13	Calcic Chernozems	Ck	106670.9				106670.9	
14	Luvic Chernozems	Cl	317893.7		2940.9		320834.6	
15	Dystric Podzoluvisols	Dd	471690.7		1112785.6		1584476.3	
16	Eutric Podzoluvisols	De	942113.5		6546.9		948660.4	
17	Gleyic Podzoluvisols	Dg	105382.5	0.057	72521.5		177904.0	0.057
18	RENDZINAS	E	12427.1				12427.1	
19	GLEYSOLS	G	55785.8	0.169	4339.1	0.023	60124.9	0.192
20	Calcaric Gleysols	Gc	18861.3				18861.3	
21	Dystric Gleysols	Gd	252254.0	0.060	289107.9	-0.012	541361.9	0.047
22	Eutric Gleysols	Ge	65979.7	0.202	25992.3		91972.0	0.202
23	Humic Gleysols	Gh	226134.0	0.453	35028.2	0.170	261162.2	0.623
24	Mollic Gleysols	Gm	106988.2	0.404	43414.0	0.502	150402.2	0.907
25	Gelic Gleysols	Gx	78938.6	0.131	1424645.4	2.424	1503584.0	2.555
26	PHAEOZEMS	H	12974.2				12974.2	
27	Gleyic Phaeozems	Hg	22.9				22.9	
28	LITHOSOLS	I	515508.8		1574543.6	1.501	2090052.4	1.501
29	FLUVISOLS	J	34784.5	0.131	7923.1	0.000	42707.6	0.132
30	Calcaric Fluvisols	Jc	132.6				132.6	
31	Dystric Fluvisols	Jd	39036.2		26261.0	0.067	65297.2	0.067
32	Eutric Fluvisols	Je	149256.7	0.517	58796.2	-0.001	208052.9	0.516

Appendix 2. (continued)

NN	SOIL GROUP/UNIT (FAO/UNESCO, 1974)	SOIL GROUP/UNIT CODE	NON-PERMAFROST		PERMAFROST		TOTAL TERRITORY OF RUSSIA	
			AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}
33	KASTANOZEMS	K	8326.1				8326.1	
34	Haplic Kastanozems	Kh	285005.6		5978.6		290984.2	
35	Calcic Kastanozems	Kk	29302.1				29302.1	
36	Luvic Kastanozems	Kl	25012.3				25012.3	
37	LUVISOLS	L	12312.7	-0.001			12312.7	-0.001
38	Albic Luvisols	La	24812.9				24812.9	
39	Chromic Luvisols	Lc	2360.4				2360.4	
40	Gleyic Luvisols	Lg	187264.8				187264.8	
41	Orthic Luvisols	Lo	179006.4	-0.013	103.0		179109.4	-0.013
42	Gleyc Greyzems	Mg	60881.6		15384.3		76265.9	
43	Orthic Greyzems	Mo	235792.9	0.068	7628.2		243421.1	0.068
44	HISTOSOLS	O	4758.8	0.019			4758.8	0.019
45	Dystric Histosols	Od	508037.1	1.416	653142.7	0.660	1161179.8	2.077
46	Eutric Histosols	Oe	158407.8	0.599	258719.5	5.939	417127.3	6.539
47	Gelic Histosols	Ox	17761.5	0.002	167501.7	0.715	185263.2	0.717
48	PODZOLS	P	68020.6	0.009	2215.7	0.001	70236.3	0.010
49	Gleyic Podzols	Pg	233215.1	0.044	67971.3	0.027	301186.4	0.071
50	Humic Podzols	Ph	148452.3	-0.005	23476.5		171928.8	-0.005
51	Leptic Podzols	Pl	9054.1	-0.003			9054.1	-0.003
52	Orthic Podzols	Po	272454.8	-0.092	21190.4		293645.2	-0.092
53	REGOSOLS	R	12137.6	-0.001			12137.6	-0.001
54	Calcaric Regosols	Rc	5740.8		111208.3		116949.1	
55	Dystric Regosols	Rd	27768.1		82210.9		109979.0	
56	Eutric Gleysols	Re	175.1	-0.000			175.1	-0.000
57	Gelic Regosols	Rx	40137.9		871719.6	7.912	911857.5	7.912
58	SOLONETZ	S	6043.5				6043.5	
59	Gleyic Solonetz	Sg	26110.5		10231.9		36342.4	
60	Mollic Solonetz	Sm	88033.0				88033.0	
61	Orthic Solonetz	So	58722.5				58722.5	
62	ANDOSOLS	T	46911.5		3323.9		50235.4	
63	Humic Andosols	Th	2912.4				2912.4	
64	Ochric Andosols	To	43165.9		9313.2		52479.1	
65	Vitric Andosols	Tv	22127.0		1776.8		23903.8	

Appendix 2. (continued)

NN	SOIL GROUP/UNIT (FAO/UNESCO, 1974)	SOIL GROUP/UNIT CODE	NON-PERMAFROST		PERMAFROST		TOTAL TERRITORY OF RUSSIA	
			AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}	AREA km^2	FLUX Tg yr^{-1}
66	RANKERS	U	11781.0		179.5		11960.5	
67	Eutric Planosols	We	124.5				124.5	
68	Solodic Planosols	Ws	17093.6		33671.5		50765.1	
69	XEROSOLS	X	6043.5				6043.5	
70	Haplic Xerosols	Xh	20190.9				20190.9	
71	Luvic Xerosols	Xl	24557.0				24557.0	
72	SOLONCHAKS	Z	441.7				441.7	
73	Gleyic Solonchaks	Zg	2368.2				2368.2	
74	Mollic Solonchaks	Zm	9194.5				9194.5	
75	Orthic Solonchaks	Zo	11923.4		769.7		12693.1	
	UNEXAMINED AREA OF SOILS:		2606879.4		3888981.5		6495860.9	
	EXAMINED AREA OF SOILS:		4575760.5	4.134	5485329.0	19.928	10061089.5	24.062
	TOTAL AREA of SOILS:		7182639.9		9374310.5		16556950.4	
76	DUNES, SHIFTING SANDS	DS	32158.2				32158.2	
77	GLASIER	GL	6355.6				6355.6	
78	ROCKS	RK	20222.0		35149.3		55371.3	
79	WATER	WR	186959.7				186959.7	
80	NO DATA	ND	237.6				237.6	
	TOTAL AREA of MISCELLANEOUS LAND UNITS:		245933.1		35149.3		281082.4	
	TOTAL UNEXAMINED AREA:		2852812.5		3924130.8		6776943.3	
	TOTAL EXAMINED AREA:		4575760.5	4.134	5485329.0	19.928	10061089.5	24.062
	TOTAL AREA:		7428573.0		9409459.8		16838032.8	
	UNEXAMINED AREA OF TOTAL AREA OF RUSSIA (%)		38.403		41.704		40.248	
	EXAMINED AREA OF TOTAL AREA OF RUSSIA (%)		61.597		58.296		59.752	

APPENDIX 3. Duration of frostless period for various locations in the territory of Russia. According to "Principal data on the climate of the USSR" (Osnovnye dannye po klimatu SSSR 1976).

NN	CITY/PLACE NAME	LATITUDE* N decimal degrees	LONGITUDE* E decimal degrees	FROSTLESS PERIOD days
1.	Abakan	53.70	91.40	119
2.	Aktyubinsk	50.28	57.09	138
3.	Aldan	58.58	125.60	97
4.	Anadyr’	64.70	177.40	82
5.	Arkhangelsk	64.60	40.60	118
6.	Astrakhan’	46.40	48.10	189
7.	Bakchar	57.10	82.11	102
8.	Barabinsk	55.45	78.27	121
9.	Barnaul	53.28	83.89	118
10.	Belgorod	50.60	36.60	154
11.	Birobidzhan	48.80	132.90	137
12.	Biysk	52.50	85.20	115
13.	Blagoveschensk	50.30	127.50	144
14.	Bratsk	56.10	101.60	99
15.	Bryansk	53.20	34.40	136
16.	Cheboksary	56.10	47.30	148
17.	Chelyabinsk	55.10	61.40	118
18.	Chelyuskin, cape	76.86	104.81	0
19.	Cherkessk	44.30	42.10	191
20.	Chita	52.00	113.50	83
21.	Dikson	73.43	80.54	56
22.	Dnepropetrovsk	48.56	34.93	190
23.	Donetsk	47.97	37.84	171
24.	Dudinka	69.40	86.20	80
25.	Ekaterinburg	56.80	60.70	115
26.	Elista	46.30	44.20	178
27.	Eniseysk	58.48	92.09	103
28.	Gomel’	52.41	30.88	161
29.	Grodno	53.64	23.88	161
30.	Grozny	43.30	45.70	187
31.	Gur’ev	47.16	51.88	172
32.	Igarka	67.54	86.50	86
33.	Ilimsk	56.84	103.81	87
34.	Irkutsk	52.30	104.20	98
35.	Ishim	56.20	69.39	108
36.	Ivanovo	57.00	41.00	116
37.	Izhevsk	56.80	53.30	128
38.	Kaliningrad	54.70	20.50	181
39.	Kaluga	54.50	36.30	130
40.	Kandalaksha	67.22	32.19	102
41.	Karaganda	49.86	73.16	125
42.	Kazan’	55.70	49.10	150
43.	Kemerovo	55.40	86.00	108
44.	Khabarovsk	48.40	135.10	159
45.	Khanty-Mansiysk	61.00	69.00	122
46.	Khatanga	72.00	102.36	73
47.	Kirov	58.60	49.30	122
48.	Kokchetav	53.36	69.33	120
49.	Kolpashevo	58.40	82.92	113

Appendix 3. (continued)

NN	CITY/PLACE NAME	LATITUDE* N decimal degrees	LONGITUDE* E decimal degrees	FROSTLESS PERIOD days
50.	Komsomolsk-na-Amure	50.50	137.00	137
51.	Kostroma	57.80	40.90	135
52.	Krasnodar	45.00	39.00	192
53.	Krasnoyarsk	56.00	92.80	120
54.	Kudymkar	59.00	54.60	102
55.	Kulunda	52.50	78.98	132
56.	Kurgan	55.40	65.30	119
57.	Kursk	51.70	36.20	164
58.	Kustanay	53.28	63.63	120
59.	Kyzyl	51.70	94.40	116
60.	Lipetsk	52.60	39.70	154
61.	Lugansk	48.56	39.40	155
62.	Makhach-Kala	43.00	47.50	234
63.	Maykop	44.60	40.10	196
64.	Mogilev	53.92	30.40	153
65.	Moscow	55.70	37.60	139
66.	Murmansk	69.00	33.10	109
67.	Nadym	65.68	72.72	74
68.	Nalchik	43.50	43.60	195
69.	Naryan-Mar	67.60	53.00	93
70.	Nikolaevsk-na-Amure	53.17	140.89	119
71.	Nizhne-Angarsk	55.78	109.41	117
72.	Nizhniy Novgorod	56.30	43.90	150
73.	Nizhniy Tagil	57.90	60.00	85
74.	Novgorod	58.50	31.30	127
75.	Novosibirsk	55.00	82.90	120
76.	Okhotsk	59.41	143.27	111
77.	Olekminsk	60.34	120.51	100
78.	Olenek	68.58	112.55	47
79.	Omolon	63.24	158.27	47
80.	Omsk	55.10	73.20	114
81.	Orenburg	51.80	55.10	147
82.	Oryel	53.00	36.10	145
83.	Oymyakon	63.64	143.02	0
84.	Penza	53.20	45.00	151
85.	Perm’	58.00	56.20	115
86.	Petropavlovsk (Kazakhskiy)	54.93	69.11	124
87.	Petropavlovsk-Kamchatskiy	53.00	158.60	121
88.	Petrozavodsk	61.70	34.40	123
89.	Provideniya, (bay)	64.44	185.36	79
90.	Pskov	57.80	28.30	146
91.	Riga	56.89	24.07	133
92.	Rostov-na-Donu	47.20	39.60	178
93.	Ryazan’	54.60	39.70	148
94.	Salekhard	66.50	66.60	96
95.	Samara	53.10	50.10	157
96.	Sankt-Peterburg	59.90	30.40	156
97.	Saransk	54.20	45.20	135
98.	Saratov	51.50	46.00	163
99.	Semipalatinsk	50.36	80.28	116

Appendix 3. (continued)

NN	CITY/PLACE NAME	LATITUDE* N decimal degrees	LONGITUDE* E decimal degrees	FROSTLESS PERIOD days
100.	Syktyvkar	61.70	50.80	102
101.	Smolensk	54.80	32.00	129
102.	Sochi	43.60	39.70	259
103.	Srednekolymsk	67.42	153.56	78
104.	Stavropol’	45.00	42.00	187
105.	Surgut	61.17	73.41	98
106.	Tallinn	60.56	24.60	164
107.	Tambov	52.70	41.40	152
108.	Tartu	58.32	26.74	151
109.	Tiksi, (bay)	71.59	128.90	50
110.	Tobol’sk	58.17	68.32	125
111.	Tomsk	56.50	85.00	114
112.	Tselinograd	51.11	71.44	123
113.	Tula	54.20	37.60	141
114.	Turukhansk	65.76	88.00	89
115.	Tver’	56.91	35.95	120
116.	Tyumen’	57.10	65.50	121
117.	Ufa	54.80	56.10	142
118.	Ukhta	63.60	53.70	84
119.	Ulan-Ude	51.80	107.60	102
120.	Ul’yanovsk	54.30	48.40	130
121.	Ural’sk	51.25	51.51	144
122.	Ust’-Barguzin	53.35	108.88	93
123.	Ust’-Kamenogorsk	49.86	82.55	132
124.	Velikie Luki	56.30	30.50	130
125.	Verkhoyansk	67.59	133.59	67
126.	Vilyuysk	63.66	121.55	98
127.	Vil’nyus	54.67	25.41	160
128.	Vitim	59.52	112.48	85
129.	Vladikavkaz	52.40	61.70	186
130.	Vladimir	56.10	40.40	141
131.	Vladivostok	43.10	131.90	188
132.	Volgograd	48.70	44.50	162
133.	Volochanka	71.09	94.63	74
134.	Vologda	59.30	39.90	116
135.	Volokolamsk	56.12	35.98	121
136.	Voronezh	51.80	33.50	159
137.	Yakutsk	62.00	129.70	97
138.	Yaroslavl’	57.60	39.90	117
139.	Yoshkar-Ola	56.60	47.90	121
140.	Zaporozh’e	47.95	35.18	187
	MAX	76.86	185.36	259
	MIN	43.00	20.50	0

* The geographical coordinates of the big cities were kindly given by O. Rigina during her stay at IIASA, where she participated in the Young Scientists Summer Program (YSSP), Forest Resources Project, in the summer of 1995. The coordinates for the rest of the locations were determined according to the *Atlas of the World* (1967).