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Interim Report **IR-00-021**

Full Carbon Account for Russia

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Contents

Abstract

The Forestry Project (FOR) at IIASA has produced a full carbon account (FCA) for Russia for 1990, together with scenarios for 2010. Currently, there are rather big question marks regarding the existing carbon accounts for Russia, and Russia is critical to the global carbon balance due to its size. IIASA is in a position to perform solid analysis of Russia because of the databases that the Institute has built over the years.

FOR based this work on a comprehensive geographic information system comprising georeferenced descriptions of the environment and land of Russia, which in turn are based on a number of thematic, digitized maps and databases. For the Russian energy sector and other industrial sectors (except the forest industry), the project used emissions estimates from the recent IIASA study *Global Energy Perspectives* (1998). The project carried out a separate substudy for the Russian forest industry sector.

According to FOR's estimate, the total fluxes (including energy and industry sectors) in Russia were a net source of 527 teragrams of carbon (Tg C) in 1990. To illustrate the possible development of the carbon pools and fluxes over the next 10 years, FOR developed three different scenarios for the period 1990–2010, reflecting different assumptions regarding Russia's GDP growth. According to these scenarios, Russia will continue to be a net source of carbon to the atmosphere with 156–385 Tg C in 2010, including the emissions from energy and other industrial sectors.

However, analysis of the FCA also shows considerable uncertainties involved in the carbon accounting. These uncertainties exceed the calculated changes in the full flux balance for the period 1990–2010. At present, this raises grave questions regarding the reliability of any accounting system used to measure terrestrial ecosystems for compliance with the Kyoto Protocol.

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Executive Summary

The Forestry Project (FOR) at IIASA has produced a full carbon account (FCA) for Russia for 1990, together with three alternative scenarios for 2010. The objectives of this work were:

- To calculate a more complete carbon balance for Russia than has been produced by previous attempts, based on spatial inventories, and re-estimate crucial indicators of the carbon account;
- To use the Russian FCA as a case study to identify and illustrate uncertainties in determining the carbon balance;
- To use the Russian case study as a tool to identify important policy issues to be considered by policy makers at different levels and by the United Nations Framework Convention on Climate Change (UNFCCC); and
- To identify important policy-relevant research tasks for the future with respect to carbon and greenhouse gases.

Sooner or later, verifiable carbon accounts will become a necessary precondition for mutual recognition and implementation of legally binding commitments, such as those established by the Kyoto Protocol of the UNFCCC. They will be even more important when it comes to carbon trading. Based on earlier studies and on our own research, we concluded that the only scientifically justifiable way to deal with carbon accounting is to produce a full carbon account that encompasses and integrates all carbon-related components, and is applied continuously in time. We assume that the components can be described by adopting the concept of pools and fluxes to capture their function. As this report shows, an FCA system has the advantage that it identifies some possible biases, which may be ignored under partial carbon accounting (PCA), the approach recommended by the Intergovernmental Panel on Climate Change (IPCC).

The platform for our work was a system of georeferenced descriptions of the environment and land of Russia developed at IIASA in cooperation with a network of Russian partners. The analyses followed a systems approach, and considered various pools and fluxes in soils, terrestrial biota, agricultural products, animal husbandry, forest products, and the energy sector.

FOR carried out the FCA for the base year of 1990 and for three alternative scenarios for the year 2010. To ensure consistency in the carbon accounts, we built the scenarios around three possible trajectories of economic development in Russia between the years 2000 and 2010. The low-growth scenario postulated an annual GDP growth rate of approximately 2 percent over 1990 levels, the mean growth scenario postulated a growth rate of approximately 5 percent, and the high growth scenario postulated a growth rate of some 7 percent. We estimated that the total carbon pool in 1990, including the 0–1.0 m organic soil layer, was 347.3 Pg C; the estimate for 2010 is 350.0 to 351.1 Pg C. Thus, we assume an increase in the total carbon pool in the range of 2.6

to 3.8 Pg C during the period 1990–2010. The increase in the pool is mainly generated by increased live vegetation. In relation to the total carbon pool of Russia in 1990, this change corresponds to only about 1%.

Our calculation of the total flux balance (including both industrial sectors and the terrestrial ecosystem) shows that in 1990 Russia was a net source of 527 Tg C; in other words, the emissions to the atmosphere exceeded the fluxes out of the atmosphere. If only the interaction between the atmosphere and the terrestrial ecosystem is considered (excluding the energy and industry sectors), the Russian ecosystems acted as a sink of –149 Tg C in 1990.

To ensure relevance to the Kyoto Protocol, IIASA sought to determine the absolute changes between 1990 and 2010. However, this exercise includes all changes, many of which currently are not eligible according to the Protocol. The scenarios for 2010 indicated that the total flux balance would improve by 142–372 Tg C compared to 1990. This resulted in an assumed total balance (including the energy and industry sectors) of 156–385 Tg C in the form of net fluxes into the atmosphere. If the energy and industrial sectors are excluded, we calculated that the terrestrial ecosystems would be a net sink of –272 to –283 Tg C in 2010, an improvement of between 124 and 134 Tg C, or an improvement of 83 to 90% compared to 1990. These are the improvements that theoretically could be considered for implementation by the Kyoto Protocol.

In this study we have taken the first step toward verifiability by illustrating (quantifying) uncertainties and laying out the nature of the uncertainties involved in developing an FCA. As a basis for this work, we calculated not only the quantities making up major components of the FCA, but also the uncertainty of these accounts. We used precision calculations to perform an expert estimation of the uncertainties in the major components of the FCA, and recalculated the accounts. We were not able to assess uncertainties for all components of the FCA; moreover, methods for the uncertainty assessments are available only for the 1990 account and not for the scenarios for 2010. Thus, the uncertainty estimates are not complete, but they are more complete than current IPCC estimates.

The uncertainty range for the estimate of the 1990 total flux balance amounts to some 129%, which results in a range of –155 to +1209 Tg C around our assessment of a mean net emission to the atmosphere of 527 Tg C. These uncertainty ranges do not take into account any biases. From the literature we know that these biases can be substantial. This means that the improvement in the total balance identified above—142–372 Tg C for 1990–2010—is completely within our assessed uncertainty range of –155 to +1209 Tg C. Thus, the changes over time in the total flux balance are small in relation to the uncertainties of the accounts.

As these results demonstrate, the uncertainties surrounding the carbon accounts must be significantly reduced. Therefore, it is essential to develop new methods for assessing the uncertainties in the carbon account; otherwise, it is impossible to present reliable policy recommendations with respect to carbon accounting and management.

The large differences in the relationship between changes in the carbon balance during 1990–2010 and the assessed uncertainties generate severe problems in verifying the implementation of the Kyoto Protocol. These differences seem to occur for all nations; for example, an adjunct project that developed an FCA for Austria showed the same relationship presented here for Russia.

FOR applied the methods described in an earlier IIASA study to estimate the verification times for the changes in four types of accounts: fossil fuel balance, atmosphere and ecosystem balance (excluding fossil fuels), total flux balance (including fossil fuels), and Kyoto mimic (fossil fuels with anthropogenic biospheric changes [ABCs]). The analysis assumed that all ABCs were eligible under the Kyoto Protocol. The fossil fuel balance showed the greatest dynamics (temporal changes) and the atmosphere and ecosystem balance (excluding fossil fuels) the slowest dynamics of behavior. The dynamics strongly affect the verification time, which is the time when the emission changes outstrip the uncertainties. When the ABCs are considered together with the fossil fuel balance there is a mixture of fast and slow dynamics, and the verification times depend heavily on the uncertainties connected with the estimation of the ABCs.

Detailed analyses of the above accounts show:

- With no uncertainties included in the accounting, no verification can take place with respect to changes in the net emissions in 2010 (the commitment period according to the Kyoto Protocol).
- With no verification tool available, which follows from the above, we cannot compare the effectiveness of fossil fuel or land-use change and forestry activities with respect to reduced emissions.
- There is no possible way to conduct top-down verification (atmospheric measurements) for individual biosphere components.
- There is no possible way to verify that so-called Kyoto measures do not influence the non-Kyoto biosphere from the carbon balance viewpoint.
- The reductions of emissions are small during the commitment period and the uncertainties are large.
- From the above it follows that FCA with uncertainty estimation is essential for all carbon accounting.

As noted above, methods sufficiently accurate to estimate the uncertainties connected with the FCA are not yet available. Substantial resources should be allocated for further development of ways to assess uncertainty, as a prerequisite for verification of the Kyoto Protocol. Moreover, because the data available are currently collected primarily for other purposes than carbon accounting, there is a need to design and implement new inventory systems directed specifically toward carbon accounting. This includes introduction of efficient remote sensing methods for data collection and for reliable verification of the implementation of the Kyoto Protocol.

Our experience in producing an FCA for Russia shows that the resulting balance is very sensitive to how the boundaries of the overall system and subsystems are set. Therefore, any future carbon accounting must be accompanied by a clear and transparent description of the boundaries established for that particular analysis. This is also required in order to make comparisons with other studies.

The overall policy conclusion based on this study and adjunct FOR studies is that, given the uncertainties in place, most of the so-called Annex 1 countries of the Kyoto Protocol will not be able to verify their Kyoto targets at the country level.

Full Carbon Account for Russia

Sten Nilsson, Anatoly Shvidenko, Vladimir Stolbovoi, Michael Gluck, Matthias Jonas and Michael Obersteiner

1. Introduction

The concentrations of carbon dioxide (CO_2) in the atmosphere have increased substantially during the last century, mainly as a result of fossil fuel combustion, but also because of changed utilization of the land resource over time and forestry practices (IPCC, 1995, 1997).

The concentration of CO_2 in the atmosphere has increased by some 30% since 1750, and if no action is taken it will double its pre-industrial value at the end of the century, which is assumed to cause a greater rate of warming than at any time during the past 10,000 years. The concerns connected with this temperature increase are, among other things, higher sea levels that will threaten many coastal regions, disrupted water distribution and availability, and increased natural disasters, such as floods and droughts. International agreements are necessary to deal with these threats. The first step in reaching such agreements was the UN Framework Convention on Climate Change (UNFCCC).

The Kyoto Protocol of the UNFCCC has raised the political profile of the carbon issue substantially (UNFCCC, 1992, 1998). The protocol contains commitments that, if ratified by governments, legally bind participating nations to limit or reduce the emissions of six greenhouse gases or groups of gases. According to the protocol, Annex 1 parties (the industrialized nations) must reduce emissions by at least 5 percent from their 1990 levels within the commitment period 2008–2012. Article 3.3 of the protocol states that these parties should use biological sources and sinks to meet the commitments during the stipulated period, but limits these sources and sinks to afforestation, reforestation and deforestation since 1990. Article 3.4 provides for the possibility of meeting reduction commitments through additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils, as well as the land-use changes and forestry activities mentioned in Article 3.3.

These articles in the Kyoto Protocol raise serious concerns for nations seeking to comply with requirements under the UNFCCC. Such compliance depends on the ability to account rigorously for anthropogenically induced net changes in the carbon balance, yet no sufficiently accurate or universally accepted methods exist to do so. The Intergovernmental Panel on Climate Change (IPCC) has developed guidelines on how to carry out carbon accounting (IPCC, 1997), but these guidelines are incomplete. Thus, considerable uncertainties remain in estimating carbon budgets, which consist of various pools and fluxes of different sizes that interact among each other. IPCC (2000) defines a carbon pool as “a reservoir that has the capacity to accumulate or release carbon”; examples are biomass, wood products, soils, and atmosphere. The IPCC definition used for carbon flux is “the transfer of carbon from one carbon pool to another per unit area and time.”

The uncertainties in carbon budgets are linked to such factors as the limited availability of relevant data, the inaccuracies induced by scaling data up from a micro level (plot) to a regional level (subcontinental), and incomplete knowledge about the ecological processes (see, e.g., Jonas *et al.*, 1999a, b; Battle *et al.*, 2000; Schimel *et al.*, 2000). They result in large deviations among different estimates of carbon sinks and flows.

Several examples demonstrate the magnitude of this problem. At the global level, the best current techniques estimate that human activities release 7.1 petagrams of carbon (Pg C) into the atmosphere each year, yet 1.8 Pg remain unaccounted for in known carbon sinks on land or in the oceans. The disparities are also illustrated by the estimates of the carbon sink strength of the Russian forests for the early 1990s obtained through numerous investigations. The sink estimates vary between 0.02 and 450 million tons C/year (Melillo *et al*., 1988; Sedjo, 1992; Dixon *et al*., 1994; Kokorin and Nazarov, 1994; Krankina and Dixon, 1994; Kolchugina and Vinson, 1993a, b, and 1995; Isaev *et al*., 1995; Kokorin *et al*., 1996; Krankina *et al*., 1996; Lelyakin *et al*., 1997; Isaev and Korovin, 1998 and Shvidenko and Nilsson, 1998).

Building on earlier studies carried out by Bolin (1998), Steffen *et al*. (1998), Jonas *et al*. (1999a, b) and Pearce (1999), and on our own research results, we have therefore concluded that the only scientifically justifiable way to deal with carbon accounting is to carry out full carbon accounting (FCA), which encompasses and integrates all carbon-related components of all terrestrial ecosystems and is applied continuously in time. We conclude that:

- only FCA could serve as the main accounting system within the current Kyoto Protocol and act as the legal basis for compliance; and
- only FCA can give a full picture of the underlying uncertainties in the carbon accounting and thereby validate the partial accounts.

Thus, FCA is essential both as the legal basis for compliance with the Kyoto Protocol and as the only mechanism for assessing the uncertainties in carbon accounting. Both scientists and policymakers can use the FCA to identify the most efficient actions to achieve verifiable carbon reduction.

1.1. The Russian Case Study

Because of its size, Russia plays an important role in the global greenhouse gas balance. Russia’s total fluxes of carbon to the atmosphere amount to some 5000 million tons annually, compared with the yearly global human-induced net releases to the atmosphere of about 7100 million tons of carbon. Russia’s forests comprise approximately one-fifth of the world’s total forests. Therefore, a better understanding of the Russian carbon balance is not only important in itself, but is also critical to better understanding of the global carbon balance.

IIASA is ideally suited to carrying out an FCA for Russia. Over the years IIASA's Forestry (FOR) Project and Land-Use Change (LUC) Project, together with Russian collaborators, have built unique databases of all the terrestrial ecosystems in Russia. Special attention has been paid to the forest sector and land-use changes. IIASA's Environmentally Compatible Energy Systems (ECS) Project has studied the energy consumption in Russia over an extended period (e.g., Nakićenović *et al.*, 1998).

In addition, FOR is especially suited to carry out an FCA analysis of Russia. The project has operated in Russia since the mid-1980s, and has a huge network of Russian collaborators who are experts in the different disciplines needed for an FCA exercise. The core team of the FOR Project at IIASA consists of experts on Russian soil and land use, Russian inventories and forest resources, ecology, and the Russian forest industry, as well as geophysicists who specialize in analyzing the carbon budget and specialists in constructing geographical information systems (GIS).

In producing an FCA for Russia for the period 1990–2010, FOR's objectives were:

- to present a more complete carbon balance for Russia compared to previous attempts,
- to use the full Russian carbon account as a case study to identify and attempt to quantify uncertainties in the global carbon balance,
- to use the Russian case study as a tool to identify important policy issues to be considered by the UNFCCC, and
- to identify important policy-relevant research tasks for the future with respect to the carbon issue.

1.2. Overview of the Report

This report describes IIASA's FCA for Russia for 1990 and presents alternative scenarios for 2010. Because it includes nontechnical analysis as well as data and details on estimation methods, the report should be useful not only to scientists and technical researchers, but also to policymakers. Figure 1 provides guidance for navigating through the paper.

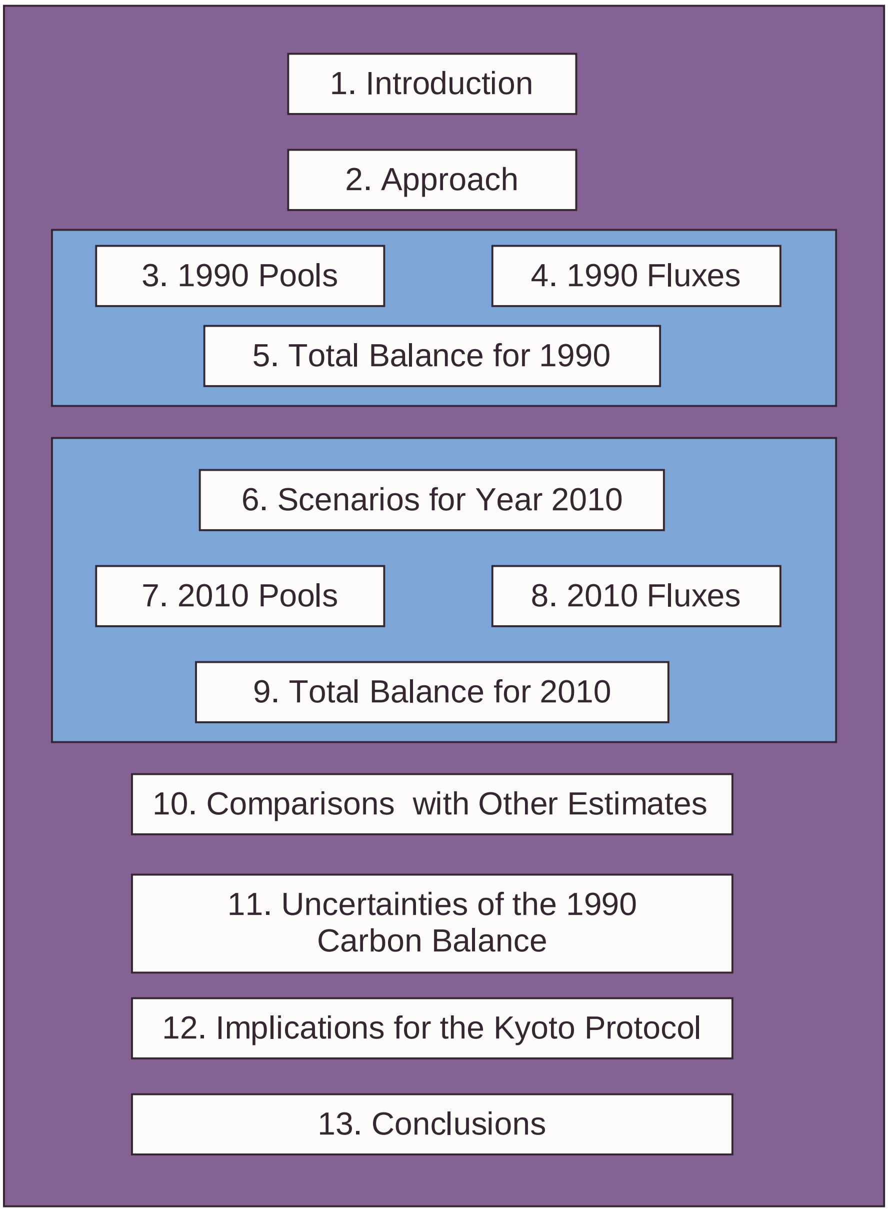


Figure 1. Overview of the Report.

Section 2 describes our overall approach to the study, including the principles of FCA, information sources and limitations. Most important, it notes that a key goal of our study is to identify and quantify the uncertainties in existing knowledge of the carbon balance, rather than to obtain final numerical answers—a task that is impossible given the current state of knowledge.

Sections 3 through 11 present the data from IIASA's Russian case study, as well as detailed discussion of the methodology and assumptions used to obtain our results. Sections 3, 4 and 5 deal specifically with the 1990 FCA. Section 3 describes the methods and results of the 1990 pool estimation including soil (Subsection 3.1), terrestrial biota (Subsection 3.2), agricultural products (Subsection 3.3) and forest products (Subsection 3.4). Section 4 describes the methods and results for the estimation of fluxes for 1990, including a description of the modular approach taken (Subsection 4.1); then, as above, soil (Subsection 4.2), terrestrial biota (Subsection 4.3), agricultural products (Subsection 4.4), forest products (Subsection 4.5) and energy and other sectors (Subsection 4.6). Finally, Section 5 summarizes and describes the total balance for 1990.

Sections 6 through 9 describe the 2010 FCA scenarios. In Section 6 we explain the background assumptions used for our 2010 projections. Section 7 describes the methods and results of the 2010 pool estimation, including soil (Subsection 7.1), terrestrial biota (Subsection 7.2), agricultural products (Subsection 7.3) and forest products (Subsection 7.4). Section 8 describes the methods and results for the estimation of fluxes for 2010, including fluxes for soil (Subsection 8.1), terrestrial biota (Subsection 8.2), the agricultural sector (Subsection 8.3), forest products (Subsection 8.4) and energy and other sectors (Subsection 8.5), and a summary in Subsection 8.7. Section 9 describes the changes in the total flux balance for 2010.

In Section 10 we compare our carbon budget estimates to those found in other studies. Section 11 contains a discussion of the uncertainties we identified in the 1990 balances.

The report concludes with assessments that should be especially useful to policymakers. Section 12 describes the implications of this study for the Kyoto Protocol, while Section 13 discusses other lessons we learned from developing an FCA for Russia and provides our overall conclusions.

2. Approach

2.1 Principles

The global carbon cycle represents the total contributions of large sources and sinks. Huge amounts of carbon are sequestered by oceans and living biomass and are released into the atmosphere through natural processes or by human intervention. A carbon account, defined mainly by its terrestrial components, is a temporal cross-cut at a specific point in time of the various elements of the carbon cycle, not necessarily interacting in a linear fashion. We have not included the oceans in the analysis of Russia, and we cannot currently provide an atmospheric balance. However, we do estimate the net changes that Russia causes in atmospheric carbon. The dynamics of terrestrial pools and fluxes depend on interseasonal weather variability, climate, and disturbance regimes, among other factors. Any scientifically rigorous, verifiable, and transparent regional FCA must take the above characteristics of the carbon budget into account.

Our estimates of the FCA for Russia were based on the following considerations and principles:

1. *Formal and logical strictness of definitions* is essential, particularly for a complete FCA. Completeness is closely tied to the structuring of the FCA with respect to compartmentalization of pools, identification of fluxes, comprehensiveness of the greenhouse gases taken into account, and development of unified classifications at the process, ecosystem, and land-use/land-cover levels.
2. A *full system analysis* is an inevitable platform for aiming at compatibility of all parts of the carbon account estimates for achieving completeness.
3. In the absence of adequate stochastic models for the FCA, we used approaches that did not predict the process itself, but instead used some computed expected values. Interseasonal variability of disturbance regimes and available data structure made it necessary to calculate pools and fluxes for 1990 as an average for 1988 to 1992.
4. To provide *transparency* and *verifiability of accounting*, as well as a real basis for uncertainty assessments, all assumptions, model-based results and calculation schemes are presented in an explicit algorithmic form.
5. Some human-induced impacts on terrestrial systems that could not be reliably identified and separated (e.g., air pollution, nitrogen and CO_2 fertilization, etc.) are accounted for as a part of the aggregated bioproductivity estimates.

The FCA encompasses and integrates all (carbon-related) components of all terrestrial ecosystems and is applied continually in time (past, present and future). We assume that the components can be described by adopting the concept of pools and fluxes (see definitions in Section 1) to capture their functioning. The pools may be undisturbed, impacted directly or indirectly by human activity, and linked internally or externally by the exchange of carbon, as well as other matter and energy (c.f. Steffen *et al.*, 1998 and Jonas *et al.*, 1999a, b). The pools and fluxes taken into account are schematically presented in Figure 2. As follows from the scheme, we consider the FCA of terrestrial vegetation as an open system with irreversible flows of carbon to the hydrosphere and lithosphere (sediments). These fluxes are taken out of the atmosphere/terrestrial ecosystem for a period of time corresponding to the geological scale. The same assumption is made for charcoal. The pools and fluxes illustrated in Figure 2 cover more than 99% of the total known carbon amount. Figure 3 illustrates the ecosystem approach used in preparing the Russian FCA.

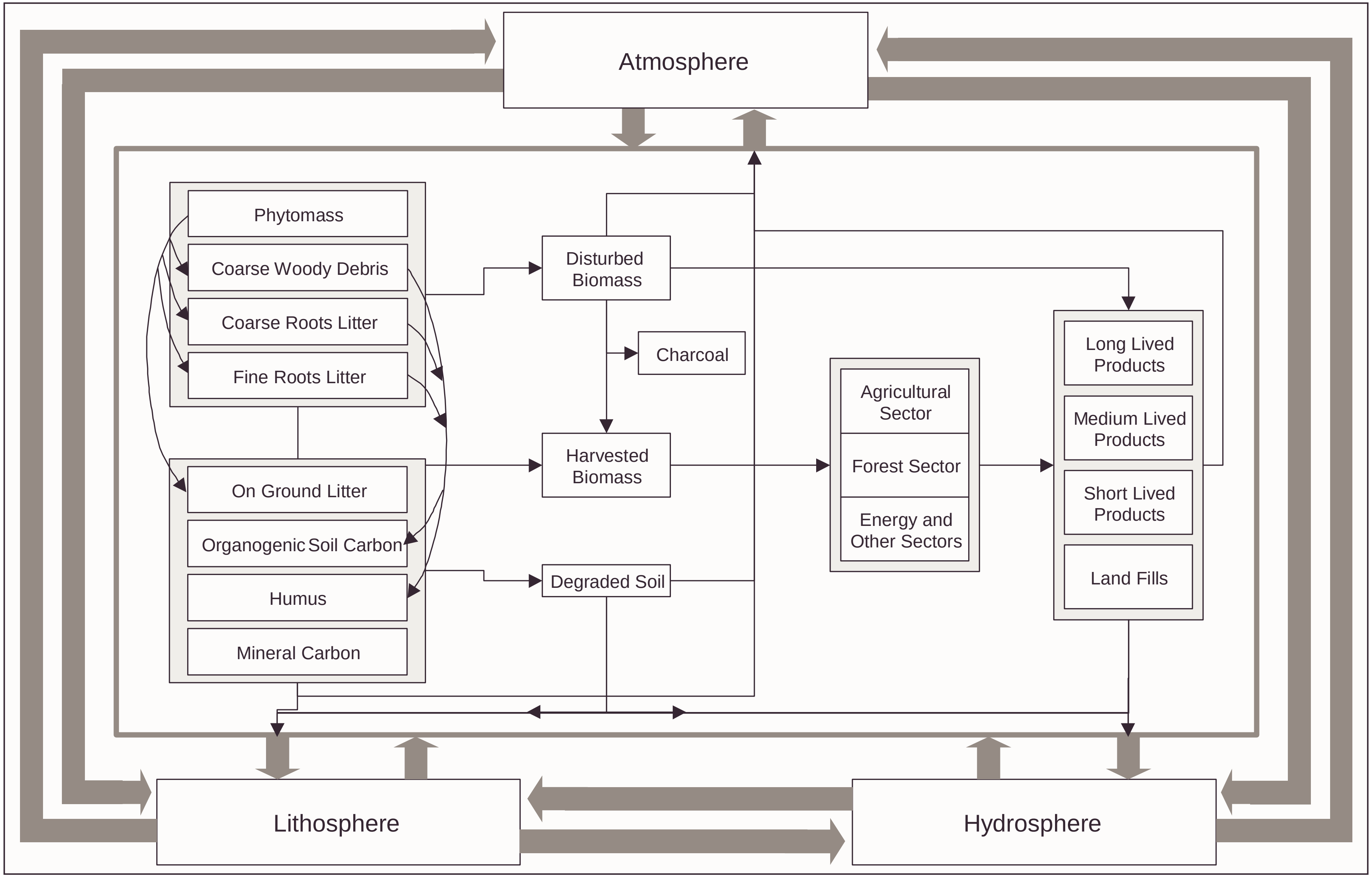


Figure 2. Pools and fluxes considered in the Russian FCA.

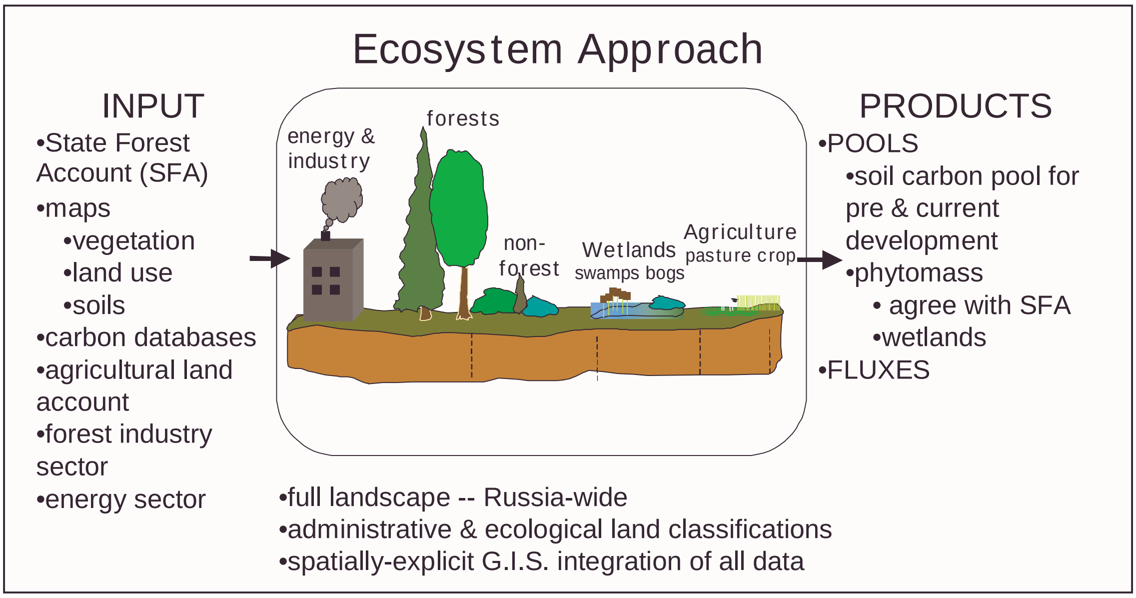


Figure 3. Ecosystem approach used in the Russian FCA.

2.2 Data Sources

The basis for the work was a system of georeferenced descriptions of environment and land of Russia (Nilsson *et al*., 1998). The information sources can be divided into two groups. One group consists of integrated GIS products based on different thematic maps with related databases. The latter databases include modified and formalized legends and attributes from scientific publications, archives, surveys and specific field measurements. The second group of information comprises a number of attributive databases, which are not directly related to a definite GIS component (e.g., State Forest Account [SFA], terrestrial vegetative production, etc.), but are georeferenced tools. Figure 4 provides a schematic description of the integrated information system used in FOR's analyses.

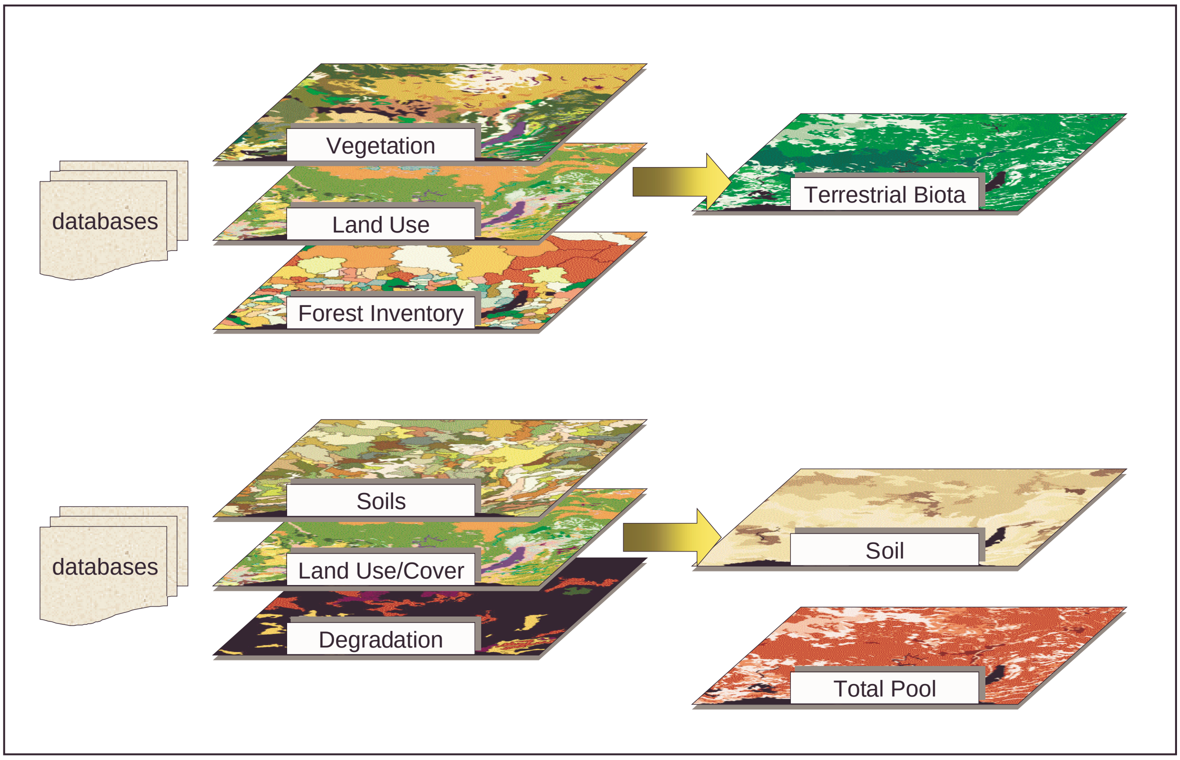


Figure 4. Schematic description of the integrated information system used in the analyses for Russian FCA.

The most detailed GIS elements allow aggregations at the level of (1) landscape, (2) administrative regions (so-called "subjects of the Russian Federation"), and (3) a combination of landscape features with administrative units. The latter is a mixture of two information sources; one characterizing natural conditions associated with natural boundaries and the other characterizing socioeconomic variables linked with administrative units.

Table 1 summarizes the data sources used in this study. The table is followed by illustrations of the maps referenced in the table.

Table 1. Description of data used in this study.

Database Name	Source(s)	Scale and Resolution	Database Description	Use in this Study	IIASA Reference
Vegetation (VEG)	Based on the map "Vegetation of the USSR" (Isachenko *et al.*, 1990)	1:4 million. 4200 polygons	Presents vegetation divided into 133 classes by combining all available vegetation data derived from publications, archives, manuscripts, and results of direct measurements. Additional information includes vegetation zones, macrorelief (plains and mountains), types of major vegetation associations, etc.	To estimate phytomass and NPP by introducing key bioproductivity processes. Also to identify the distribution and extent of terrestrial biota and also to delineate bioclimatic zones. To assist in creating Land Class Map	Stolbovoi *et al*., 1997. (Figure 5)
Soil (SOIL)	Based on a simplified version of the "Soil Map of Russian Federation," originally created at a scale of 1:2.5 million (Fridland, 1988)	Simplified to 1:5 million. 1300 polygons	Attributes include 168 soil units aggregated by 3 texture classes, 7 slope conditions and 12 degradation types (including causative factors, severity, rate, productivity effects of degradation, etc.). Each soil unit is described by organic and mineral carbon characteristics stratified by depth, texture, land use classes for natural and human-impacted soils.	To estimate the soil carbon densities and subsequently the pools. Also to delineate wetland land classes. To assist in creating Land Class Map	Stolbovoi *et al*., 1997. (Figure 6)
Land Categories (CAT)	Based on the map "Land Categories of the USSR" (Yanvaryova *et al*., 1991).	1:4 million. 11,000 polygons	Characterizes land-use/land cover divided into 6 top-level classes (cultivated land, perennials, cultivated forage/grazing, forest, natural vegetation, other lands).	To identify the distribution and extent of land classes.	Stolbovoi *et al*., 1997. (Figure 7)
Degradation (DEG)	Map of Water and Wind Soil Erosion in Russia (Dokuchaev Soil Institute, 1992); Map of Recent Land Status of Forest Fund of Russia (All Russia Research Institute of Forest Resources, 1993); Map of Natural Grassland Degradation in Russia (All Russia Research Institute of Fodder, 1992).	1:5 million 1300 polygons	Based on the ASSOD methodology (van Lynden, 1995).	To identify the type, distribution and extent of soil degradation used to estimate "actual" soil carbon pools.	Stolbovoi and Fischer, 1999. (Figure 8)

Database Name	Source(s)	Scale and Resolution	Database Description	Use in this Study	IIASA Reference
Physiographic Map (PHYS)	Derived from topographic map of USSR (Government Administration of Geodesy and Cartography of Russia 1976).	1:2.5 million 1200 polygons	Based on the ASSOD methodology (Van Lynden, 1995).	To identify non-vegetated land areas with slopes greater than 60%	Stolbovoi, 1996.
Landscape Map (LND)	Based on the map: "Landscapes of the USSR" (Goudilin 1987)	1:2.5 million 27,000 polygons	Comprehensively describes all components of natural landscapes by 8 hierarchical levels.	To identify the non-vegetated land class, and as one of several sources to generate the forest map.	Rojkov *et al.*, 1996.
Administrative Map (ADM)	"Administrative Map of Russia" (Government Administration of Geodesy and Cartography of Russia, 1995).	1:1 million 89 polygons	Administrative boundaries at the oblast and krai level.	To spatially distribute statistical data for agriculture, Land State and Forest State Accounts.	Figure 9
Ecoregion Map (ECO)	IIASA Sustainable Boreal Forest Resources Project (1993–8)	1:1 million 160 polygons	Quantification of 141 ecoregions (a territory with homogeneous climate, soil, major vegetation formations, degree of transformation of natural vegetation, and similar disturbance regimes). Data include lithology, pedosphere, hydrosphere, atmosphere, vegetation and anthroposphere.	To assist in developing the Forest Map. To distribute SFA-based forest phytomass estimates.	Shvidenko *et al.*, 1996 (Figure 9)
Forest Map (FOR)	IIASA Sustainable Boreal Forest Resources Project (1998)	1:1 million 14,300 polygons	An amalgamation of all applicable IIASA data with the State Forest Account of 1993.	To assist in estimates of forest phytomass and NPP. To display forest litter estimates.	Figure 10
State Land Account (SLA)	Agriculture of Russia, 1995; National Report, 1993; Land of Russia, 1995	Administrative Units	Tabular databases of annual state statistics, cross-checked by different sources,	To assist in creating Land Class Map	

Database Name	Source(s)	Scale and Resolution	Database Description	Use in this Study	IIASA Reference
State Forest Account (SFA)	Russian State Forest Account	Administrative and Forest Management Units	Data is grouped in three sets. The first set contains data from the forest inventory by “Forest Enterprises” (used as a common name for forest management enterprises (*leskhozi*), natural reserves (*zapovedniki*), national parks, etc.) included in the State Forest Account for 1988 and 1993 (about 1800 enterprises for each year of the account). The second set is constituted by ecoregional data. The third set contains forest inventory data aggregated by administrative units for each 5-year period during 1961-1998.	The enterprise level data was used to estimate forest phytomass. The ecoregional data was used for; 1) estimation of increment of forests, 2) estimation of phytomass by fractions. The administrative unit data was used for; (1) estimation of the dynamics of forest land-use categories, (2) estimation of phytomass dynamics, and (3) control of the productivity of forests.	Shvidenko and Nilsson, 1997.
Land Class Map (LCM)	Aggregation of all above data.	1:4 million	Generated by combining the above data in an iterative process that assigned geographic areas to one of 6 land classes to match, as closely as possible, the State Land and State Forest Accounts area distribution. Decision rules are described in Appendix 1.	To display pool and flux estimates.	Figure 11
Bio-productivity Database	Russian sample plot data of measurements of biological productivity of Russian terrestrial biota. Based on roughly 3000 sample plots and “semi-empirical” calculations in Russia.	Point data applied to VEG database.	Data on phytomass by 7 fractions (stemwood over bark, bark, crownwood over bark, foliage, roots, understory, green forest floor) and NPP [1] by aggregated fractions (green parts, woody aboveground phytomass, below ground phytomass, coarse woody debris, and below ground mortmass).	3000 points were used for estimations of phytomass and NPP. Means were adjusted for the disturbance regimes. Mean forest average growing stock was adjusted to the most current forest inventory. 2090 sample plots for the estimation of forest phytomass.	
		Point data applied to VEG database.	Reference data for phytomass and NPP was estimated for 10 classes (5 bioclimatic zones and 2 aggregated land-cover classes, i.e., swamps and bogs). Average values for these classes were derived from the VEG database and corrected for the zonal north-south gradients of productivity and the average fire return intervals for wetland types and zones.	To estimate wetland phytomass and NPP	

Database Name	Source(s)	Scale and Resolution	Database Description	Use in this Study	IIASA Reference
Soil Reference Profiles	The soil profile database originates from some 60 different published studies, numerous field measurements (Stolbovoi and Fridland, 1972; Stolbovoi, 1986) and archive data.	Point data	A number of soil genetic horizons that describe organic and mineral carbon content, thickness, and bulk density. The calculation matrix for soil organic carbon considers 163 soil classes, 12 soil horizons, 3 texture classes and 4 depths.	To estimate the soil carbon densities and subsequently the pools.	
Analytical Soil Survey Data	Russia-wide soil surveys in 1967–71, 1981–85, 1986–90 and laboratory analysis (Krylatov, 1996).	Point data	Humus contents in the 1950 soil profiles and aggregated estimates for administrative units.	To estimate a finer resolution on soil carbon density for agricultural soils, i.e. croplands and hay land.	
Dissolved Organic Substances	Data derived from numerous records (Djakonova, 1972; Ponomareva and Plotnikova, 1972)	Point data	Basic data have been obtained by lysimeter analysis in laboratory analyses of the chemical composition of soil solutions.	To estimate dissolved organic carbon pools.	
Agricultural Statistics	Derived from agricultural statistics at administrative unit level (Agriculture of Russia 1995; Romanenko, 1995, Volumes 1–3).	Administrative Units	Description of seeded areas, crops, yield, application of manure, number of cattle and swine.	To estimate agricultural phytomass, livestock related issues, and agricultural fluxes.	
Forest Disturbance	Assembled from official statistics, annual reports on the state of the Russian forests, special investigations, and forest pathological surveys (Federal Forest Service 1988–1996).	Administrative Units	Regional data on forest fires, harvests, insect outbreaks, and diseases for the period of 1960–1998.	To estimate carbon fluxes generated by disturbances and the impact of disturbances on bioproductivity of forests and major carbon pools.	Shvidenko *et al*., 1996; Shvidenko and Nilsson 2000a, b
Forest Industry Sector	Forest industry databases (Obersteiner, 1999)	Administrative Units	Regional data on timber harvest and output statistics of the forest industry over the period 1928 to 1997.	To quantify the stocks and flows of carbon induced by Russian forest industry activities.	Obersteiner, 1999

Database Name	Source(s)	Scale and Resolution	Database Description	Use in this Study	IIASA Reference
Energy and Other Sectors	Data from existing studies (INEN, 1995; CS1 1997; NCR 1995, 1998; Nakićenović *et al.*, 1998).	All Russia	Apparent consumption calculations are cross-checked, and losses are estimated.	To describe the energy consumption and related emissions in the energy sector.	Nakićenović *et al.*, 1998

[1] NPP = net primary productivity

Figure 5. Vegetation database (VEG).

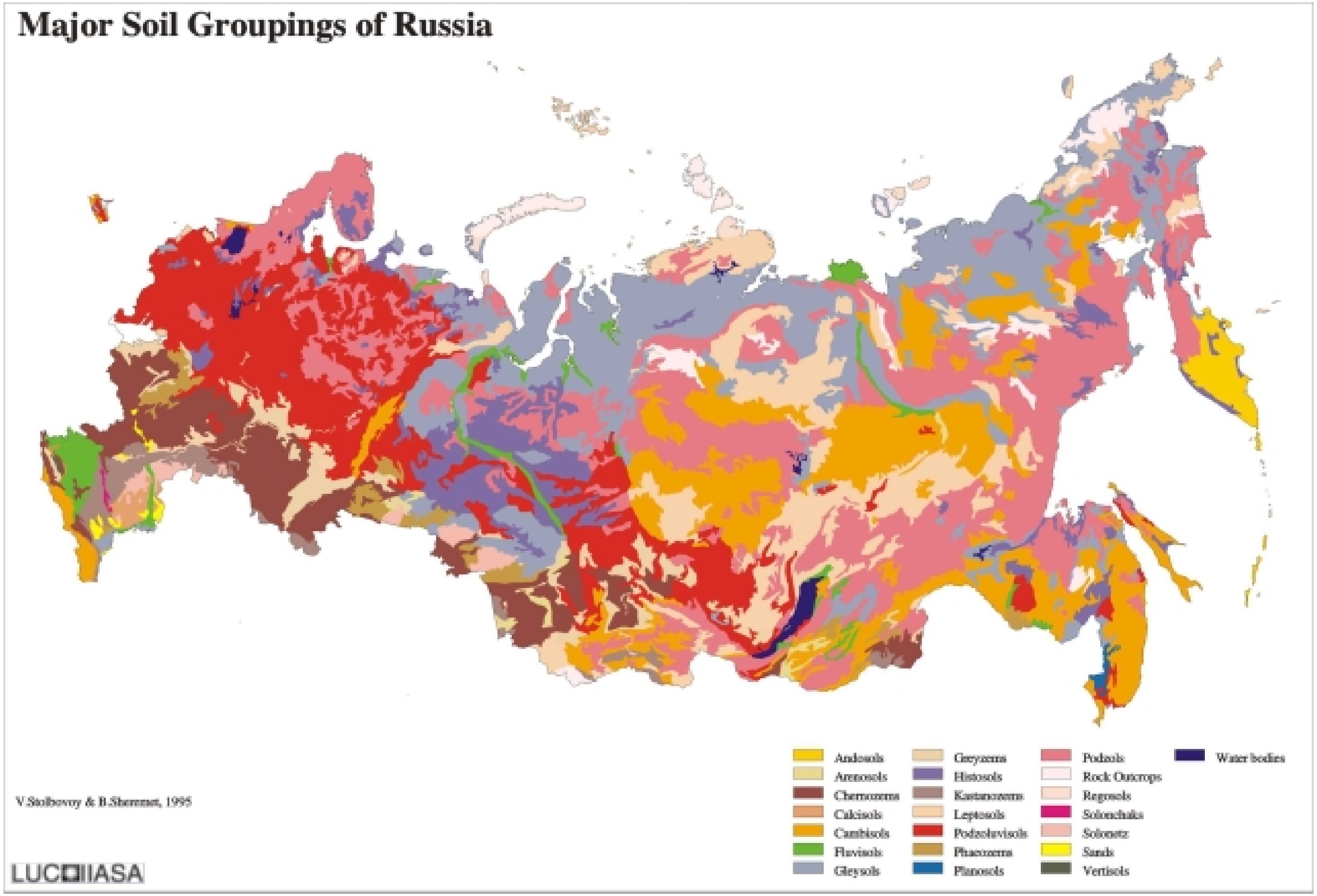


Figure 6. Soil database (SOIL).

Figure 7. Land categories database (CAT).

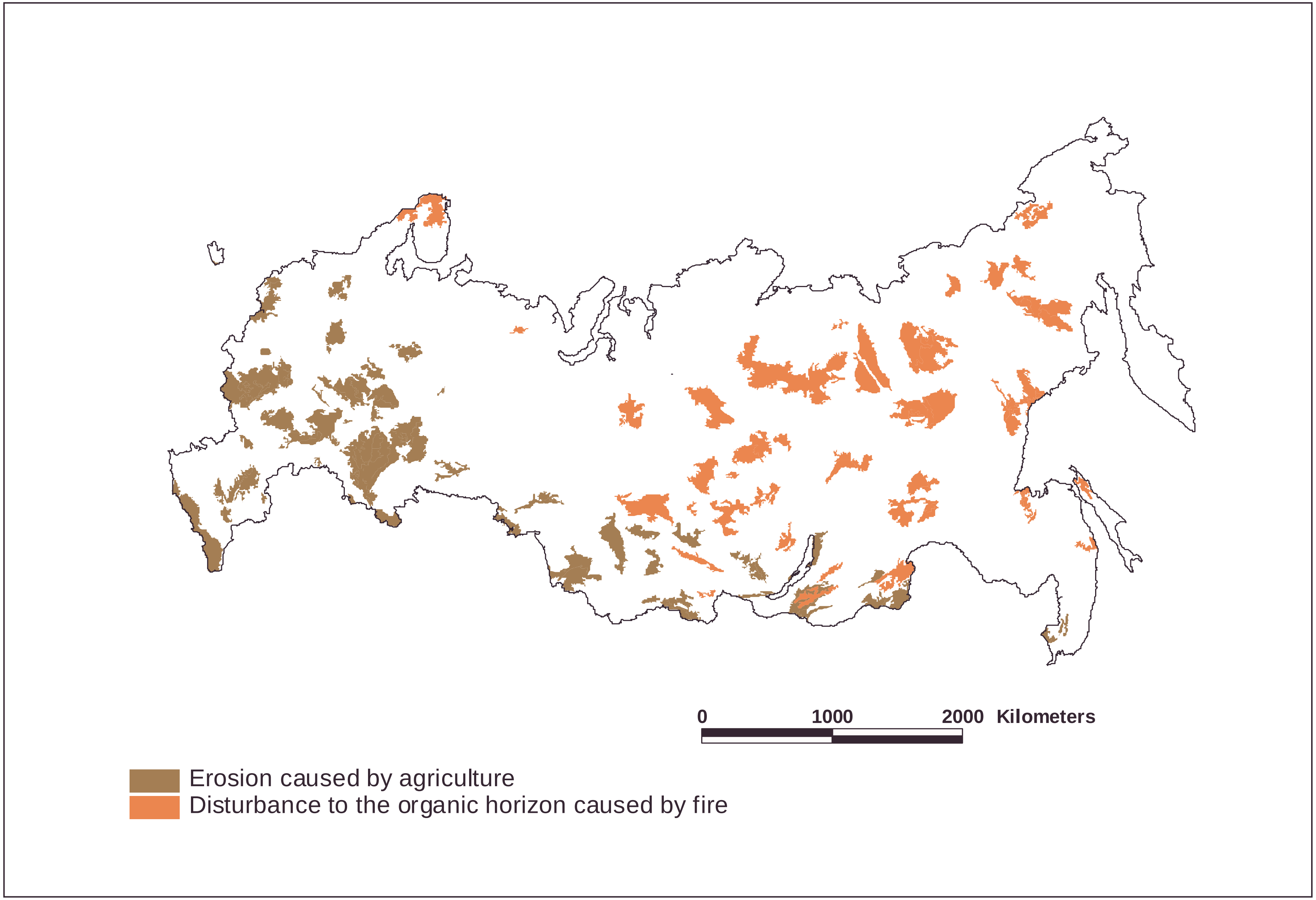
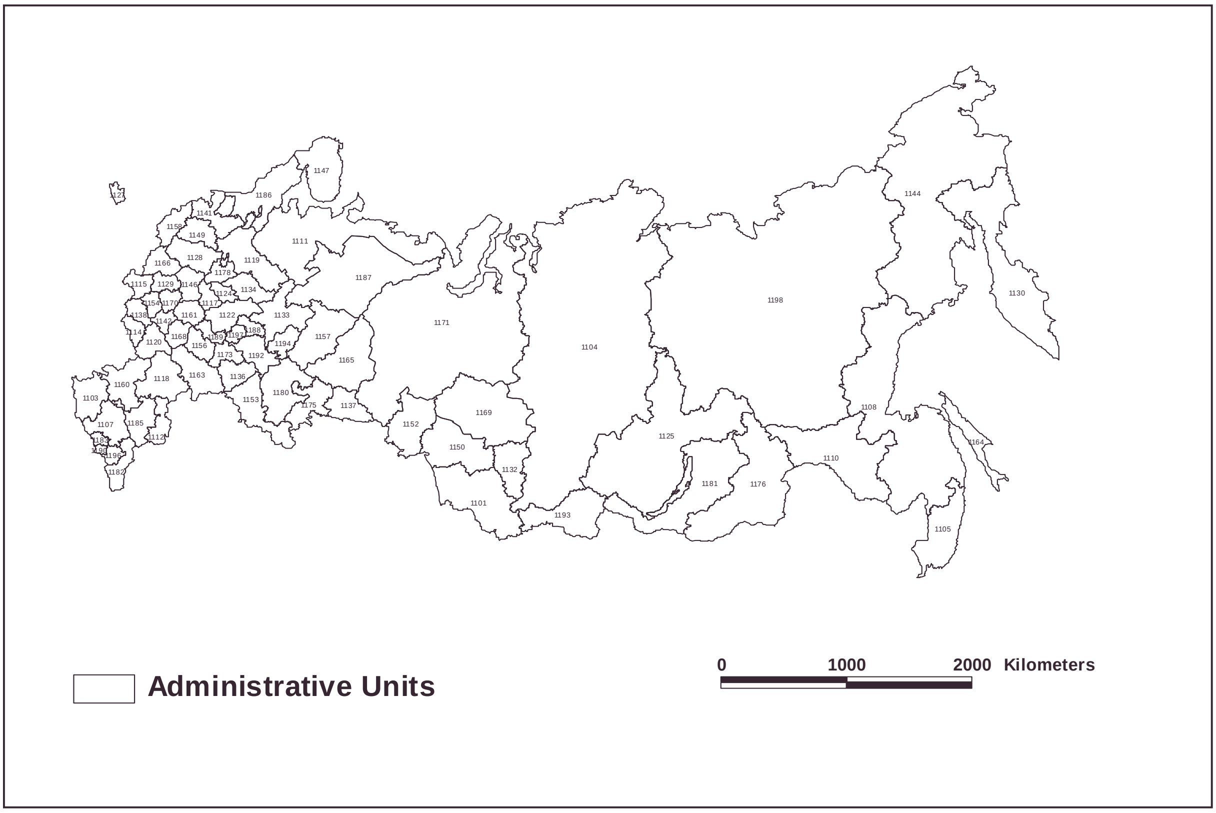


Figure 8. Degradation database (DEG).



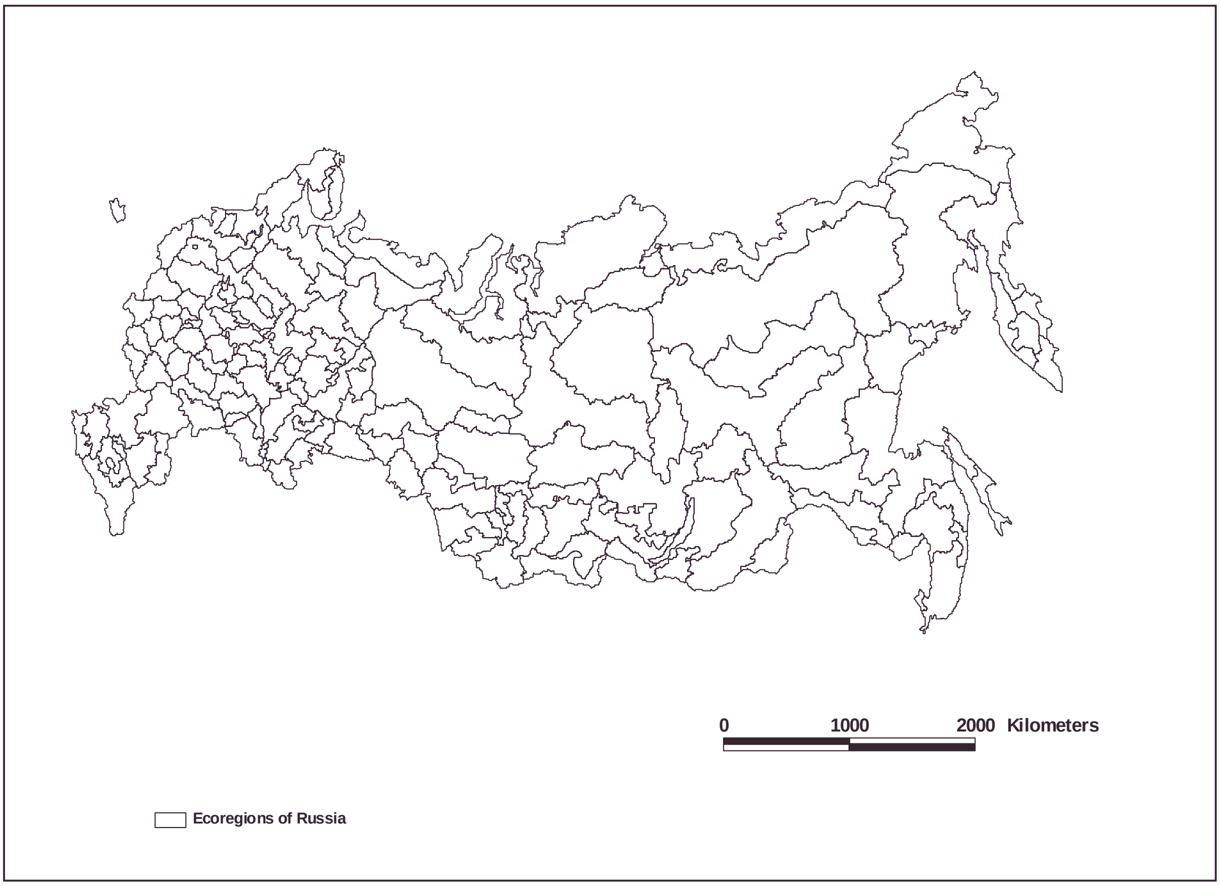


Figure 9. Administrative (ADM) and ecoregion (ECO) maps.

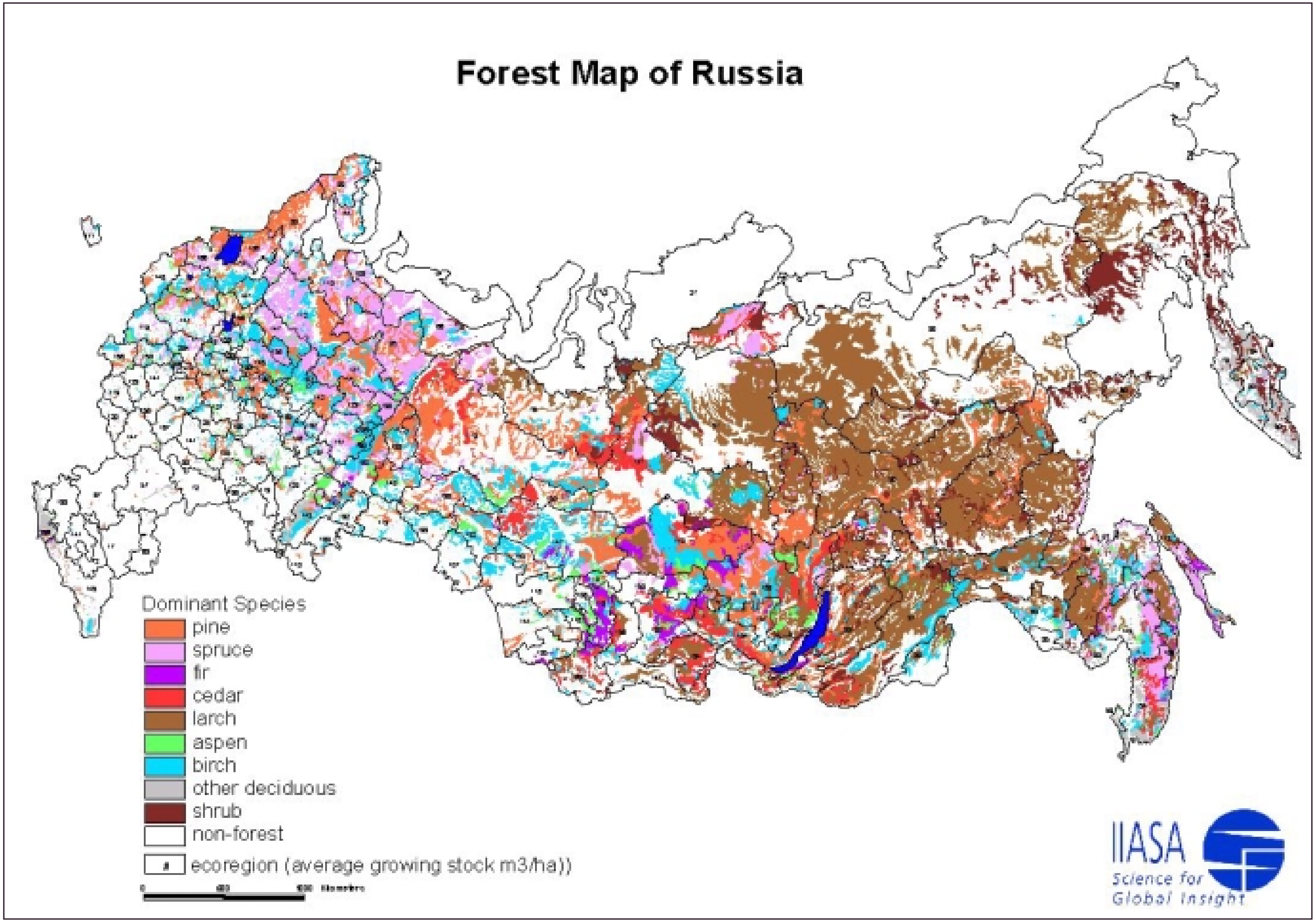


Figure 10. Forest map (FOR).

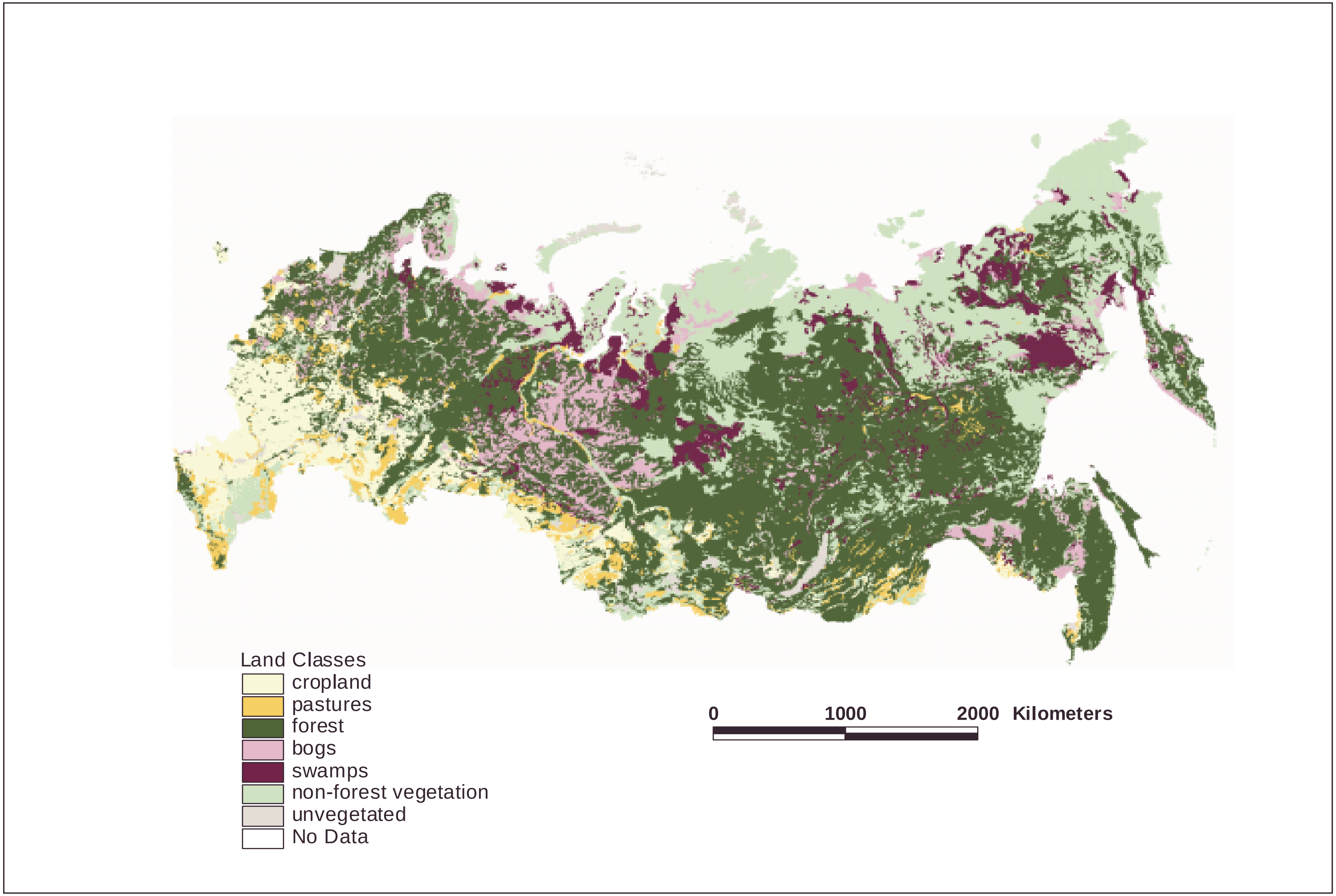


Figure 11. Land class map (LCM).

2.3 Land Class Balance for 1990

The land class balance for 1990 is presented in Appendix 1. We estimate the total land area of Russia to be 1,709.4 million ha (which corresponds to the officially reported figures), of which 1,629.8 million ha are vegetated. Appendix 1 also provides a detailed description of the selection criteria for deriving the Land Class Map (LCM) and the land class balance for 1990.

2.4 Auxiliary Models

FOR used a number of auxiliary models in estimating the FCA. These models are presented in Appendix 2.

2.5 Uncertainties

We argue that the verifiability of carbon accounts will sooner or later become a necessary condition for the mutual recognition of legally binding commitments and will be even more important when it comes to carbon trading. In this paper, we continue our earlier work on the issue of verifiability (Jonas *et al*., 1999b) with the aim to assess uncertainties and lay out the nature of those uncertainties involved in FCA. An FCA system, as applied to Russia, has the advantage that some of the possible biases can be identified, which may have been ignored under PCA. FCA, however, may have the disadvantage that the estimates of fluxes show higher random errors (lower precision) than those made under PCA. This occurs because PCA is a subsystem of the largest possible system, namely the FCA.

One of the objectives of this study is to illustrate uncertainties in the carbon accounting. To our knowledge, other scientists dealing with the carbon issue have never developed a definition of the term *uncertainty* that can be applied to quantify lack of knowledge. Our current estimates—summarized carbon fluxes—should only be considered approximations of a true value for assessing the uncertainty of the results. In other words, it is impossible to assess quantitatively how far our uncertainty estimates are from an unknown true value. Thus, we consider uncertainty as an aggregation of insufficiencies of our system outputs, regardless of whether these insufficiencies result from a lack of knowledge, the intricacies of the system, or other causes.

There are two types of knowledge, sometimes referred to as *hard* (or codified) and *soft* (tacit) knowledge. Hard knowledge can be expressed formally and systematically. It is knowledge that can be expressed in words, numbers, formulas, procedures and universal principles and at the same time can be easily communicated. It is gained through codifying previously experienced and applied information into understandable representations of the tacit knowledge. Most important, hard knowledge, or the lack of it, can be quantified. By contrast, soft knowledge is gained through experience and application of contexts and resides within an individual or organization. Polanyi (1966) defined tacit knowledge as “knowing more than we can tell,” and viewed this knowledge as largely inexpressible. Clearly such structuring can be important in the cognitive sense, but cannot be employed in quantitative modeling. If we consider, for example, numerical expert estimates as soft knowledge, then, using this terminology, we inevitably come to the conclusion that the final result of the carbon account is a sophisticated mixture of hard and soft knowledge. This situation requires an appropriate approach to uncertainty analysis.

Uncertainties could be structured based on their sources. In the context of carbon accounting, Shvidenko *et al*. (1996) and Jonas *et al*. (1999a), among others, identify the most important as:

- *Definitions and classification schemes* used in calculations. As a rule, these schemes have been introduced for other purposes than carbon budget analysis, and they often correspond to inappropriate and obsolete standards.
- *Shortcomings of available data*. Some important data have never been and are not measured, which leads to incomplete and sometimes inappropriate substitutions.
- *Unknown or insufficient precision of data of measurements*. Data on forest disturbances are sometimes based on subjective (biased) sampling and estimation of technologies.
- *Lack of a proper basis for upscaling*. There is no solid, objective platform to estimate the accuracy of upscaled point measurements, for example of net ecosystem exchange or soil respiration.
- *Short time series*. Modeling post-disturbance biogenic fluxes requires historical reconstruction of the Northern Eurasia forests for up to 150 years.
- *Lack of knowledge of some important processes*. The post-disturbance processes in soil on permafrost, for instance, are still a typical "black box."
- *Oversimplification of the modeling approach*. Stochastic processes are sometimes represented by deterministic models, leading to imprecise results.
- *Insufficient or territorial gaps in observation systems*. Researchers currently lack up-to-date data for unmanaged and unmonitored remote areas of Northern Russia.

Any data are a result of observations, measurements or modeling, in which uncertainty has a specific nature that can be expressed in terms of a combination of random and systematic errors. In addition, unknown biases may exist in each process and in the way it is measured. In view of the lack of an appropriate terminology to define and describe uncertainty, we present some key definitions in Text Box T.1 and an illustration of a hypothetical uncertainty range in Figure 12. These definitions deviate from the draft glossary produced by IPCC (1999). We are of the opinion that the draft IPCC guidelines do not deal with the complete uncertainty issue because the IPCC approach is based on partial accounting.

Text Box T.1 Uncertainty: Major Definitions

- *Observation* is the simple registration of a phenomenon or indication of its qualitative characteristics.
- *Measurement* is the collection of quantitative data. Measurement involves comparison of the quantity of interest with a standard called a unit. The comparison is never perfect. As a result, measurements always include error. We discuss the reliability of the measurements used to make decisions or estimate other quantities. The qualitative difference between observation and measurement is only a difference of scales in the measurements: the first is basically associated with nominal and rank scales, the second with the interval and especially the relation among scales.
- *Systematic errors* (also called *bias*) have an identifiable cause and affect the accuracy of results. Because the cause of errors can be identified, they are also known as determinate errors.
- *Accuracy* is correctness or a measure of the systematic error. The accuracy of a measurement is assessed by comparing the measurement with the accepted value (the difference between the true and accepted value is unknown in itself; perceiving this difference is soft knowledge), based on evidence independent of the measurement.
- *Random errors* affect the precision of a set of measurements, or, under some restrictions, the precision of any continuous function of random variables. Random error scatters measurements above and below the empirical mean of various distributions, with small random errors being more likely than large ones.
- *Precision* is reproducibility or a measure of the random error.
- A *mistake* is a measurement that is known to be incorrect; the mistake may be due to carelessness, accident, or the ineptitude of the experimenter. It is important to distinguish mistakes from errors: mistakes can be avoided completely, whereas errors can be minimized but not entirely avoided, because they are part of the process of measurement. Mistaken (incorrect) data should be discarded. Data that includes errors can still be useful if the size of the error can be estimated.
- *Unknown biases* may exist in the measurements of each individual process.

Finally, each variable has a specific uncertainty that is usually a complicated function of the sources and error types discussed above, of which only part can be estimated using the classical theory of mathematical statistics. If the quantified specific uncertainties are aggregated according to the law of error propagation (see Appendix 3), the resulting aggregated uncertainty is called *summarized error.*

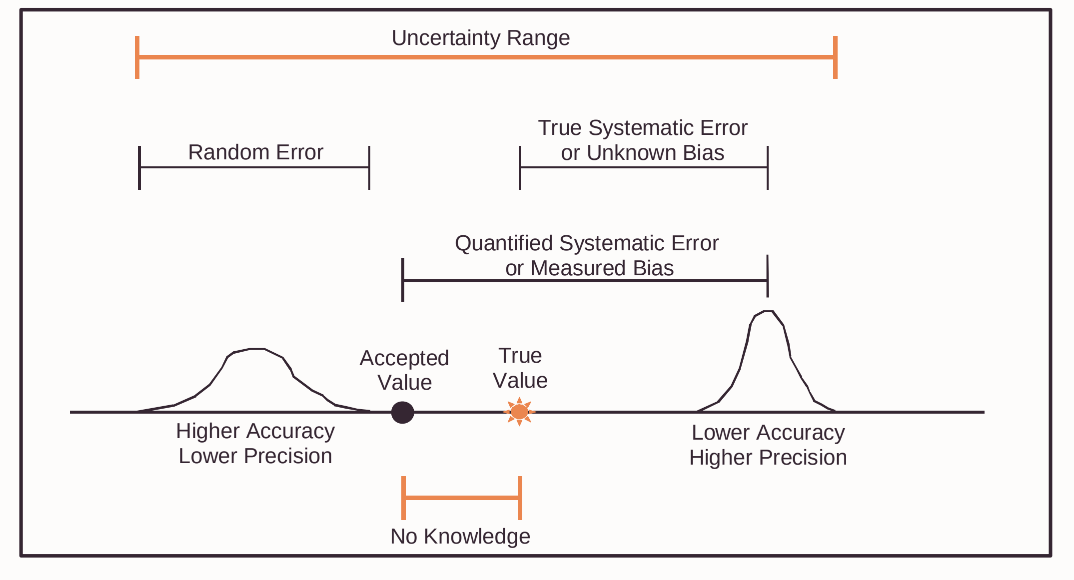


Figure 12. A hypothetical uncertainty range for two sets of measurements of the same phenomenon (individual variable).

The carbon account estimates include uncertainties that cannot be considered "hard knowledge": for example, judgments as to the "best" model for describing a definite process. This is why comparing results obtained by different methods and independent studies is one of the most appropriate approaches for understanding uncertainty. However, as shown by Jonas *et al*. (1999a), such comparisons are not entirely accurate.

As the discussion above indicates, there are almost no methods that consider the problem of estimating the uncertainties in the carbon account in a more or less sufficient way. Existing statistical information is not optimal for classical statistical analysis. This hinders sound application of traditional error propagation theory. To the extent possible, this study compared results obtained by different independent methods to assess the uncertainties in our measurements.

To illustrate the uncertainties, we have tried to estimate the precision of the major components of the carbon budget in a formal manner. Appendix 4 presents an example of these estimates relative to the forest phytomass assessments of the study. These precision estimates served as the platform for simplified expert estimations of the uncertainties, which will be discussed later in the report.

2.6 A Remark on Map Accuracy

The accuracy of all map geometry depends on (1) the initial scales of the maps used, taking into account that the limit error of polygon borders is 2 mm (Nefedova, 1995); and (2) the number and configuration of polygons. Thematic accuracy for these maps is considered to be the best available for Russia. All maps were manipulated in a 1000 m raster format.

3. Carbon Pools, 1990

This section describes the methods and results of our 1990 carbon pool estimates.

3.1 Soil Pools

3.1.1 Primary soil pool

We estimated the total organic (organogenous and organic-mineral compounds) and mineral (carbonates and calcareous rocks) soil carbon pool (SCP) based upon the soil reference profiles and soil type areas as measured from the SOIL map (see Table 1). The 1990 SCPs were estimated in the following steps:

1. For all the combinations mentioned above, the natural soil (organic and mineral) carbon density SCD_h (kg • m^{-2}) of horizon *h* was calculated as

   $$SCD_h = C_h \bullet V_h \bullet H_h \bullet K_s \qquad (3.1)$$

   where C_h is carbon content in kg C • kg soil^{-1}, V_h is bulk density in kg • m^{-3}, and K_s is a correction coefficient on abundance (by soil volume) of rock fragments, $0.1 < K_s < 1.0$.

2. *Natural organic and mineral* SCP_{sd} for a standard depth *sd* of soil type *q* was calculated based on densities found in step 1 and areas of soil classes from the SOIL database

   $$SCP_{sd} = \sum_q SCD_{sdq} * A_{sdq} \qquad (3.2)$$

   where SCP_{sd} is the soil carbon pool for the standard depth *sd*, *q* is type of soil, A_q is the corresponding area derived from the soil map.

3. To estimate the impact of land use on soil carbon content and therefore calculate the actual SCPs, we selected agricultural soils based on the CAT database (> 50% agriculture) and SOIL database (soil suitable for agriculture). For these selected soils we applied a degradation coefficient $[\varphi(D)]$ from the DEG database. Soils not belonging to the selected group did not have any degradation. The formula used was:

   $$ASCD_{qs} = SCD_{qs} \times D_s \qquad (3.3)$$

   where $ASCD_{qs}$ are carbon pool densities affected by degradation for type *q* of a natural soil class. The degradation coefficient *D* is a function of losses of carbon content due to land use and associated soil erosion, grazing and overgrazing in agriculture, fire in forests, etc.

The actual soil carbon pool for Russia $ASCP$ was calculated according to

$$ASCP = \sum_q ASCD_{qs} * A_q \ , \tag{3.4}$$

where A_q is the area of the finer spatial element of the calculation as in equation (3.2).

Many publications are devoted to the carbon content in soils of Russia. The major conclusions are presented in recently published studies by Orlov *et al*. (1996) and Rozhkov *et al*. (1996). However, there are inconsistencies in the cartographic sources used for these soil carbon calculations. For example, Orlov *et al*. based their estimate on a natural-agricultural regionalization published more than 25 years ago (1975) that does not contain soil polygons. The Rozhkov *et al*. study is based on a soil map (Gerasimova *et al*., 1995) that was compiled to illustrate basic soil geographic concepts. The different soil cartographic bases in these two studies led to inconsistencies in soil units and disparity in soil extents. For example, Orlov *et al*. used a total soil area of 1,714 million ha, which exceeds even the officially reported country area (1,709.4 million ha). The soil area used in the Rozhkov *et al*. study is 1,682 million ha.

Different sources and calculation methods in the two studies resulted in different assessments. The total SCP estimate for the 0–1 m layer varies from 296 Pg (Orlov *et al*., 1996) to 342 Pg (Rozhkov *et al*., 1996). However, it should be pointed out that Orlov *et al*. used soil carbon data based on analysis on net combustion and Rozhkov *et al*. made corrections in their estimates for the absolute content of soil organic carbon based on dry combustion. Kogut and Frid (1993) showed that the differences between the two approaches is in the range of 3–34% (depending on soil type), with the higher value for dry combustion. With this correction taken into account, the Rozhkov *et al*. estimate was only 6% higher than the Orlov *et al*. estimate.

We estimate the pre-development total organic and mineral SCP for the 0–2 m layer of Russia to be 448.0 Pg (Table 2), of which 166.2 Pg is accumulated in the 0-0.3 m layer, 231.0 Pg in the 0–0.5 m layer and 337.0 Pg in the 0–1 m layer. Organic carbon (Table 2) tends to concentrate in the topsoil. On average about 55% of organic matter is captured in the 0–0.3 m layer and around 75% in the 0–0.5 m layer. It is important to note that deep soil horizons (1.0–2.0 m) accumulate a considerable amount of organic carbon (about 75 Pg, or roughly 25% of total captured in the 2.0 m layer). This indicates an intensive migration of dissolved organic matter within soil profiles (Djakonova, 1972; Ponomareva and Plotnikova, 1972), which is characteristic of humid soils of the boreal zone (Glazovskaya, 1996). The practical implications illustrate the need to take deep soil horizons and even quaternary sediments into account when estimating the SCP in humid climates (Kramer, 1994).

In contrast to organic carbon, the mineral carbon manifests a gradual increase with depth that indicates an intensive leaching of carbonates from soils formed from calcareous parent materials. Non-pedogenic carbonization may also take place if soils develop under the influence of hard ground water.

Table 3 illustrates the distribution of the SCP by soil divisions. The soil organic carbon is concentrated in six soil divisions: Al-Fe-humic, gleyzems, texture-differentiated, metamorphic, humic-accumulative, and peat. Gleyzems occupy 16% of the area and sequester 26% of the SCP in the 0.3 m layer. The hydromorphism and reduction conditions (gleyization) favor organic conservation. The same features are observed for metamorphic soils, but to a lesser degree. Better-drained and finer-textured soils, such as Al-Fe-humic, do not follow this pattern because fine-textured soils in the boreal zone are cooler and coarse textured. The share of peat in the SCP increases with soil depth and reaches 32% for the 0–1.0 m layer and even 42% for the 0–2.0 m layer.

Table 2. Total organic and mineral carbon pools for pre-development soils of Russia, in Pg.

Depth, m	Organic		Mineral		Total	
	Pg	% of 0-100	Pg	% of 0-100	Pg	% of organic
0-0.3	164.0	55	2.3	6	166.2	99
0-0.5	221.1	74	9.9	25	231.0	96
0-1.0	297.5	100	39.4	100	337.0	88
0-2.0	373.0	125	75.0	190	448.0	83

Table 3. Organic soil carbon pools for different pre-development soil divisions of Russia, in Pg C and percentage.

Soil Division	Area		0–0.3 m		0–0.5 m		0–1.0 m		0–2.0 m	
	10^6 h ha	% of total	Pg	% of total	Pg	% of total	Pg	% of total	Pg	% of total
Alkaline clay differentiated	12.5	1	0.6	0	0.7	0	0.9	0	1.0	0
Al-Fe-humic	364.8	23	22.3	14	26.9	12	31.1	10	32.3	9
Alluvia	54.2	3	3.3	2	5.0	2	7.7	3	9.7	3
Cryozems	9.4	1	0.4	0	0.6	0	0.6	0	0.6	0
Gleyzems	250.0	16	43.1	26	54.8	25	57.8	19	60.3	16
Halomorphic	2.0	0	0.1	0	0.1	0	0.2	0	0.2	0
Humic-accumulative	163.5	10	18.7	11	26.6	12	32.9	11	36.1	10
Lithozems	7.2	0	0.5	0	0.5	0	0.5	0	0.5	0
Low-humic accumulative calcareous	4.4	0	0.1	0	0.1	0	0.1	0	0.1	0
Metamorphic	207.7	13	24.0	15	27.5	12	30.2	10	31.0	8
Peat	116.2	7	23.8	15	43.3	20	94.4	32	156.0	42
Shallow weakly developed	34.5	2	0.4	0	0.4	0	0.4	0	0.4	0
Sod organic-accumulative	92.4	6	8.7	5	10.3	5	11.4	4	12.1	3
Texture-differentiated	248.7	16	16.8	10	22.8	10	26.7	9	29.5	8
Volcanic	14.5	1	1.1	1	1.5	1	2.6	1	3.2	1
Non-soil formulations incl. fragments within vegetation communities	47.8		0.0	0	0.0	0	0.0	0	0.0	0
Total for Country	1629.8	100	164.0	100	221.1	100	297.5	100	373.0	100

The above analysis is based on a new assessment of the soil resources of Russia. About 75% of Russia is covered by cold, humid, soil-forming assemblages resulting in a large extent of Al-Fe-humic (podzols, according to the major groupings of the FAO-Unesco [1988]), gleyzems (gleysols), texture-differentiated (podzoluvisols, gleyzems), metamorphic (cambisols), and peat (histosols) soil groups. Most of these soils are formed in cold climate under forests, swamps, and meadow vegetation. Low microbiological activity and slow mineralization of vegetation residual cause the accumulation of raw under-decomposed organic horizons , such as peat, peat-muck, and sod. The extent of warm soil-formation in semi-arid environments is very limited in Russia.

SCD varies greatly with the soil division. For the topsoil (0–0.3 m) the highest density is found in peat soils (20.9 kg • m^2) containing practically pure organic matter (Table 4). The lowest (1.7 kg • m^2) SCD is in low-humic accumulative calcareous soils. These two soil divisions represent the extremes for SCD in Russia.

The SCD (Table 4) for standard layers (0–0.3, 0–0.5, 0–1.0, 0–2.0 m) illustrates again that the majority of soil divisions concentrate the density of organic carbon in the topsoil. This completely follows the morphological features of soils in Russia.

Table 4. Area-weighted average organic carbon density (kg • m^{-2}) by pre-development soil depths (m) and soil divisions.

Soil division	0–0.3 m	0–0.5 m	0–1.0 m	0–2.0 m
Peat	20.9	37.2	81.3	134.1
Gleyzems	17.6	22.0	23.1	24.1
Metamorphic	12.2	13.6	15.2	15.7
Humic-accumulative	11.7	16.2	20.2	22.4
Sod organic-accumulative	10.3	11.9	13.9	15.1
Volcanic	7.0	10.1	18.2	22.3
Texture-differentiated	7.0	9.3	10.8	11.9.
Lithozems*	6.8	6.9	6.9	6.9
Al-Fe-Humic	6.7	8.3	9.7	10.0
Alluvial	6.2	9.2	14.1	18.0
Halomorphic	5.0	7.0	9.0	10.4
Alkaline clay-differentiated	4.8	5.5	7.3	8.2
Cryozems*	4.6	6.6	6.6	6.6
Shallow weakly developed*	3.1	4.0	4.0	4.0
Low-humic accumulative-calcareous	1.7	2.2	2.6	2.9

*Note: Deep depths of shallow soils are assumed to have a soil carbon density of the topsoil horizon.

3.1.2 SCP by bioclimatic zones

We overlaid our primary SCP estimates with a bioclimatic zone map (derived from the VEG database) in order to distribute SCP by bioclimatic zones. Our results showed that the total (organic and mineral) density of carbon in soils is rather evenly distributed across bioclimatic zones (Table 5). The pre-development organic carbon constitutes 297.5 Pg of the total amount of carbon of 336.9 Pg in the 0–1.0 m layer.

Table 5. Extent of soils and total organic and mineral carbon distribution in the 0–1.0 m pre-development soil layer by bioclimate zones.

Bioclimatic Zone	Soil Area[1]		Total Organic & Mineral Carbon			
	10^6 ha	% of vegetated	Density, (kg • m^{-2})	Pools, Pg C	% of vegetated	% organic
Polar desert	0.7	<1	6.61	<0.1	<0.1	43
Tundra	266.9	16	17.21	46.0	14	96
Pre-tundra & northern taiga	233.0	14	28.49	66.4	20	94
Middle taiga	683.6	42	18.63	127.4	38	87
Southern taiga	211.5	13	20.46	43.3	13	94
Temperate forest	60.4	4	15.64	9.4	3	93
Steppe	148.4	9	26.42	39.2	12	70
Semi-desert & desert	25.4	2	20.76	5.3	2	46
Total Vegetated	1629.8	100	20.67	336.9	100	88

[1] including intrazonal soils of valleys and azonal bogs

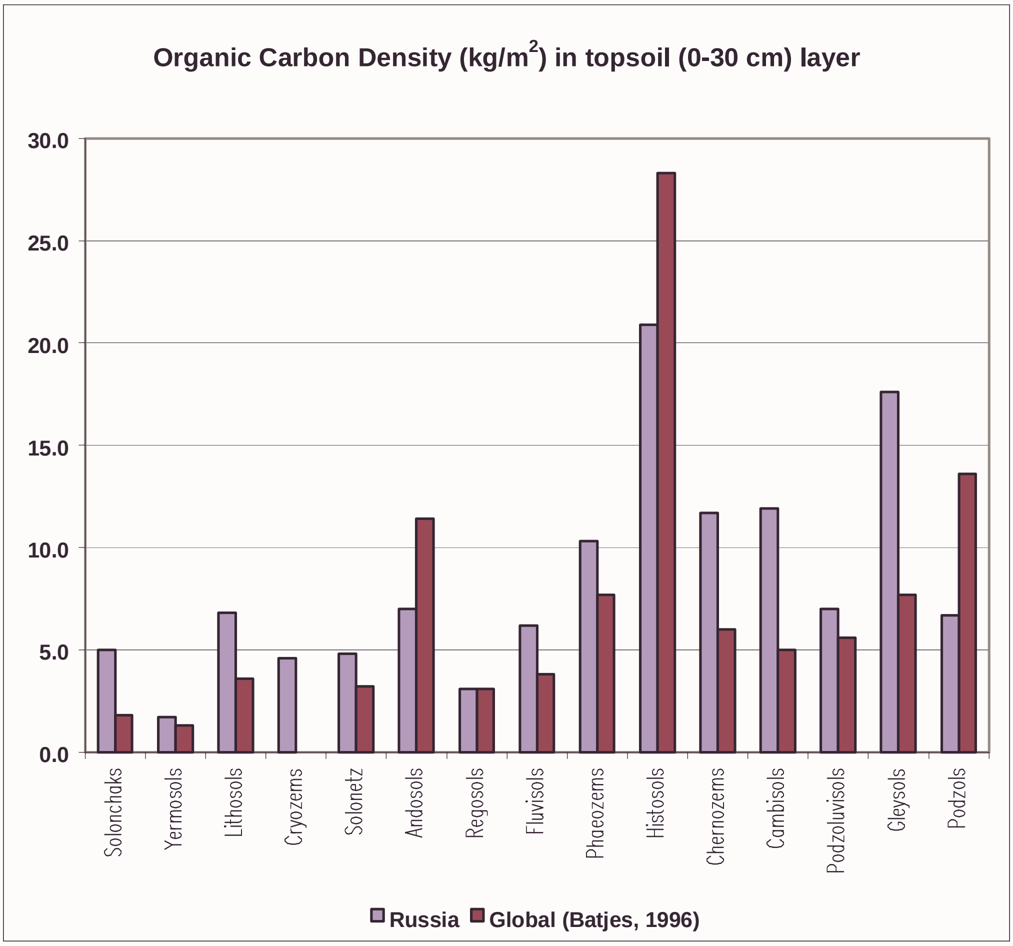
Soils of the cold, humid bioclimatic zones (tundra and forest biomes) are characterized by an intensive accumulation of raw organic materials in the topsoil (about 90% of total carbon). The results also illustrate a high sensitivity of soil carbon to possible climate change. The slow transformation of organic residuals results in a specific fractional composition (Orlov *et al.*, 1996) of organic matter composed of biologically active celluloses and hemicelluloses, easily decomposable acids, sugars, low-molecular weight organic substances, fulvic acids, etc. The latter comprise the major portion of dissolved organics in the soil liquid phase present in the form of chelate metal-organic complexes.

The soils of the steppe zone shift in the balance between organic input and decomposition towards complete mineralization of vegetation as residuals due to organic transformation and humification. High-molecular weight organic substances, including stable humic acids and humin, characterize the organic fractional composition

Moisture deficits in polar desert, semi-desert, and desert zones limit photosynthesis and consequently reduce productivity and organic input into soils. On the other hand, the high air temperature in the semi-desert and desert zones intensifies organic decomposition, and lowers organic carbon accumulation. Text Box T.2 compares the soil organic carbon in predevelopment times with the Global Soil Database.

Text Box T.2. Comparison of the pre-development organic carbon densities in the soils of Russia with the Global Soil Database.

Our SCP estimate is based on the Russian national soil classification, which is not compatible with international global soil databases. Global soil databases (Batjes, 1996) do not include many profiles of the soils characteristic of Russia and, therefore, the country's contribution to the global soil carbon is uncertain in these estimates. Based on the FAO's revised soil legend (Stolbovoi, 2000), we illustrate the carbon soil organic profiles for the soils of Russia (cryozems are not included in the FAO legend).



The topsoil layer of Russia is richer in organic matter compared to the average global organic content for the same soil units. This coincides well with the conservation of easily decomposable organics in the soil surface caused by cold climate. Some physically "warmer" soils (coarse textured podzols) do not follow this path due to intensified biological activity, low organic absorption capacity, lack of active clay minerals, etc.

3.1.3 Land use effects on SCP

Land use practices in Russia have led to a general decline of the SCP from pre-development times to 1990. Some (e.g., Batjes, 1999) interpret the soil organic carbon lost as a carbon sequestration potential. The soil degradation has led to a carbon imbalance in the ecosystem and to dehumification processes in soils (Tyrin, 1965; Orlov, 1990). In our SCPs we assessed the effect of erosion, overgrazing and disturbances of the topsoils due to harvests and wildfires. We considered a cumulative effect of degradation that differs from place to place depending on the land use history. For example, the cultivation period of Siberia lasted 40–90 years, including the resettlement program in Russia in the early 20th century and cultivation of virgin lands in the mid-1950s. Although some regions in European Russia have a relatively long history of cultivation, going back to the 13th–14th centuries, most of areas have been cultivated only during the past 300–400 years.

We overlaid the soil degradation (DEG) database (Stolbovoi and Fischer, 1998; also see Table 1) with our SCP estimates in order to calculate the land use effect on the SCP. Degradation coefficients were applied for erosion, overgrazing and cultivation (Stolbovoi and Fischer, 1998). The degradation coefficients for each soil category were averaged for all soils classified as cropland, pasture and forest per oblast to determine the total soil carbon loss.

On average, Russian soils have lost about 3.4 Pg C or around 2% of the soil organic matter accumulated in the upper 0–0.3 m since pre-development times (Table 6). Land use affects not only the topsoil, but also the total carbon cycling in the ecosystem, as shown by the 1.3 Pg C of organic matter removed from the 0.3–1.0 m layer as a result of land-use practices.

Table 6. Human-induced changes of the soil organic carbon pools of Russia from pre-development times to 1990, in Pg C.

Land Class	0–0.3 m depth				0–1.0 m depth			
	Pre-development state, Pg C	1990 Pg C	Lost Pg C	% of natural	Pre-development state, Pg C	1990, Pg C	Lost Pg C	% of natural
Cropland	13.5	10.8	2.6	20	22.6	19.0	3.6	16
Pasture	6.4	5.9	0.5	7	10.0	8.9	1.1	11
Total Agriculture	19.8	16.8	3.1	16	32.6	27.9	4.7	14
Forest	61.9	61.6	0.3	1	87.6	87.6	0.0	0
Swamps	28.4	28.4	0.0	0	37.5	37.5	0.0	0
Bogs	24.3	24.3	0.0	0	94.3	94.3	0.0	0
Total Wetlands	52.7	52.7	0.0	0	131.9	131.9	0.0	0
Grassland & shrubs	29.2	29.2	0.0	0	45.5	45.5	0.0	0
Total Country	163.7	160.3	3.4	2	297.5	292.9	4.7	2

The largest proportion of the loss (about 3.1 Pg C in the 0–0.3 m layer) is caused by agricultural practices, of which 2.1 Pg C are due to from cultivation and about 0.5 Pg C to grazing. In total, the cropland soils have lost about 20% and pastures about 7% of the initial SCP. In the 0–1.0 m layer the losses are even greater. It is important to note that the cultivation effect is stronger in the upper layer, while grazing has a greater effect on deeper soil horizons. There could be different explanations for the enhanced effect of grazing on carbon content of deeper soil horizons, but we suspect the selective consumption by animals of grass species plays a key role.

We found that 0.4 Pg C of soil organic carbon, or about 15% of the total losses (2.6 Pg C), is caused by erosion (Table 7). Soil erosion influences not only topsoils but also deep soils. The latter is indicated by the loss of 0.1 Pg C of organic matter in the 1.0 m layer. Several mechanisms decrease organic content in deep soils, but the most probable explanation is that soil erosion leads to the destruction of well-structured and richly voided topsoils. This results in exposure of the compacted subsoils that substantially constrain root development. There is also evidence of nutrient and water deficits that deteriorate crop density and consequently decreases organic input into soils (Shishov *et al.*, 1991). We estimate the loss of the soil organic carbon in forest soils in the 0–1.0 m layer to be as high as 0.3 Pg C distributed over an area of some 24 million ha (Stolbovoi, 1997).

Table 7. Effects of cultivation and erosion on the organic soil carbon pools (0-0.3 m and 0-1.0 m) of croplands of Russia from pre-development times to 1990, in Pg C.

Depth, m	Pre-development Soil Carbon Pools, Pg C	Actual Soil Carbon Pools, Pg C	Losses of Soil Organic Carbon					
			Total		Caused by tillage		Caused by erosion	
			Pg C	% of initial pool	Pg C	% of total lost	Pg C	% of total lost
0.3	13.47	10.8	2.6	20	2.2	85	0.4	15
0-1.0	22.60	19.0	3.6	16	3.0	85	0.5	15

3.1.4 SCP by land class

We distributed our primary SCP estimates across land classes using a GIS overlay of the CAT and SOIL databases.

Soil organic density and human-induced impacts vary according to land class due to differences in major natural soil-forming factors (Table 8). This variability illustrates the possibility of changing the carbon sequestration in soils through different management regimes. Thus, wetland management may play a major role in carbon sequestration in Russia. The highest carbon densities (from 26.8 in 0–0.3 m to 133.92 kg • m^{-2} in 0–2.0 m) occur in wetland soils.

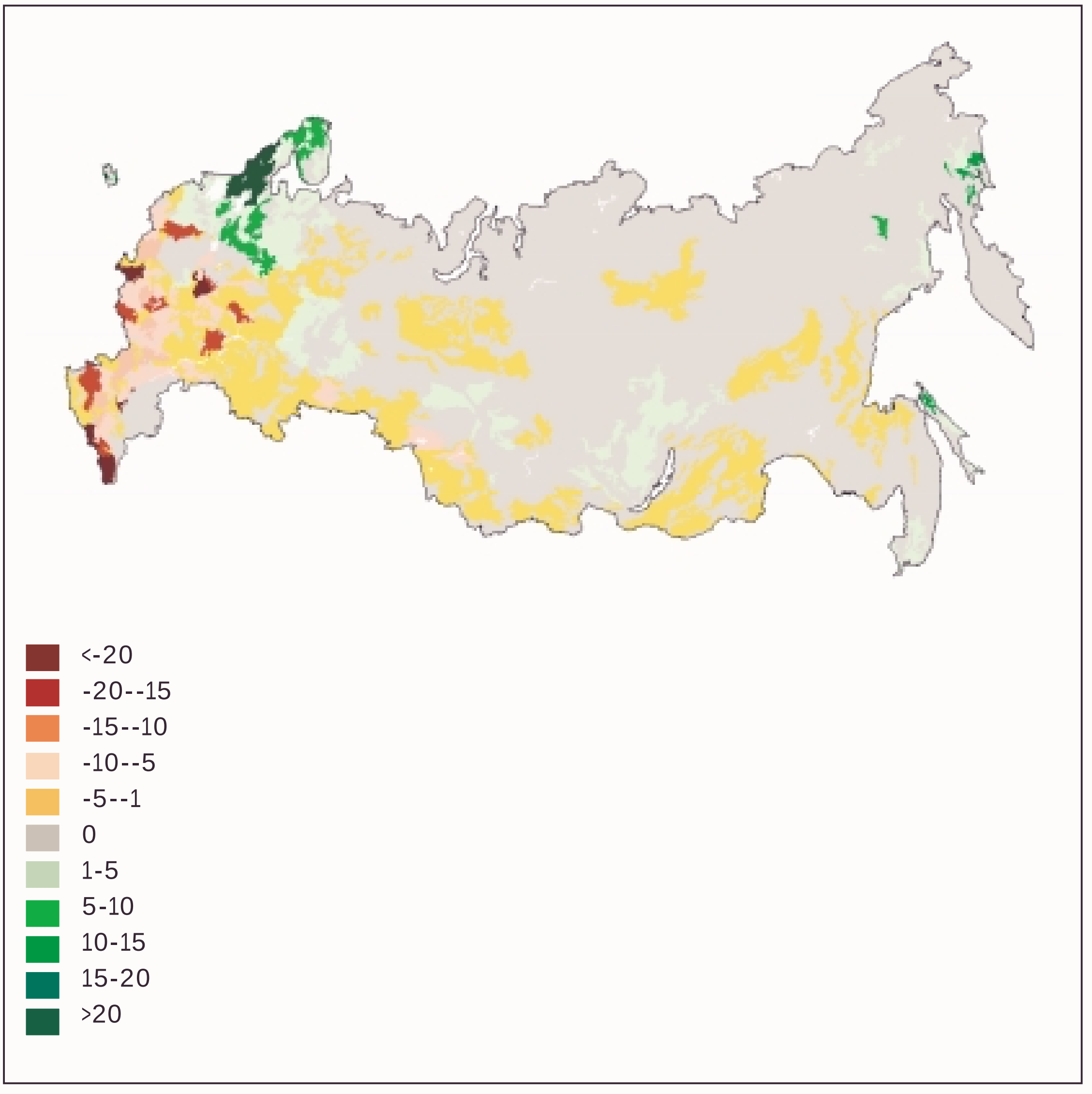
Differences between soil carbon densities by land-use classes increase with soil depth. For example, organic carbon content in the 0–0.3 m layer is 7.26 kg • m^{-2} for pastures compared to 20.91 kg • m^{-2} for bogs (i.e., only a third as great), yet organic content in the 0–2.0 m layer of pastures is 11.68 kg • m^{-2} compared to 133.92 kg • m^{-2} for bogs (i.e., only one-twelfth as great).

Table 8. Soil organic carbon densities for different depths (m) by land classes (1990), in kg • m^{-2}.

Land Class	Soil Carbon Densities (kg • m^{-2}) by Depth (m)			
	0-0.3	0-0.5	0-1.0	0-2.0
Cropland	8.32	11.39	14.59	16.43
Pasture	7.26	9.14	10.94	11.68
Average Agriculture	7.91	10.52	13.19	14.60
Forest	8.07	9.84	11.47	12.33
Swamps	26.83	34.60	35.48	36.40
Bogs	20.91	37.21	81.19	133.92
Total Wetlands	23.73	35.96	59.40	87.44
Grassland and shrubs	6.76	9.20	10.51	11.23
Average Country	9.83	13.32	17.97	22.56

We estimate the average carbon density of soils in Russia to be 17.97 kg C • m^{-2} in the 0–1.0 m layer. This high content is explained by a significant amount of carbon in wetlands (35.48 kg C • m^{-2} for swamps and 81.19 kg C • m^{-2} for bogs). The average carbon density for forest soils (0–1.0 m) is estimated as 11.47 kg C • m^{-2}, which is 3.12 kg • m^{-2} less than for cropland soils. Text Box T.3 shows human-induced changes of the organic carbon content in soils in Russia.

Text Box T.3 Human Induced Changes of the Organic Content in Soils in Russia. Changes in percentage of the content in pre-development times.



Different regions of Russia have different changes of the SCPs. About 15 of the 89 administrative oblasts show an increase of SCP in cultivated soils. For example, cropland soils in Karelia show 64% more organic matter compared with those of natural soils. By contrast, cropland soils in Novosibirsk oblasts have lost about 31% of the initial organic matter.

Although the result is found to be in line with other publications (e.g., Batjes, 1999a) the map illustrates that besides agronomic measures the soil nature plays an important role in potential carbon sequestration. Obviously, soils that lack a humus horizon under natural conditions tend to have an enrichment of carbon and absorb organic matter.

3.2 Terrestrial Biota

3.2.1 Methods

Two principal methods were used for the calculations of the vegetation pools; (1) VEG database approach, and (2) approach based on data of agriculture statistics (for agricultural land) and forest inventory (for forests).

By the VEG database, phytomass C pools Ph_{ijm} of land class *i*, fraction *j*, and unit of spatial aggregation *m* (administrative region, bioclimatic zone), kg C • m^{-2}, were calculated for all land classes (excluding agricultural land) as:

$$Ph_{ijm} = \alpha_v \sum_{k=1}^{n} S_{ijmk} Ph_{ijmk} \tag{3.5}$$

where

i is land class; *i* =1,…,7,

j is phytomass fraction, *j* =1,… S_I ,

k is classes of the vegetation database, $k = 1, \ldots n_i$, (e.g. n_i = 133 for the vegetation database) and n_I = 12 for wetland,

m is the index of spatial units of aggregation (administrative region or bioclimatic zone),

S_{ijmk} is the area of the initial classification unit used,

α_v is the coefficient for recalculation of dry matter units in carbon units; the conversion factor for carbon content used was 0.50 for wood and 0.45 for green parts.

For all land classes, we produced estimates for the following phytomass fractions: green parts, woody (above-ground) phytomass, total above-ground phytomass, root phytomass, total phytomass, coarse woody debris, and dead roots (below-ground mortmass). The specific approaches of the phytomass calculations of forests and agricultural land are briefly considered below.

As a second approach, we also estimated the forest phytomass Ph_{for} based on the State Forest Account (SFA) data, using the formula:

$$Ph_{for} = d_j \sum_m Ph_m = d_j \sum_m \sum_{pjABP} R_{pmj(ABP)} \bullet M_{pmABP} \tag{3.6}$$

where:

d_j is carbon content in a unit of phytomass dry matter

p is dominant species (according to SFA classification)

j is phytomass fraction, *j* = 1,…,7 (stem overbark, bark, crown, foliage, roots, understory, green forest floor)

A, B, P are age, site index and relative stocking of dominant species *p* and unit of aggregation *m*

M_{pmjABP} is growing stock volume $m^{-3} \bullet ha^{-1}$

m is index of ecoregion, *m* = 1,…,141, and

$R_{pmj(ABP)}$ is the ratio between mass of fraction *j* of species *p*, age *A*, site index *B* and relative stocking *P*, to (green) growing stock expressed by the formula presented in Appendix 2.

3.2.2 Agricultural phytomass

Agricultural land includes croplands and pastures (including perennial crops). In our analysis, we used the most recent crop statistics (Agriculture of Russia, 1995). Because this information does not consider the content of all phytomass fractions—such as straw, above-ground residuals, and roots—we also introduced crop- and yield-specific regression equations (Rodin and Krylatov, 1998). To convert the amount of yield and byproducts expressed in metric phytomass units into carbon units we applied a coefficient of 0.86 for grain and 0.5 for the rest of the phytomass fractions. We assume that living biomass (LB) is equal to net primary productivity (NPP) and that the phytomass of agricultural land has an annual life cycle.

In the calculations, LB of cropland was considered as a sum of yields *Y* and residuals *R*. Values of *Y* were derived from crop statistics. The residual *R* is a function of *Y* that depend on crop specifics and the amount of *Y*. Three phytomass fractions are used for cereals: straw, surface residuals and roots, whereas only the surface residuals and roots fractions are used for pasture phytomass. Each fraction is calculated by the general regression equation:

$X = aY + b$, where a and b are empirical coefficients. (3.7)

R is calculated as:

$$R_{Cr} = X_s + X_f + X_r$$

$$R_h = X_f + X_r,$$

where R_{Cr} and R_h consequently are residual phytomasses of cropland and pastures represented by fractions X_s (straw), X_f (surface residuals), and X_r (roots).

FOR estimated the total phytomass of croplands and haylands of Russia in 1990 at 2,186.8 Tg of dry matter (Table 9), of which cropland comprises 1,441.0 Tg and pastures 745.8 Tg. Above-ground phytomass accounts for about 57%, and below-ground for 43%. The density of dry matter phytomass differs among the types of agricultural land: cropland (1.11 kg • m^{-2}) and pasture (0.91).

Table 9. Phytomass of agricultural biota (1990), in Tg.

Land Class	Area, 10^6 ha	Phytomass, million tons, dry matter						Density, kg/m^2	
		Green part	Woody part	Above ground	Below ground	Total dry matter	Total carbon	Dry matter	Carbon
Cropland	130.3	883.1	0.0	883.1	557.9	1,441.0	648.5	1.11	0.50
Pastures	81.5	319.6	55.5	375.0	370.8	745.8	338.4	0.91	0.42
Total	211.9	1,202.7	55.5	1,258.2	928.7	2,186.8	986.8	1.03	0.47

About two-thirds of the total agricultural phytomass are located in the zones of steppe and temperate forests (Table 10). The average dry matter density of phytomass varies geographically from 0.74 kg • m^{-2} in northern tundra to 0.98 kg • m^{-2} in the southern steppe. This variability is less than that of grasslands and shrubs.

Table 10. Distribution of agricultural phytomass by bioclimatic zone (1990), in Tg.

Bioclimatic Zone	Area, 10^6 ha	Agricultural Land				Density, kg/m^2	
		Crop	Pastures	Total dry matter	Total carbon	Dry matter	Carbon
Polar desert	0.0	0.00	0.00	0.00	0.0	0.00	0.00
Tundra	1.8	0.00	13.49	13.49	6.2	0.74	0.00
Pre-tundra & northern taiga	1.6	2.77	7.64	10.41	4.6	0.66	0.00
Middle taiga	14.6	59.88	65.80	125.68	56.7	0.86	0.01
Southern taiga	35.3	315.10	102.42	417.51	188.9	1.18	0.11
Temperate forest	29.4	239.16	87.57	326.74	148.2	1.11	0.48
Steppe	111.7	781.00	315.75	1,096.75	494.0	0.98	1.35
Semi-desert & desert	17.3	43.12	153.14	196.26	88.4	1.13	1.10
Total	211.9	1,441.02	745.81	2,186.84	986.9	1.03	0.07

3.2.3 Forest phytomass

Table 11 and Table 12 contain aggregated estimates of forest phytomass in closed forests (forested areas) by bioclimatic zones and major tree species in 1990. Data were estimated using the SFA method.

Table 11. Distribution of forest phytomass of closed forests by bioclimatic zones (1990), in Tg of dry matter.

Zones	Area, x 10^6 ha	Phytomass, Tg		Density, kg • m^{-2}	
		Dry matter	Carbon	Dry matter	Carbon
Polar desert	0.0	0.0	0.0	0.00	0.00
Tundra	3.8	109.2	53.5	2.86	1.40
Forest tundra & northern taiga	141.2	6,860.4	3,375.3	4.86	2.39
Middle taiga	455.0	41,590.4	20,586.7	9.14	4.52
Southern taiga	126.5	13,802.3	6,832.1	10.91	5.40
Temperate forests	26.5	3,318.1	1,635.8	12.53	6.18
Steppe	9.3	720.8	354.6	7.79	3.83
Semi-desert & desert	1.3	48.5	23.9	3.79	1.87
Non-vegetated area	0.0	0.0	0.0	0.00	0.00
Total	763.5	66,449.7	32,861.9	8.70	4.30

Table 12. Extent and densities of phytomass dry matter of closed forests ($kg \cdot m^{-2}$) by dominant species (1990), in Tg.

Major Forest Formations	Area, $x10^6$ ha	Total Phyto-mass, Tg, dry weight	Density of Forest Phytomass Components ($kg \cdot m^{-2}$, dry weight)						Carbon Density, $kg \cdot m^{-2}$
			Stem	Bran-ches	Foli-age	Roots	US, UG and GFF[1]	Total	
Coniferous	540.5	50008.0	5.75	0.75	0.40	1.60	0.75	9.25	4.57
of which Pine	127.7	11137.5	5.50	0.74	0.43	1.41	0.64	8.72	4.31
Spruce	84.6	9535.1	6.02	1.37	0.93	2.36	0.58	11.27	5.56
Larch	269.1	22353.9	5.42	0.50	0.16	1.38	0.85	8.31	4.11
Cedar	43.2	5352.2	7.57	1.02	0.70	2.16	0.94	12.39	6.11
Fir	15.9	1629.4	6.80	0.98	0.70	1.19	0.58	10.25	5.06
Soft deciduous	133.5	12399.8	5.75	1.12	0.27	1.80	0.35	9.29	4.61
Hard deciduous	19.5	2278.6	6.30	1.54	0.29	2.95	0.60	11.68	5.80
Other species and shrubs	70.0	1763.3	–	–	–	–	–	2.52	1.26

[1] Abbreviations: US = understory; UG = undergrowth; GFF = green forest floor.

The total phytomass of the Russian forested areas is estimated to be 66,449.7 Tg of dry matter and 32,861.9 Tg C. The forests of European Russia contain 25.6% of the forest carbon and the forests of Asian Russia 74.4%. The above-ground phytomass constitutes 77.3% of the total forest phytomass in Russia.

Approximately 95% of Russian forests are taiga forests. The middle and southern taiga zones comprise 62.6% and 20.8% of all forest phytomass, respectively. There is a significant zonal variation in the forest phytomass density, from 1.40 kg C • m^{-2} in tundra to 6.18 kg C • m^{-2} in temperate forests to about 1.87 kg C • m^{-2} in semi-desert forests.

The distribution of the basic phytomass fractions is: stemwood over bark 60.2% of total phytomass, roots of trees 17.5%, crown wood 8.8%, understory including green forest floor 7.0%, and foliage 3.9%. Shrubs, as a separate category of forested area where closed forests are unable to grow, contain 2.6% of the total phytomass.

The average carbon densities *D* (total forest phytomass/forested area) for the whole country, European and Asian Russia is estimated to be 4.30, 5.07 and 4.09 kg C • m^{-2}, respectively.

Coniferous-dominated forests contain the major part of forest vegetational carbon (24,691.2 Tg C, or 75.2%), of which 33.6% are in larch forests, 16.7% in pine, 14.3% in spruce, 8.1% in Russian cedar (*Pinus sibirica* and *P. korejansis*), and 2.5% are in fir forests. Soft deciduous forests contain 6158.4 Tg C or 18.7% (birch stands 13.7% and aspen stands 3.6%). This means that about 92% of the phytomass of Russian forests is in stands dominated by seven species. Only 3.4% of the total forest vegetational C is located in hard deciduous forests.

In terms of the distribution of phytomass by age groups, young stands contain 5.2%, middle-aged stands 25.1%, immature stands 12.7%, mature stands 30.8%, and overmature stands 26.2% of the total phytomass in Russia's forest ecosystems. Further details are presented in Shvidenko *et al.* (1999).

To validate the main approach discussed above, FOR also estimated the phytomass of forest ecosystems by a second method. This second method and the resulting estimate are discussed in Text Box T.4. Text Box T.5 compares the estimates of terrestrial biota for the IIASA LCM and the IGBP land class map.

Text Box T.4 Forest Phytomass Comparison

We estimated forest phytomass using two independent approaches: the SFA, as described in the main body of this report, and a second method using the Forest Map and average phytomass densities from the ecological database adjusted to species and age structures of forests by ecoregions. As discussed in Section 2.2, the Forest Map is a spatial distribution of the SFA based on overlay of available maps of which forest class polygons were selected to match SFA distribution by administrative units or ecoregions. These selected polygons were used as the area (*S*) of overlaying the initial classification unit.

A comparison of the results of this approach with those from the SFA estimates shows comparable (within 2.3% overall) estimates for phytomass and 2.2–2.7% for fractions.

Comparison of phytomass of forest ecosystems estimated by independent methods.

Estimation Method	Phytomass, Tg, dry matter					Density, kg • m^{-2}
	Green part	Woody part	Above ground	Below ground	Total	
SFA	4,959.1	47,384.4	52,343.5	14,106.2	66,449.7	8.7
Forest Map	4,826.4	48,681.7	53,508.1	14,469.6	67,977.8	8.9
Difference, Tg	132.7	–1297.3	–1164.6	–363.4	–1528.1	n/a
Difference, %	+2.7	–2.7	–2.2	–2.6	–2.3	n/a

Text Box T.5 What if we used different areas in terrestrial biota estimates?

Our LCM can be compared with a global land cover characteristics database by using a summarized version of the International Geosphere Biosphere Programme Legend (USGS, 1999). If we examine the sensitivity of our terrestrial phytomass pool calculations by multiplying the areas from the IGBP map, distributed by bioclimatic zone, by our phytomass densities, we see that this latter approach estimates the total phytomass pool at 64,301 million tons of dry matter—nearly 20 percent less than our estimate.

Phytomass (Tg) of land classes by bioclimatic zones based on IIASA LCM.

Bioclimatic zone	Area (Mha)	Agriculture	Forest	Wetlands	Grassland and Shrubs	Total
Polar desert	1	0	0	0	1	1
Tundra	267	13	109	987	2,660	3,770
Pre-tundra & northern taiga	233	10	6,860	1,572	487	8,930
Middle taiga	684	126	41,590	2,060	3,460	47,236
Southern taiga	212	418	13,802	860	480	15,560
Temperate forest	60	327	3,318	59	50	3,754
Steppe	148	1,097	721	13	391	2,221
Semi-desert & desert	25	196	49	5	78	328
Grand Total	1,630	2,187	66,450	5,556	7,607	81,799

Phytomass (Tg) of land classes by bioclimatic zones based on IGBP land class map.

Bio-climatic zone	Area (Mha)	Agriculture	Forest	Wetlands	Grassland and Shrubs	Total
Polar desert	2	0	0	0	0	0
Tundra	268	4	417	136	1,511	2,068
Pre-tundra & northern taiga	233	4	6,190	1,071	1,388	8,653
Middle taiga	682	320	31,516	1,003	3,207	36,046
Southern taiga	211	1,184	9,576	64	172	10,996
Temperate forest	60	417	1,817	0	147	2,381
Steppe	148	1,091	852	1	1,362	3,306
Semi-desert & desert	25	113	105	1	357	576
Total	1,629	3,133	50,473	2,276	8,144	64,026

3.2.4 Wetland phytomass

The major part of the wetland areas (about 85%) is distributed rather equally among the northern zones of tundra, forest tundra, northern taiga and middle taiga. Shrub tundra and sparse forests (not classified as forested areas), constitute some 50% of the total swamp areas, which amount to 105.8 million ha. These sparse forests contain mainly *Larix gmelinii*, *L. sibirica*, *Pinus sibirica*, *P. sylvestris*, *Betula pendula* and shrubs (*Betula ovalifolia, B. fruticosa, Salix brachypoda, S. abscondita*). Bogs contain treeless wetland vegetation types with a dominance of *Sphagnum* species. *Betula nana* and *B. exilis* are typical for bogs of the tundra zone.

FOR estimated the wetland phytomass according to formula (3.5). In the estimates 14 wetland classes were treated individually.

We estimated the total swamp phytomass to be 2,817.3 Tg dry matter, of which the above-ground portion comprises about 65%. The above-ground woody part accounts for the dominant share (1,329.5 Tg, or 47.2% of the total.). The average density is 2.66 kg • m^{-2} dry matter, or 1.26 kg C • m^{-2}.

The total area of bogs is estimated to be 116.2 million ha and the total amount of phytomass is estimated to be 2,738.5 Tg. The average density is 2.36 kg • m^{-2} or 1.09 kg C • m^{-2}. Bog phytomass contains more green parts (27.1%) and fewer woody parts than swamps. The estimate on the carbon content of phytomass of wetlands is 2,602.9 Tg C. Table 13 and Table 14 summarize our estimates for phytomass in the wetlands.

Table 13. Estimate of swamp land class phytomass and carbon by bioclimatic zone (1990).

Bioclimatic Zone	Area (10^6 ha)	Phytomass (Tg tons)						Density	
		Green	Woody	Above Ground	Below ground	Total dry matter	Total carbon	Dry matter	Carbon
Polar desert	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Tundra	53.38	284.5	24.6	309.0	525.7	834.8	376.9	1.56	0.71
Pre-tundra & northern taiga	28.24	118.3	510.6	628.9	189.5	818.4	393.8	2.90	1.39
Middle taiga	21.21	94.8	717.6	812.5	224.6	1,037.1	502.6	4.89	2.37
Southern taiga	1.62	7.7	58.6	66.4	18.3	84.7	41.1	5.22	2.53
Temperate forest	0.60	4.9	17.9	22.8	6.1	28.9	13.9	4.81	2.31
Steppe	0.51	3.4	0.1	3.5	5.6	9.1	4.1	1.78	0.80
Semi-desert & desert	0.26	1.6	0.0	1.6	2.7	4.3	1.9	1.67	0.75
Total	105.82	515.3	1,329.5	1,844.8	972.5	2,817.3	1,334.3	2.66	1.26

Table 14. Estimate of bog land class phytomass and carbon by bioclimatic zone (1990).

Bioclimatic Zone	Area (10^6 ha)	Phytomass (Tg tons)						Density	
		Green	Woody	Above Ground	Below ground	Total dry matter	Total carbon	Dry matter	Carbon
Polar desert	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Tundra	8.91	53.7	9.0	62.7	89.2	151.9	68.8	1.71	0.77
Pre-tundra & northern taiga	36.52	191.4	172.4	363.7	390.0	753.7	347.8	2.06	0.95
Middle taiga	40.75	276.7	302.4	579.1	443.8	1,022.9	475.4	2.51	1.17
Southern taiga	28.55	209.8	229.0	438.8	336.3	775.1	360.2	2.72	1.26
Temperate forest	1.17	8.1	13.2	21.3	8.7	30.1	14.2	2.57	1.21
Steppe	0.22	1.4	0.0	1.5	2.3	3.8	1.7	1.75	0.79
Semi-desert & desert	0.07	0.4	0.0	0.4	0.7	1.1	0.5	1.51	0.68
Total	116.19	741.6	725.9	1,467.5	1,271.0	2,738.5	1,268.6	2.36	1.09

3.2.5 Grassland and shrub phytomass

Grassland and shrub vegetation occupies vast territories (432.4 million ha) across all vegetation zones, although two major vegetation formations—tundra and middle taiga contain about 60% of total phytomass of this land class. Equation (3.1) was used to estimate phytomass for the green parts, woody (above-ground) phytomass, above ground phytomass, root phytomass, and total phytomass fractions.

Grassland and shrub vegetation phytomass comprises 9.3% of the total phytomass of Russia and has an average density of 1.76 kg • m^{-2} dry matter, or 0.81 kg C • m^{-2}. We estimated the total phytomass of grassland and shrub vegetation to be 7,607.1 Tg of dry matter, with a carbon content of 3,494.1 Tg C. The estimates for phytomass content of the grassland and shrub vegetation are summarized in Table 15.

Table 15. Estimates of phytomass and carbon content of grasslands and shrubs (1990), in Tg.

Bioclimatic Zone	Area (10^6 ha)	Phytomass (Tg)						Density	
		Green	Woody	Above Ground	Below ground	Total dry matter	Total carbon	Dry matter	Carbon
Polar desert	0.68	0.6	0.0	0.6	0.2	0.7	0.3	0.00	0.00
Tundra	198.95	832.0	277.9	1,109.9	1,550.2	2,660.1	1,210.9	1.34	0.61
Pre-tundra & northern taiga	25.48	113.7	90.2	203.9	283.2	487.1	223.7	1.91	0.88
Middle taiga	151.98	602.4	941.9	1,544.3	1,915.7	3,460.0	1,604.1	2.28	1.06
Southern taiga	19.52	113.6	100.6	214.2	265.8	480.1	221.1	2.46	1.13
Temperate forest	2.67	10.4	2.4	12.8	37.3	50.2	22.7	1.88	0.85
Steppe	26.65	74.3	1.0	75.2	315.3	390.6	175.8	1.47	0.66
Semi-desert & desert	6.46	12.6	5.3	17.9	60.5	78.3	35.5	1.21	0.55
Grand Total	432.40	1,759.5	1,419.3	3,178.8	4,428.3	7,607.1	3,494.1	1.76	0.81

3.2.6 Carbon pool of coarse woody debris

Coarse woody debris (CWD) includes dead above-ground and on-ground stems and branches that have a top diameter of more than 1 cm and have not lost their initial morphological structure (smaller branches and twigs are included in the category of litter). The amount of CWD depends on the age and structure of forests, previous management and disturbance history. In this section we estimate CWD for forests, grasslands and shrubs and wetland land classes.

The Russian forest inventory identifies CWD as dead standing stems and downed wood in each inventoried stand. To our knowledge, the inventory has not reported any aggregated data on CWD storage. Nevertheless, many publications that describe forest productivity, formations or disturbances present data sufficient for approximate estimates of the CWD (e.g., Bazilevich, 1993a; Krankina *et al*., 1998; Harmon *et al*., 2000; Shvidenko and Nilsson, 2000a, b).

We used an average of the results of two independent methods to estimate the carbon content of CWD in forests. The VEG database method applied the initial polygon classes to the CWD per hectare in IIASA's ecoregional database (see Table 16). This estimate was 8,967.2 Pg of dry matter. The forest inventory method combined average volume (m^3 per ha) of dry standing trees and on-ground CWD estimates for ecoregions, phytomass/mortmass data and samples from the Russian forest inventory by forest enterprises. Using this method, the total amount of CWD was estimated as 8,650.2 Tg dry matter (or 17% of the above-ground phytomass of closed forests). The accuracy of each estimate is approximately the same, and we used the average of 8,808.7 Tg dry matter or 4,404.4 Tg C in our subsequent calculations.

Forests contain 89% of the CWD in all terrestrial ecosystems in Russia, wetlands 6.8%, and grassland and shrubs 4.1% (in trees outside forests). The total phytomass of CWD is estimated to be 9.91 Pg of dry matter, or 4.96 Pg C.

Table 16. Distribution of coarse woody debris by bioclimatic zone and carbon content (1990), in Tg.

Bio-climatic Zone	Area (10^6 ha)	CWD (Tg, dry matter)							Total Carbon Density, kg • m^{-2}	
		Forests			Wet-lands	Grass-land and shrubs	Total dry matter	Total carbon	Dry matter	Carbon
		VEG	Forest Inventory	Mean						
Polar desert	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Tundra	265.1	13.7	12.3	13.0	27.3	167.4	207.7	103.9	0.78	0.39
Pre-tundra & northern taiga	231.4	1,485.6	1,419.1	1,452.4	197.9	23.4	1,673.7	836.8	7.23	3.62
Middle taiga	669.0	5,381.7	5,491.8	5,436.8	321.9	156.5	5,915.2	2,957.6	8.84	4.42
Southern taiga	176.2	1,808.6	1,498.0	1,653.3	117.6	25.4	1,796.3	898.2	10.19	5.10
Temperate forest	30.9	253.8	185.2	219.5	9.4	3.6	232.5	116.3	7.52	3.76
Steppe	36.6	17.1	40.1	28.6	0.2	38.5	67.3	33.7	1.84	0.92
Semi-desert & desert	8.1	6.7	3.7	5.2	0.0	14.0	19.2	9.6	2.38	1.19
Total	1,417.9	8,967.2	8,650.2	8,808.7	674.3	428.8	9,911.8	4,955.9	6.99	3.50

Above-ground litter was calculated with the help of a litter map jointly developed by the Dokuchaev Soil Institute (Moscow) and the IIASA Forest Study. We used the reference soil profiles of the Soil Map of the Former Soviet Union at a scale of 1: 2,500,000 million (Fridland, 1988) as a basis for soil types. For each polygon of the Soil Map we calculated two indicators of litter: depth and density. By overlaying the soil, forest and bioclimatic zone maps, we could calculate the average litter density (kg C • m^{-2}) for forest by dominant species. Estimates for other natural vegetation were aggregated for all other land classes. Because the litter data were reported for undisturbed litter, we introduced correction coefficients for average severity of disturbance regimes by group of dominant species, and land classes of other vegetation and bioclimatic zones (in addition to crops and cultivated haylands and pastures, for which litter was assumed to be zero). These corrections changed the total results for forests by 10.8%. In order to recalculate dry matter in terms of carbon units, we used the average coefficient of 0.50 for aggregated dominant species.

The actual densities of litter for forests and other land classes of natural vegetation are presented in Table 17. From the results, we can conclude that different forest types have significantly different amounts of above-ground litter (e.g., 1.36 kg C • m^{-2} for larch and 2.07 kg C • m^{-2} for spruce stands). The table also shows an evident zonal gradient over species and for the total of forests and other land classes.

Table 17. Density of above-ground litter by major forest-forming species and bioclimatic zone (1990), in kg C • m^{-2}.

Bioclimatic Zone	Major Forest-Forming Species										Other Vegetation	Total
	pine	spruce	fir	larch	cedar	birch	aspen	other trees	shrubs	Total Forest		
Polar desert	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.11
Tundra	9.92	0.00	0.00	8.42	0.00	2.59	0.00	0.00	3.23	3.52	3.12	3.12
Pre-tundra & northern taiga	16.86	21.97	0.00	13.68	19.43	18.24	17.13	10.36	8.57	15.83	8.82	13.07
Middle taiga	18.81	21.71	12.86	13.62	16.21	16.50	18.60	16.56	14.79	15.82	15.04	15.55
Southern taiga	13.95	16.50	15.57	12.21	14.38	13.44	14.50	10.38	13.87	14.11	12.00	13.26
Temperate forest	5.00	10.96	6.76	0.00	7.89	7.24	5.74	6.42	9.77	6.53	4.99	5.69
Steppe	0.73	0.00	0.00	0.00	7.51	0.76	5.07	0.43	0.70	1.34	0.75	0.79
Semi-desert & desert	4.27	0.00	0.00	0.00	0.00	1.53	0.00	1.57	0.92	1.74	0.58	0.63
Total	16.28	20.67	13.67	13.59	16.09	14.51	14.54	9.80	13.37	14.96	8.34	10.41

The total actual forest litter is estimated to contain 11421.5 Tg C, which gives an average density of 1.496 kg C • m^{-2} (Table 17). Litter of other classes of natural vegetation is estimated to hold 5,482.2 Tg C for the area of 657.0 million ha, i.e., an average density of 0.83 kg C • m^{-2}. Of the latter value, 88% is located in or to the north of the middle taiga zones. Our estimate for the above-ground litter for all land classes covered by natural vegetation is 16,903.3 Tg C (Table 18).

Table 18. Above-ground litter pool by major forest-forming species and bioclimatic zone (1990), in Tg C.

Bioclimatic Zone	Major Forest-Forming Species										Other Vegetation	Total
	pine	spruce	fir	larch	cedar	birch	aspen	other trees	shrubs	Total Forest		
Polar desert	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Tundra	0.6	0.0	0.0	1.7	0.0	1.4	0.0	0.0	9.7	13.4	814.1	827.5
Pre-tundra & northern taiga	367.2	524.8	0.0	983.9	141.5	141.1	4.8	1.4	69.5	2,234.2	796.5	3,030.8
Middle taiga	1,136.7	934.7	142.9	2,601.7	485.0	771.3	146.1	169.8	808.3	7,196.5	3,218.3	10,414.8
Southern taiga	575.4	291.9	81.1	93.0	46.2	516.3	155.6	23.9	1.2	1,784.7	604.5	2,389.2
Temperate forest	15.3	2.0	0.8	0.0	20.6	31.9	14.0	92.2	2.0	178.7	23.0	201.8
Steppe	1.5	0.0	0.0	0.0	0.7	2.2	5.8	0.8	0.2	11.2	21.8	33.0
Semi-desert & desert	0.6	0.0	0.0	0.0	0.0	0.4	0.0	1.1	0.2	2.2	4.0	6.2
Total	2,097.2	1,753.5	224.8	3,680.4	694.0	1,464.5	326.3	289.1	891.2	11,421.1	5,482.2	16,903.3

We did not find any estimates for total above-ground litter for the entire country in available publications. Alexeyev and Birdsey (1994) provided a detailed inventory for forests. They reported 13,848.9 Tg C in forest litter for an area of 771.1 million ha (in 1988). This yields a density of 1.796 kg C • m^{-2}, or 12.0% above our estimate, which is very close to our estimated “potential” amount of litter.

3.2.7 Carbon pool of below-ground dead vegetation (dead roots)

We estimated below-ground dead vegetation organic matter (below-ground mortmass) by using methods corresponding to the phytomass calculation (Section 3.2.1). The total amount of below-ground mortmass is estimated at 19.65 Pg of dry weight, of which forests comprise 40.1%, swamps and bogs 21.4% and non-forest vegetation 38.4% (Table 19). Thus, the total carbon content of below-ground dead vegetation is estimated to be 8,841.9 million tons. The table shows an evident zonal gradient of below-ground dead vegetation.

Table 19. Distribution of below-ground dead vegetation by bioclimatic zones and carbon density (1990).

Bioclimatic Zone	Area (10^6 ha)	Below-Ground Mortmass (Tg, dry matter)						Total Carbon Content Density, kg • m^{-2}	
		Agri-cult-ural land	Forests	Wetlands	Grass-land & shrubs	Total dry matter	Total carbon	Dry matter	Carbon
Polar desert	0.7	0.0	0.0	0.0	0.1	0.1	0.0	0.01	0.01
Tundra	266.9	0.0	55.6	1,630.5	2,928.1	4,614.2	2,076.4	1.73	0.78
Pre-tundra & northern taiga	233.0	0.1	1,249.8	1,585.3	443.1	3,278.3	1,475.2	1.41	0.63
Middle taiga	683.6	0.2	4,996.1	655.6	3,494.3	9,146.2	4,115.8	1.34	0.60
Southern taiga	211.5	1.8	1,271.7	274.6	272.8	1,820.9	819.4	0.86	0.39
Temperate forest	60.4	2.0	193.2	10.5	34.8	240.5	108.2	0.40	0.18
Steppe	148.4	1.2	108.8	43.8	309.0	462.8	208.3	0.31	0.14
Semi-desert & desert	25.4	0.6	15.5	10.3	59.3	85.7	38.6	0.34	0.15
Total	1,629.8	5.9	7,890.7	4,210.6	7,541.5	19,648.7	8,841.9	1.21	0.54

3.3 Agricultural Products

The agricultural products pool is a subdivision of the agricultural phytomass pool. The total carbon content of the agricultural products pool is estimated to have been 478 Tg C in 1990, split between products for consumption by livestock and by humans.

3.4 Forest Products

A separate analysis conducted as part of FOR's overall study (Obersteiner, 1999) estimated the stock of carbon sequestered in forest products to be 725.8 Tg C in 1990. For this calculation, consumption and production patterns were traced back to the year 1928. Carbon pools prior to this date were estimated to be 503 Tg C, based on rough per capita stock estimations of rural and urban population. Fiber flows from the forest and within the forest industry were reconstructed by using various production statistics and domestic trade data. Fiber flows of product baskets to the end-user and re-flows were calculated for the major economic activities. For the carbon calculations the study identified fiber carbon pools for each of 10 economic activities; the deposition of each pool varied with respect to time and pattern. Results are provided on a regional basis for all 89 subjects of the Russian Federation. Due to accumulation and rapid increase in the use of long-lasting timber products, the formation of carbon stocks due to forest product consumption follows an exponential path. More details on methodology and results are given in Obersteiner (1999).

3.5 Summary of 1990 Pools

The total phytomass of Russian terrestrial ecosystems is estimated to have been 81,799.5 Tg of dry matter or 39,945.8 Tg C in 1990. An additional 4,955.9 Tg C were stored in coarse woody debris and 8,841.9 Tg C in dead below-ground organic vegetation. This means that the carbon in all Russian vegetation is estimated to have been 53,743.6 Tg C in 1990. If the forest products pool of 725.8 Tg C is added, the total pool is 54,469.4 Tg C. If the organic soil carbon pool in the 0–1.0 m layer (292,868.2 Tg) is taken into account, the total pool for 1990 adds up to 347,337.6 Tg C (Table 20).

It can also be concluded that some 84% of the total organic carbon is located in the 1 m topsoil layer and carbon of vegetation and forest products comprises about 12%. Two land-use classes—forests and grasslands and shrubs—comprise about 90% of all terrestrial organic ecosystem carbon. The carbon in dead plant organic matter (except litter) comprises about one-third of the carbon of the live phytomass of vegetation. Our estimates of organic carbon in the live vegetation of terrestrial ecosystems are significantly lower than all previously reported estimates.

Table 20. 1990 Pools, in Tg.

Aggregated Land Cover Classes	Area, 10^6 ha	Phytomass, million tons, dry matter					Total Organic Carbon, Tg	C Density, kg/m^2
		Green part	Woody part	Above ground	Below ground	Total		
Organic soil (0–100 cm)	1,582.0						292,868.2	18.51
Terrestrial products pools								
Cropland	130.3	883.1	0.0	883.1	557.9	1,441.0	648.5	0.50
Pastures	81.5	319.6	55.5	375.0	370.8	745.8	338.4	0.42
Total agricultural lands	211.9	1,202.7	55.5	1,258.2	928.7	2,186.8	986.8	0.47
Forests (SFA)	763.5	4,560.0	47,179.1	51,739.1	14,710.6	66,449.7	32,861.9	4.30
Forest products	N/A						725.8	
Swamps	105.8	515.3	1,329.5	1,844.8	972.5	2,817.3	1,334.3	1.26
Bogs	116.2	741.6	725.9	1,467.5	1,271.0	2,738.5	1,268.6	1.09
Total wetlands	222.0	1,256.9	2,055.4	3,312.3	2,243.6	5,555.8	2,602.9	1.17
Grasslands and shrubs	432.4	1,759.5	1,419.3	3,178.8	4,428.3	7,607.1	3,494.1	0.81
Total phytomass	1,629.8	8,779.0	50,709.3	59,488.3	22,311.1	81,799.5	39,945.8	2.45
Carbon Total for Phytomass	1,629.8	3,950.6	25,354.6	29,305.2	10,640.6	39,945.8	39,945.8	2.45
Coarse woody debris	1,629.8			9,911.8			4,955.9	0.30
Below-ground dead vegetation	1,417.9				19,648.7		8,841.9	0.54
Total plant carbon	1,629.8	8,779.0	50,709.3	69,400.1	41,959.8	81,799.5	53,743.6	3.30
Non-vegetative land	79.6							
Total Pool	1,709.4						347,337.6	20.32[1] 21.31[2]

Notes. [1] Average for all Russian land (1709.4 million ha). [2] Average for carbon-related land (1629.8 million ha).

The majority of the carbon of the terrestrial ecosystems is located in the forest land class (Table 21), especially in stemwood including bark (58%). The middle taiga bioclimatic zone contains 57% of the total carbon of phytomass. The majority (65.2%) of the vegetational carbon is stored in the above-ground wood and 10.2% in green parts of the vegetational ecosystems. We estimate the average Russian phytomass density to be 5.02 kg • m^{-2} for vegetative lands (based on 1629.9 million ha) or 2.45 kg C • m^{-2}.

Table 21. Distribution of phytomass carbon (Tg C) by bioclimatic zones (1990).

Zone	Area, 10^6 ha	Agricultural land			Forest	Wetlands			Grass-land and Shrubs	Total	Density, kg/m^2
		Crop	Pasture	Total[1]		Swamps	Bogs	Total			
Polar desert	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.05
Tundra	266.9	0.0	6.1	6.1	53.5	376.9	68.8	445.7	1,210.9	1,716.2	0.64
Pre-tundra & northern taiga	233.0	1.2	3.5	4.7	3,375.3	393.8	347.8	741.6	223.7	4,345.3	1.87
Middle taiga	683.6	26.9	29.7	56.7	20,586.7	502.6	475.4	978.0	1,604.1	23,225.5	3.40
Southern taiga	211.5	141.8	47.1	188.9	6,832.1	41.1	360.2	401.3	221.1	7,643.3	3.61
Temperate forest	60.4	107.6	40.6	148.2	1,635.8	13.9	14.2	28.1	22.7	1,834.8	3.04
Steppe	148.4	351.4	142.6	494.0	354.6	4.1	1.7	5.8	175.8	1,030.2	0.69
Semi-desert & desert	25.4	19.4	69.0	88.4	23.9	1.9	0.5	2.4	35.5	150.2	0.59
Total	1,629.8	648.5	338.4	986.9	32,861.9	1,334.3	1,268.6	2,602.9	3,494.1	39,945.8	2.45[2]
Mean Density	1,629.8	0.50	0.42	0.47	4.30	1.26	1.09	1.17	0.81	2.45[2]	

Notes.[1] The total and average for agricultural land also include 78.4 million tons of dry matter on land used by the human population (orchards, vineyards, summerhouse plots, etc.), with a total area of 2.56 million ha. [2] Average for the lands covered by vegetation (1630.06 million ha).

3.6 Comparison with Other Estimates

A significant number of publications are devoted to estimates of the soil carbon content in Russia. Details can be found in Orlov *et al*. (1996). The same authors estimate the organic soil carbon in the 0–100 cm layer to be 296,000 Tg, which is close to our estimate of 292,868.2 Tg.

As noted above, we estimated the average density of phytomass of terrestrial biota for vegetative land of Russia to be 5.02 kg • m^{-2}, and for the total land area of Russia to be 4.79 kg • m^{-2}. This corresponds to 2.45 and 2.34 kg C • m^{-2}. Because some publications do not explicitly state which land area they used, we use for comparison below the average of our estimates, i.e., 2.39 kg C • m^{-2}.

The average global estimate of phytomass is 4.64 kg ± 0.64 C • m^2 (Schlesinger, 1977; Atjay *et al*., 1979; Goudriaan and Kettner, 1984; Olson *et al*., 1985; Polgasse and Wang, 1992; Cramer and Solomon, 1993; and Goldwijk *et al*., 1994: Smith *et al*., 2000). Our result for Russia is only 52% of this average. The differences between our findings and recently reported model results are even greater. The IMAGE 2.0 estimate for the CIS countries (Goldwijk *et al*., 1994) is 4.9 kg C • m^2. Calculations for Russia based on these data result in 5.9 kg C • m^2.

From these results, we conclude that all existing global vegetation models overestimate the total biome phytomass for the boreal zone by a factor of 1.5 to 2. We present a couple of recent examples. The Terrestrial Ecosystem Model (TEM, Version 3, McGuire *et al*., 1993; Melillo *et al*., 1993) for grasslands and coniferous forests (McGuire *et al*., 1996) estimates the average C density of Russian forests to be 6.56 kg C • m^2.

During the last decade, estimates of Russian phytomass that were calculated based on results published by Bazilevich (1993a, b) have been widely used and cited. These estimates exceed ours by at least two times, but such a comparison is hardly useful, because Bazilevich's data are presented for so-called *restored vegetation cover*. Thus, Bazilevich's data are an approximate estimate of *achievable* productivity and not actual productivity. We estimate the phytomass of untransformed (undisturbed) vegetation in pre-industrial times to be 104.8 Pg of dry matter. This should be compared with FOR's estimate for 1990 of 81.8 Pg of dry matter. Thus, human use of land has resulted in a decrease of the initial phytomass by about 30%. Text Box T.6 compares these findings.

Previously reported results for particular land classes, specifically for forests, are much more numerous. Two phytomass estimates for the total Russian forest, based on SFA data of 1988, have previously been reported (Alexeyev and Birdsey, 1994; Isaev *et al*., 1995). The average carbon density calculated by Isaev *et al*. (1995) was 4.55 kg C • m^{-2} (+5.7% compared to our results). The corresponding figures calculated by Alexeyev and Birdsey (1994) are 3.63 kg C • m^{-2} (–13.6%).

Dixon *et al*. (1994) estimated C densities for the vegetation of Russian forests to be 8.3 kg C • m^{-2} versus 4.30 kg C • m^{-2} in our estimate. For the forest biome of the former USSR Kolchugina and Vinson (1993a) report 6.3 kg C • m^{-2}. An estimate by Whittaker and Likens (1973) for boreal forests is 9.00 kg C • m^{-2}. Bonnor (1987) reported the above-ground tree phytomass density to be 5.90 kg • m^{-2} (dry matter) for all Canadian forests; this can be compared with our average of 6.34 kg C • m^{-2} for all of Russia.

Alexeyev and Birdsey (1996) estimated the carbon storage in Russian peatland ecosystems to be 116 Gt C. We can compare this to our sum of 140 Tg C.

Text Box T.6 Comparison of data based on Bazilevich (1993), IIASA estimates of pre-industrial phytomass dry matter pools, and IIASA estimates of 1990 terrestrial biota phytomass pool. All values in Tg.

Bazilevich (1993a) estimates potential phytomass and NPP for all of Russia by vegetation classes. Our VEG database can be used to make a very similar estimate, since it describes a pre-industrial distribution of Russian vegetation (see table below).

Bioclimatic Zone	Bazilevich (average estimate), Tg	IIASA Pre-Industrial, Tg	IIASA 1990, Tg
Polar desert	2	2	1
Tundra	11,013	4,035	3,770
Pre-tundra & northern taiga	20,920	10,546	8,930
Middle taiga	79,215	58,259	47,236
Southern taiga	45,736	21,582	15,560
Temperate forest	12,678	7,615	3,754
Steppe	6,406	2,396	2,221
Semi-desert & desert	907	373	328
Russian Total	176,877	104,808	81,799

Comparing these estimates to our current estimate of the 1990 terrestrial biota pool we see two factors affecting the amount of phytomass. The first is our more detailed estimation of forest phytomass, based on the SFA. The second deals with forest transformation. Stolbovoi *et al.* (1998) found that over 275 million ha of pre-industrial forest has been converted to non-forest or has been strongly affected by anthropogenic activities, principally in the middle and southern taiga and temperate bioclimatic regions.

Whittaker and Likens (1973) estimated vegetation carbon for temperate grasslands to be 0.700 kg. This is very close to our estimate for grasslands and shrubs.

The average of seven global estimates of dead biomass amounts to 10.9 ± 0.95 kg C per m^2 and year. For the former Soviet Union IMAGE 2.0 estimated 11.3 kg C per m^2, and Kolchugina and Vinson (1993b, c) estimated for the forest biome 24.1 kg C per m^2. Our results are significantly lower (see Table 20).

3.7 Uncertainties in the 1990 Pool Estimates

An important issue affecting the estimated carbon pools of 1990 is the uncertainty of the estimates. In Section 2.5 we described how we tried to treat the issue of uncertainty by first assessing the precision in a formal manner. This precision assessment was later used as the platform for simplified expert estimates of the uncertainties. We estimated the carbon pool in 1990 to have been 347,338 Tg C. The precision assessment of this pool is based on a statistical estimate of the precision values using primary inventory data; it is presented in Table 22. The precision estimate has a range of 326,617 to 368,058 Tg C. This precision estimate is extended to an uncertainty assessment in Table 23. The uncertainty estimate is limited to (1) changes in area resulting from the integration of soil-vegetation classification in the GIS and (2) the uncertainties discussed in Section 11, which we used as a first-order estimate of the thematic uncertainty components of Table 23. This uncertainty of the carbon pools in 1990 is assessed to be 14%, which gives a range of the carbon pool of 299,476 to 395,199 Tg C. However, the full-scale uncertainty may be even greater.

Table 22. Precision of 1990 Pool Estimate.

Pool	Sub-pool	Estimated Pools, Tg	Precision (%)				Precision, Tg C	Range, Tg C	
			thematic	area	other	total		low	high
Forest products		726	14.3		4.7	15.1	109	617	835
Soil C pool		292,868	3.5	5.0	3.5	7.0	20,605	272,263	313,473
Terrestrial biota	agriculture	987	2.5	1.0	2.5	3.7	36	951	1,023
	forest	32,862	3.5	1.0	3.5	5.0	1,659	31,202	34,521
	wetland	2,603	4.5	5.0		6.7	175	2,428	2,778
	grasslands & shrubs	3,494	4.5	7.0		8.3	291	3,203	3,785
Coarse woody debris		4,956	7.0	3.5		7.8	388	4,568	5,344
Below ground dead vegetation		8,842	14.0	5.0		14.9	1,314	7,527	10,156
TOTAL		**347,338**					**20,720**		
Precision							**6%**		

Table 23. Uncertainty of 1990 Pool Estimate.

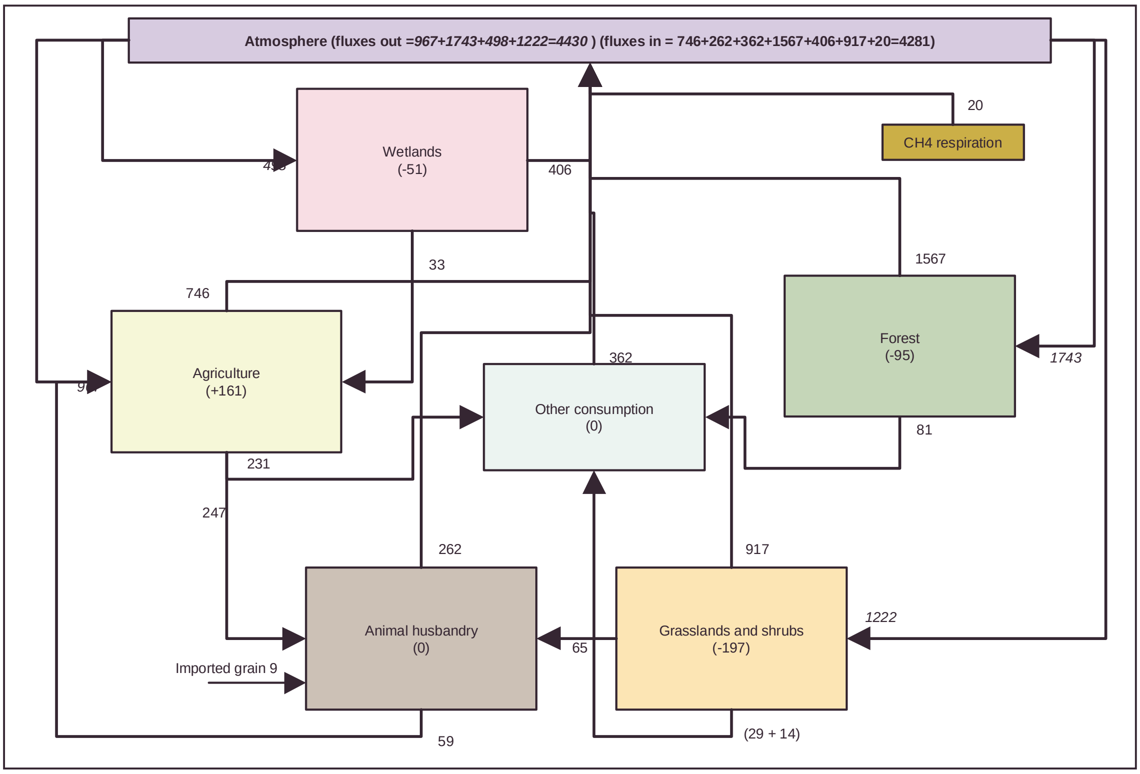
Pool	Sub-pool	Estimated Pools, Tg	Uncertainty (%)				Uncertainty Tg C	Range, Tg	
			thematic	area	other	total		low	high
Forest products		726	40.0			40.0	290	435	1,016
Soil C pool		292,868	3.5	5.0	15.0	16.2	47,427	245,441	340,296
Terrestrial biota	agriculture	987	2.5	10.0	15.0	18.2	180	807	1,166
	forest	32,862	3.5	10.0	15.0	18.4	6,035	26,827	38,897
	wetland	2,603	4.5	10.0	15.0	18.6	484	2,119	3,087
	grasslands & shrubs	3,494	4.5	10.0	15.0	18.6	649	2,845	4,143
Coarse woody debris		4,956	7.0	3.5	15.0	16.9	838	4,117	5,794
Below ground dead vegetation		8,842	14.0	5.0	15.0	21.1	1,867	6,975	10,709
TOTAL		**347,338**					**47,862**		
Uncertainty							**14%**	**299,476**	**395,199**

4. Carbon Fluxes, 1990

4.1 Modular Approach

Figure 13 summarizes the fluxes between atmosphere and terrestrial ecosystems for 1990. The following sections examine the individual modules of this figure, with the exception of the soil fluxes, which will be discussed separately.

Figure 13. Fluxes between atmosphere and terrestrial ecosystems (1990).



4.2 Soil Fluxes

Soils interact with the atmosphere, biosphere, hydrosphere, and lithosphere through the exchange of energy and/or substances. Organic transformation processes, such as decomposition of organic matter generated by photosynthesis together with the mineralization and formation of humus, are the major actors in carbon turnover within an ecosystem. These transformations of organic matter could be associated with carbon fluxes that might occur in solid, liquid or gaseous forms. Some 5–10% of the annually produced dead phytomass is subject to humification (Chagina, 1970; Bazilevich, 1993b; Glazovskaya, 1996). The rest passes mainly through biochemical metabolisms resulting in CO_2, CH_4 releases or inputs to the water solution. The mineral carbon ions arrive with atmospheric precipitation generated by biotic or abiotic processes.

This section focuses on major natural and human-impacted soil carbon fluxes. It considers gas emissions, humification, interflows between dissolved organic and mineral carbon in the soil, and estimates of agricultural fluxes.

1. The calculations of gas (CO_2, CH_4) emissions are based on soil areas derived from GIS characteristics and measured mean daily flows excluding live root and microbe respiration. Thus, our estimate of soil respiration is an aggregated estimate for the heterotrophic soil respiration. Mirchink and Panikov (1985) and Blagodatskiy *et al*. (1993) estimate the relationship between root respiration and total soil respiration to be roughly 1:3 in g • m^{-2} and day. The number of biologically active days (days with mean daily temperature >0° C) was calculated by Leemans and Cramer (1991).
2. Humification was calculated by humification coefficients taken from publications (Grishina, 1986) and according to bioclimatic zones. The amounts of postmortal vegetation residues were derived from phytomass fraction calculations and GIS areas.
3. Dissolved organic and mineral carbon soil interflows were calculated from average concentrations of soluble organics found through lysimeter measurements. The amounts of penetrating water were calculated by a simplified water balance model and based on Leemans and Cramer (1991) and associated with soil GIS areas. The runoff coefficients for the estimation of the surface organic flows were derived from different publications (e.g., Glazovskaya, 1996; Vinogradov *et al.*, 1998).
4. Estimation of agricultural fluxes follows the IPCC manual (IPCC, 1997). The fluxes were linked with corresponding GIS estimates and with statistical data on land accounts and other factors.

4.2.1 Gas emissions

The calculations of the CO_2 flux (SCF_{CO2}) used the following formula:

$$SCF_{co2} = \sum_q SCF_{qco2} * D_q * A_q \qquad (4.1)$$

where:

SCF_{co2} is the heterotrophic-soil C-CO_2 flux from soils of Russia;

SCF_{qco2} is mean daily CO_2-emission for a soil type *q*;

D_q is number of days with mean daily temperature above 0^0C (biologically active) by soil types;

A_q is soil area as measured from the SOIL database.

To determine the CH_4 fluxes (SCF_{CH4}) we used soil type areas calculated on the basis of GIS and annual mean CH_4 respiration emission rates. These were based on our futher elaboration of a database presented originally by Rozanov (1995):

$$SCF_{CH4} = \sum_q SCF_{qCH_4} * A_q \qquad (4.2)$$

where:

SCF_{CH4} is the total soil CH_4-C flux from soils of Russia;

SCF_{qCH4} is annual mean CH_4-C emissions for a soil type *q*;

A_q is soil area as measured from the SOIL database.

The heterotrophic CO_2-C flux from all Russian soils is estimated to be 3,197.5 Tg C (see Table 24). This estimate is close to the estimate of 3,120.5 Tg C made by Kudeyarov *et al*. (1996). Kudeyarov later (1999) estimated the CO_2-C flux to be 4,293 Tg C. Following our own detailed analysis of databases for soils (Stolbovoi *et al.*, 1997) and climate parameters (Leemans and Cramer, 1991), we conclude that Kudeyarov (1999) overestimated the duration of the respiration period substantially, which resulted in an estimate of strongly increased CO_2-C emissions.

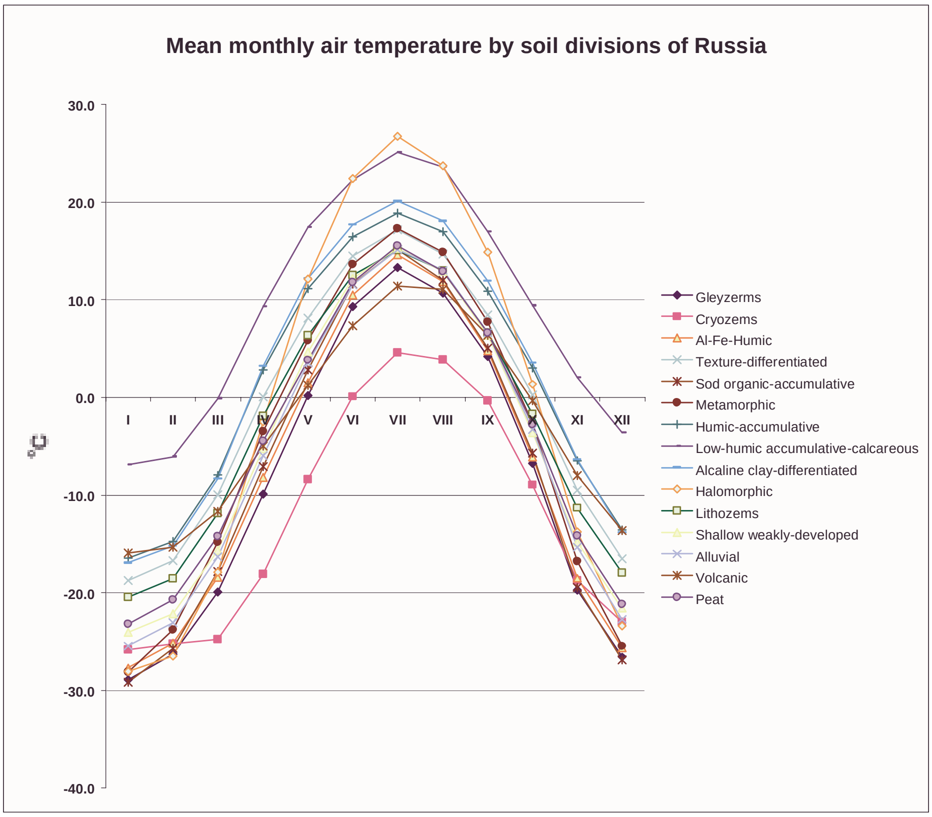
Table 24. CO_2-C and CH_4-C emissions by soil divisions (1990), in Tg.

Soil Division	Weighted Number of Days	CO_2-C			CH_4			CH_4-C,
		Tg C	$g \cdot m^{-2} \cdot d$	% of total	Tg C	$g \cdot m^{-2} \cdot d$	% of total	Tg C
Alkaline clay-differentiated	210	10.6	0.35	<1	0.00	<0.01	<1	0.00
Al-Fe-humic	150	766.2	1.19	24	0.00	0	0	0.00
Alluvial	150	84.4	0.91	3	3.09	0.06	12	2.32
Cryozems	90	4.3	0.44	<1	0.00		0	0.00
Gleyzems	150	165.3	0.40	5	15.76	0.06	59	11.82
Halomorphic	180	1.6	0.03	<1	0.02	0.01	0	0.02
Humic-accumulative	210	628.6	1.96	20	0.00	<0.01	<1	0.00
Lithozems	150	2.9	0.39	<1	0.00	0	0	0.00
Low-humic accumulative-calcareous	180	12.8	0.80	<1	0.00	<0.01	<1	0.00
Metamorphic	150	413.0	1.02	13	0.23	<0.01	1	0.17
Peat	150	292.6	1.44	9	7.24	0.06	27	5.43
Shallow weakly developed	150	24.3	0.34	1	0.00	0	0	0.00
Sod organic-accumulative	150	159.6	0.92	5	0.00	<0.01	<1	0.00
Texture-differentiated	210	614.1	0.91	19	0.27	<0.01	1	0.20
Volcanic	150	17.0	0.56	1	0.00	0	0	0.00
Total		3,197.5		100	26.61		100	19.96

Humus-accumulative and texture-differentiated soils are the major sources of gas emissions, providing about 50% of total CO_2-C fluxes (Table 24). We found no relationship between the contribution of CO_2-C by soils and the carbon density of soils. Instead, the contribution seems linked to such climate parameters as temperature and moisture, which is in line with other findings (e.g., Raich and Potter, 1995). This means that the size of the SCP itself is an insufficient basis for assessment of the carbon release to the atmosphere by soils.

The total CH_4-C emissions from Russian soils are estimated to be 19.96 Tg C (Table 24), which corresponds to an estimate by Zelenev (1996). Zavarzin and Vasilieva (1998) report that the Russian estimates of CH_4-C emissions may vary between 5 and 100 Tg. The CH_4-C flux is very soil specific and is mainly associated with soils that have reduction processes and gleyic properties. Peat, gleyzems and alluvial soils have the highest rate of emission; nearly 60% of the CH_4-C emissions are caused by gleyzems. Thus, FOR estimated the total flux for all Russian land to be 3,197.5 Tg of CO_2 and 19.96 Tg of CH_4-C. Text Box T.7 shows our estimates of the mean monthly temperature according to the soil divisions of Russia.

Text Box T.7 Aggregated, area-weighted mean monthly temperature by soil divisions of Russia: estimate of the period of time with temperature > 0º C.



The curves illustrate that the soil thermal regimes are similar for all soils of Russia. The variation in temperature is great and varies between 20º C in summer and -25º C in winter. The duration of the period with a mean temperature above 0º C varies from 90 days (cryozems) to 280 days (low humic-accumulative calcareous soils).

The middle taiga bioclimatic zone contributes most of the CO_2-C emissions from soils: about 1,200 Tg, or 38% of the total (Table 25). Emission intensity increases southward with increased temperature and moisture conditions. In relative terms, the steppe zone is the most intense emitter of CO_2-C. This zone occupies 9% of the total soil area, but provides almost twice the amount of emissions, whereas the tundra bioclimatic zone occupies 16% of the soil area and generates only 11% of the emissions.

Table 25. CO_2-C emissions from soils by bioclimatic zones (1990), in Tg C.

Bioclimatic Zone	Area covered by soils, 10^6 ha		CO_2-C Tg	
			Million tons	% of total
Polar desert	0.7	0	0.2	0
Tundra	266.9	16	342.2	11
Pre-tundra & northern taiga	233.0	14	329.8	10
Middle taiga	683.6	42	1,201.4	38
Southern taiga	211.5	13	481.0	15
Temperate forest	60.4	4	218.6	7
Steppe	148.4	9	559.3	17
Semi-desert & desert	25.4	2	64.9	2
Total Country	1,629.8	100	3,197.5	100

FOR estimated the annual average emission of CO_2-C gases by soils in 1990 to be 0.196 kg • m^{-2} • yr^{-1} (Table 26). Croplands have the highest average rate of emissions (0.374 kg • m^{-2} • yr^{-1}).

Table 26. Estimates of CO_2-C emissions by land classes (1990), in Tg C.

Land Class	Area, 10^6 ha	CO_2-C Emissions, Tg	Annual Flux Intensity (kg • m^{-2} • yr^{-1})
Cropland	130.3	488.3	0.375
Pasture	81.5	176.7	0.217
Total Agriculture	211.9	665.0	0.314
Forest	763.5	1,365.0	0.179
Wetlands	222.0	368.6	0.166
Grasslands & shrubs	432.4	799.0	0.185
Total Country	1,629.8	3,197.5	0.196

4.2.2 Humification

Humification is a process of deep transformation of postmortal organic residues that results in the formation of stable compounds of organic matter in soils, sediments and waters, i.e., humic substances, a specific component of humus (Orlov, 1990; Stevenson, 1994; Ziechmann, 1994). Various chemical and biological transformation reactions are involved—oxidation, hydrolysis, mechanical decomposition, condensation etc. The rate of humification depends geographically upon a variety of factors affecting the living conditions of microbiota, such as quantity and quality of plant foliage, climatic and soil conditions, etc. (Orlov, 1990). The time factor is very important, because the total amount of humus increases proportionally by the period of time (Orlov, 1990).

Our study uses rough estimates on the humification rate in Russia (Grishina, 1986; Fokin, 1986; Orlov, 1990). The rate of humification has been averaged to 6% of the annual postmortal organic residues for tundra, pre-tundra and northern taiga zones and, to 8% for the rest of the forest zones. We assume that the humification rate for steppe and semi-desert zones is about 10% of the postmortal organic residues.

The total amount of the carbon stock going into soil humus is estimated at 272.8 Tg C. The biggest proportion of the humified organic matter (about 102 Tg C) goes to the middle taiga soils. The second largest humus generator are soils (about 58 Tg C) of the steppe bioclimatic zone, which have well-developed deep humus horizons.

The forest vegetation provides about 114 Tg C of humus per year (Table 27) that corresponds to about 42% of total humification. This amount is less than the share of forest area in the country (about 45%). Contrary, agricultural land contributes by about 24% of total amount of the humified organic matter. The contribution is two times more than the relative extent of agricultural land (about 12%). Thus, croplands are more effective humus generators than forests.

Table 27. Humification rate in soils of Russia by bioclimatic zone and land cover patterns, in Tg C • yr^{-1}.

Bioclimatic Zone	Agriculture			Forest	Wetland			Grass-land & Shrubs	Grand Total
	Crop-land	Pasture	Total		Swamps	Bogs	Total		
Polar desert	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tundra	0.0	0.2	0.2	0.4	2.8	3.2	6.0	16.1	22.7
Pre-tundra & northern taiga	0.1	0.1	0.2	14.2	2.1	2.3	4.4	3.0	21.8
Middle taiga	1.8	1.4	3.2	68.2	4.7	4.4	9.1	21.7	102.2
Southern taiga	9.4	1.7	11.1	21.2	0.9	3.3	4.2	5.4	41.9
Temperate forest	7.1	1.4	8.5	6.4	0.0	0.4	0.4	2.9	18.2
Steppe	29.1	8.5	37.6	3.7	0.5	0.3	0.8	16.3	58.4
Semi-desert & desert	1.6	4.1	5.7	0.1	0.0	0.0	0.0	1.8	7.6
Total Country	49.1	17.4	66.5	114.2	11.0	13.9	24.9	67.2	272.8

4.2.3 Dissolved organic substances

Dissolved organic substances (DOS) are abundant in soils formed under the influence of cold humid climates and boreal forest vegetation. DOS in Russian soil solutions vary from 50 to 100 mg • L^{-1} depending upon soil texture (Djakonova, 1972; Ponomareva and Plotnikova, 1972). Thurman (1985) reported that the concentration of DOS in groundwater on average varies between 30–100 mg • L^{-1} and Glazovskaya (1996) reports a variation of 80–100 mg • L^{-1}, although colored groundwater (associated with cold humid climates and generated by peat and gleyic soils) might exceed 1000–10,000 mg • L^{-1} (Thurman, 1985). Our estimate of the flow of the DOS from soils of Russia considers organics carried by river flows (surface runoff) and by interstitial water of soils or migrated soil solutions.

4.2.3.1 Organics carried by surface runoff

Sedimentation in the Arctic Ocean is an important part of the terrestrial carbon budget because of the irreversible carbon flows (Rachold, 1999; Stern *et al*., 1999). Vinogradov *et al*. (1998) estimate the organic material carried by river flows to the Arctic sea to be 23.4 Tg C • yr^{-1}. This amount includes both DOS and mechanically transported organic substances based on a catchment area of 1,257 million ha. Assuming that the total amount of carried organics in Russia is in a proportion with these figures for the above catchment area we estimate the net organic flow carried by Russian rivers to be 30.3 Tg C • yr^{-1}.

4.2.3.2 Mineral carbon carried by soil interflows

Glazovskaya (1996) reports the annual runoff volume of mineral HCO_3^- ions per km^2 of the taiga zone to be 20 tons annually. Following this, it is reasonable to assume that the annual runoff volume of mineral HCO_3^- ions per km^2 for other zones is about 6–8 tons. Based on these rough assessments, we can estimate the total migration of mineral DOS from the territory of Russia to be 280 million tons (238 million tons for taiga + 52 million tons for all other zones), or roughly 56 Tg C.

4.2.3.3 Organic carbon carried by soil interflows

For humid forest regions—mainly in the boreal zone, where gleyic and peat soils occur widely—the average content of DOS is about 50-100 mg • L^{-1} depending on soil texture (Djakonova, 1972; Ponomareva and Plotnikova, 1972; Glazovskaya, 1996). Peats have 50 mg • L^{-1} (deep peat) and 25 mg • L^{-1} (shallow peat) solutions. We use these figures to estimate the organic carbon interflows.

We calculated only the interflows for forest zone soils and split atmospheric precipitation into cold (mean monthly temperature < 0 ^oC) and warm (mean monthly temperature > 0 ^oC) periods. We assumed that all precipitation during the cold season formed surface runoff, while precipitation during the warm season partly evaporated and partly infiltrated the soil; moreover, we assumed that the average precipitation/evaporation ratio (humidity coefficient) was 1:3. By applying this coefficient, we corrected the precipitation amounts for major soil divisions. The above-mentioned values for concentrations of DOS in soil solutions were used for estimation of the dissolved organic carbon (Table 28).

Table 28. Estimate of dissolved organic carbon interflows in major soil divisions of the Russian boreal forest zone.

Soil Division	Precipitation, mm				Dissolved Organic Carbon	
	Annual	Cold period	Warm period	Percolated	mg/L	Tg C
Metamorphic	565	194	371	86	100	18
Texture-differentiated	564	165	399	92	100	23
Peat	509	207	302	70	50	4
Gleyzems	416	164	252	58	100	15
Al-Fe-humic	503	194	309	71	50	13
Total	2557	924	1633	377		73

The estimate of total flows of DOS from soils of Russia shows that about 73 Tg C go to the unsaturated vadose zone and groundwaters. This amount accords with the average concentration in the underground runoff of about 50-100 mg • L^{-1}. Thus, a considerable amount of organic carbon is precipitated in loose deposits in various geochemical barriers.

4.3 Fluxes in Terrestrial Biota

This section describes our methods and results of terrestrial biota flux estimations.

4.3.1 Net primary production—methods

In this report, NPP is defined as an amount of live organic matter produced by vegetation on area per unit of time (Odum, 1971; Bazilevich, 1993a). In the calculations we used an annual time step. This assumption is rather rough because the lifespan of fine roots varies from months to years depending on vegetation type and climatic conditions (e.g., Vogt *et al*., 1996; Jackson *et al*., 1996; Schulze *et al*., 1999), but such a time step is usually used in large-scale estimates (Jackson *et al*., 1997). Aggregated estimates are presented in Tg C • yr^{-1} (dry matter of carbon), and averages (densities) in kg • m^{-2} yr^{-1} (dry matter or carbon).

The different current methods for NPP estimation for large territories (i.e., statistical, climatic models, gap-models, ecophysiological models of carbon fluxes, e.g., using the chlorophyll index, remote sensing methods based on the normalized differential vegetation index measurements, and others) have specific advantages and (sometimes significant) shortcomings (Goetz, 1997; Mokronosov, 1998). Our objective was to estimate the actual NPP of terrestrial biota for the definite period of 1990.

We calculated the NPP of the Russian terrestrial biota in the following way. For all land classes (excluding forests, cropland and pastures) estimations were made by using equation (4.5) with average NPP data for the same fractions and classification units as for phytomass. For cropland and pastures we assumed an annual life cycle, i.e., production was assumed to be equal to phytomass.

This approach results in a first approximation of NPP for some "quasi-stable" status of the ecosystems. In order to "update" this estimate, we tried to take into account the most important natural and anthropogenic impacts for the studied period, 1988–1992. We used a simple expert system to estimate the increase of NPP in northern ecosystems (in particular, on permafrost) after disturbances, of which the main sources are fires and mechanical destruction of surface layers due to industrial exploitation. The features of this increase are well described (e.g., by Fetcher *et al*., 1984; Sedykh, 1999, Zimov *et al*., 1999): (1) fires of medium intensity destroy the upper thick layer of surface organics, (2) disturbances improve thermic and hydrological conditions of sites, (3) disturbances increase the active soil layer, and (4) disturbances increase availability of nutrients, particularly, for fine roots (Chen and Harmon, 1999).

The numerical description of the spatial distribution of this process is approximate because only a relatively small number of direct measurements exist, and large areas are situated in territories that are not monitored with respect to fires. Remote sensing data for the majority of the Russian territory exist only for 1987, 1992 and 2000 (Cahoon *et al*., 1994 and 1996; Streets, 2000). For estimation of impacted Forest Fund areas, we used regional data of the SFA for the period 1961–1993 and the approach described in Shvidenko and Nilsson (2000a, b); for tundra and subarctic areas the estimates were done by analogy with adjoining Forest Fund areas. Forest Fund areas include both areas covered by forests and areas not covered by forests that could be used for future forestry production under certain conditions: examples are water reservoirs, bogs, and steep slopes (see Nilsson *et al*., 1992).

The above-mentioned expert system was also used to estimate the impact of drainage of wetlands. The increase of NPP by drainage of eutrophic and mesotrophic bogs and swamps could be significant (Vompersky *et al*., 1975; Valetov, 1992). Finally, using data on seasonal distribution of disturbances, we accounted for part of the NPP produced but lost on the disturbed areas during the year of the estimate. For example, under normal conditions zoogenic consumption of NPP is about 1–3% of phytomass of auxiblasts and 2–4% of production of needles (Glazov, 1979). For this reason, in addition to results calculated using the VEG database method, we provided independent estimates of gross and net growth and mortality of forests based on detailed forest inventory data and a specifically developed modeling system. Methods and results have been published earlier (Shvidenko *et al*., 1995; 1997), and here we only use findings of this research for comparison.

4.3.2 Aggregated estimate

The total NPP generated by vegetation in Russia in 1990 (a "quasi-stable" state) was estimated by the VEG database method to be 8,752.7 Tg • yr^{-1} of dry matter or 4,082.6 Tg C. The updating calculations added 591.0 Tg • yr^{-1} of dry matter, or 270.8 Tg C • yr^{-1}. This means that actual NPP of terrestrial ecosystems in 1990 was estimated to be 9,543.7 Tg C • yr^{-1} of dry matter, or 4353.4 Tg C • yr^{-1}. Table 29 and Table 30 show the distribution of 1990 NPP by land classes and bioclimatic zones in dry matter and carbon units, respectively; Table 31 presents carbon densities for the same distribution. Our results show that forests generate the major part of NPP (39.2% by carbon content). Grassland and shrubs 27.6% and agricultural land contributes 22.0%.

Table 29. Distribution of NPP by land classes and bioclimatic zone (1990), in Tg • yr^{-1} (dry matter).

Bioclimatic Zone	Agricultural Land			Forest	Wetlands			Grass-land & Shrubs	Total
	Crop-land	Pasture	Total		Swamps	Bogs	Total		
Polar desert	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Tundra	0.0	10.0	10.0	13.9	188.5	35.2	223.7	468.9	716.5
Pre-tundra	2.8	7.3	10.1	504.2	128.4	154.6	283.0	116.5	913.8
Middle taiga	59.9	62.8	122.7	2,165.5	143.0	213.2	356.1	1,188.1	3,832.4
Southern taiga	315.1	80.5	395.6	689.1	11.6	161.8	173.4	266.7	1,524.7
Temperate forests	239.2	62.6	301.8	195.8	5.0	8.0	13.0	55.3	565.9
Steppe	781.0	350.9	1,131.9	96.8	12.3	4.7	16.9	505.5	1,751.0
Semi-desert & desert	43.1	111.5	154.6	7.1	5.3	1.4	6.7	61.8	230.2
Total	1,441.0	685.6	2,126.6	3,679.3	496.0	578.9	1,075.8	2,663.0	9,543.7

Table 30. Distribution of NPP by land classes and bioclimatic zone (1990), in Tg C • yr^{-1}.

Bioclimatic Zone	Agricultural Land			Forest	Wetlands			Grass-land and Shrubs	Total
	Crop-land	Pasture	Total		Swamps	Bogs	Total		
Polar desert	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Tundra	0.0	4.5	4.5	6.4	85.3	15.9	101.2	211.9	323.9
Pre-tundra	1.2	3.3	4.5	231.6	58.8	70.1	128.9	52.7	417.7
Middle taiga	26.9	28.3	55.3	1,004.3	65.4	96.6	161.9	536.6	1,758.1
Southern taiga	141.8	36.3	178.1	325.5	5.3	73.3	78.6	120.2	702.4
Temperate forests	107.6	28.2	135.9	91.8	2.3	3.6	5.9	24.9	258.5
Steppe	351.4	157.9	509.3	44.6	5.6	2.1	7.7	227.5	789.0
Semi-desert & desert	19.4	50.2	69.6	3.2	2.4	0.6	3.0	27.8	103.7
Total	648.5	308.8	957.2	1,707.3	225.0	262.2	487.2	1,201.7	4,353.4

The average NPP density is estimated as 267 g C • m^{-2} yr^{-1}, based on 1629.8 ha of vegetated land (Table 31). Cropland has the highest productivity in the country at 498 g C • m^{-2} yr^{-1}. The average NPP density for forests is 224 g C • m^{-2} yr^{-1}, and for wetlands 219 g C • m^{-2} yr^{-1}. Grassland and shrubs produce 278 g C • m^{-2} yr^{-1}. The table shows an evident zonal gradient in the spatial distribution of NPP. The steppe zone has the highest productivity (532 g C • m^{-2} yr^{-1}); productivity of polar desert and tundra are 1.3% and 22.9%, respectively, of the NPP density in the steppe zone.

Table 31. Density of NPP by land classes and bioclimatic zone (1990), in kg C • m^{-2} yr^{-1}.

Bioclimatic Zone	Agricultural Land			Forest	Wetlands			Grass-land and Shrubs	Total
	Crop-land	Pasture	Total		Swamps	Bogs	Total		
Polar desert	0	0	0	0	0	0	0	8	8
Tundra	0	245	245	168	160	178	162	106	121
Pre-tundra	404	260	288	164	208	192	199	207	179
Middle taiga	507	304	378	221	308	237	261	353	257
Southern taiga	587	325	504	257	326	257	260	616	332
Temperate forests	508	342	461	347	378	310	333	932	428
Steppe	468	430	456	482	1,091	966	1,053	854	532
Semi-desert & desert	449	386	402	254	929	867	916	431	409
Total	498	379	452	224	213	226	219	278	267

As a control calculation of the results presented above, FOR used information based on forest increment to estimate above-ground woody NPP (Text Box T.8).

Text Box T.8: Growth and Mortality

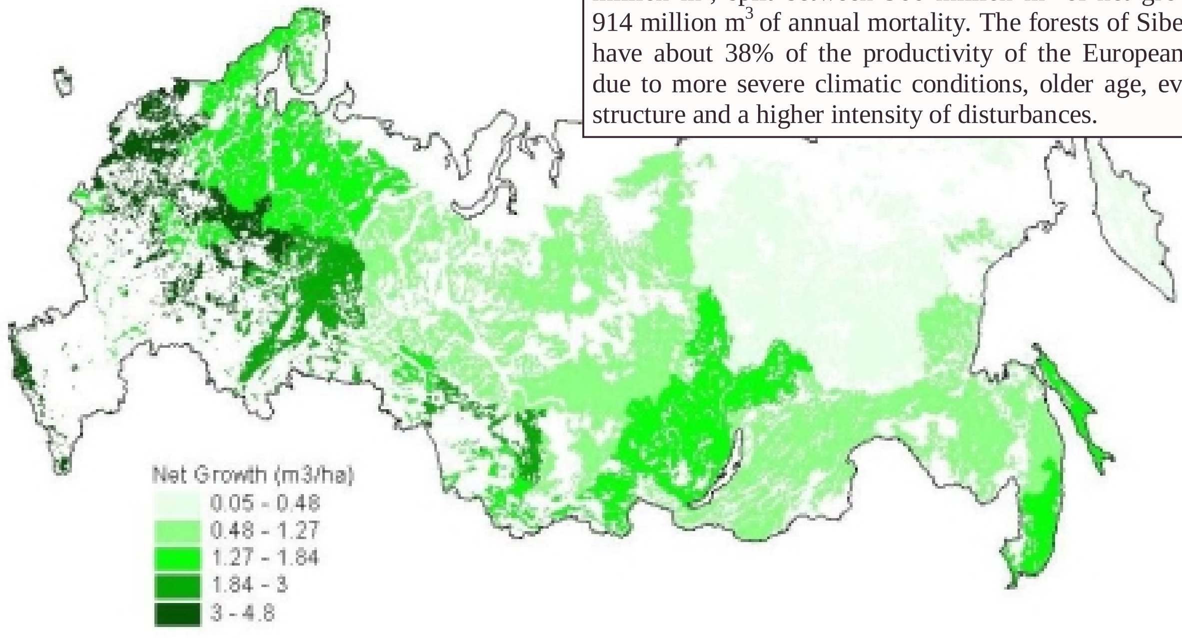
Gross growth is the total volume of stem wood over bark produced by a stand during a given year and net growth is the difference between growing stock volumes at the end and the beginning of year. These two indicators are respectively the (stem) woody part of the NPP and the NEP of forest ecosystems—the difference between them is the actual mortality. In order to calculate increment of crown we used partial derivatives for age by multidimensional regression equations of phytomass fractions, average age and site indices by group species for ecoregions. The gross growth was estimated at 1,880 C • m^{-2} yr^{-1} (Shvidenko *et al.*, 1997), increment of crown wood comprised 2.7% of the gross growth, average density of above ground woody NPP 956 Tg dry matter (with estimated average woody density of 495 kg • m^{-3}) or 478 Tg C • yr^{-1}. This estimate gives a 5.9% higher estimate compared to the VEG database method estimate.

Russian Geographic Division	Average cubic meters per hectare		
	Net Growth	Mortality	Gross Growth
Europe	2.51	2.25	4.76
Siberia	0.92	0.90	1.82
Total	1.27	1.19	2.46

Our results present the first mean aggregated estimate of growth and mortality for all Russian forests. Comparing the Russian SFA estimate of 1993 for average growth shows a good correspondence with the results of this report.

Estimate Source	million cubic meters per year	
	Growing Stock	Net Growth
SFA	73,028	830
Adjusted SFA	80,676	917
This Study	80,676	966

As shown in this map, at the beginning of the 1990s, the gross growth of stem wood of the Russian forests was about 1880 million m^3, split between 966 million m^3 of net growth and 914 million m^3 of annual mortality. The forests of Siberia only have about 38% of the productivity of the European Russia due to more severe climatic conditions, older age, even-aged structure and a higher intensity of disturbances.



4.3.3 Fluxes caused by disturbances in forests, 1990

4.3.3.1 Model

Fluxes generated by disturbances were estimated based on a unified model, in which the disturbance ρ (fire, infestation by insects and diseases, etc.) generates the total carbon flux $TCF_{\rho,t1}$ during a year t_1 (for annual time steps) (Shvidenko and Nilsson, 2000b):

$$TCF_{\rho,t1} = DF_{\rho,t1} + PDF_{\rho,t<t1} + RG_{\rho,t<t1} \quad (4.4)$$

where $DF_{\rho,t1}$ is the direct flux during the year t_1, $PDF_{\rho,t<t1}$ is the post-disturbance (as a rule biogenic) flux generated by disturbance ρ that occurred during previous years $t < t_1$, and $RG_{\rho,t<t1}$ represents post-disturbance fluxes caused by site restoration processes and regrowth. The values of $DF_{\rho,t1}$ and $PDF_{\rho,t<t1}$ as well as the explicit form of equation (4.4) depend on type, strength and scale of ρ, conditions under which ρ occurs, and type and specifics of the ecosystem, as well as on the approach and structure of the model used. For example, for forest fire the direct flux is defined as:

$$DF(t_1') = \sum_{ilkq} [C_{ilkq} \cdot S_{ilkq} \cdot (FC)_{ilkq}]_{t1} \gamma \quad (4.5)$$

where C_{ilkq} are the coefficients for the consumed forest combustibles during the fire, S_{ilkq} is the estimate of burned vegetation areas, $(FC)_{ilkq}$ is the storage of forest combustibles (tons per ha; dry matter), and γ is the coefficient for recalculation of dry organic matter to carbon units (for details, see Shvidenko and Nilsson, 2000b). The indexes are: i = territorial units; l = land-cover classes; k = forest fire types; and q = forest combustible types.

Using a simple exponential model to describe the decomposition, the post-fire biogenic flux during year t_1 caused by fires during previous years due to decomposition of both unburned residuals and post fire die-back (mortality) can be estimated by:

$$(PDF)_{ij}(t_1) = 1.05\chi\left[\exp(\alpha_{ij}) - 1\right] \cdot \sum_{\tau=0}^{\phi+1} O_{ij}(t-\tau) \cdot \exp(-\alpha_{ij}\tau) + \delta\,\mathrm{SOC}, \quad (4.6)$$

where δ, $0 < \chi < 1$, is the share of carbon from decomposed organic matter that is taken up by the atmosphere, $\phi = \mathrm{int}\left[T_{0.95}\right]$ (the integer part of $T_{0.95}$), the time required for decomposition of 95% of organic matter O_{ij} annually coming into decomposition pool j, α_{ij} is the constant of decomposition, τ is the difference between year of previous fire and year of emission accounting, and δSOC is the change of soil organic carbon during year t_1.

4.3.3.2 Disturbances

Most fluxes generated by disturbances are related to forests (Shvidenko *et al.*, 1996; Shvidenko and Nilsson, 2000a, b). Five basic types of disturbances affect 10–15 million ha of the Russian Forest Fund annually and influence the carbon fluxes. These disturbances are forest fires, pest and disease infestations, harvests, land-use changes, and, in some regions, industrial pollution (Shvidenko and Nilsson, 2000a, b).

Quantitative analysis of the extent and level of disturbances during the last 20 years (Shvidenko et al., 1996; Shvidenko and Nilsson, 2000a, b) reveals that the major impacts from disturbances in the Russian Forest Fund are: (1) increased share of pyrogenic, anthropogenic and biogenic forest successions, as well as increased extent of secondary forests; (2) decreased actual (or current) productivity and quality of forests; (3) changed formations of uneven-aged forests; (4) appearance of specific, sometimes irreversible, features of the forest forming processes; and (5) generally negative changes of biodiversity at ecosystem and landscape levels. The length of historical reconstruction relevant to estimating the impact of these disturbances on forests, could reach 100–200 years for northern subzones of the boreal zone based on average zonal indicators of vegetational organic decomposition (Table 32).

Table 32. Indicators of the decomposition rates used in flux calculations.

Zone	Fast Pool [1]		Medium-Fast [2]		Slow Pool [3]	
	α_{i1}	$T_{0.95}$	α_{i2}	$T_{0.95}$	α_{i3}	$T_{0.95}$
S & T	0.038	78.8 (50–110)	0.03	99.9	–	–
FT, SpT & MdF	0.072	41.6 (25–60)	0.043	69.7	0.017	176
Northern taiga	0.16	18.7 (15–35)	0.075	39.9	0.027	111
Middle taiga	0.32	9.4 (5–20)	0.097	30.9	0.03	100
Southern taiga	0.75	4.0 (2–8)	0.16	18.7	0.047	64
MxF, DF & FS	1.2	2.5 (1–5)	0.27	11.1	0.07	43
Steppe, semi-desert & desert	4.0	0.75 (0.2–1.5)	0.37	8.1	0.13	23

1 Fast pool comprises (dead) green part.

2. Medium-fast comprises the woody part with the diameter at the top end less than 8 cm and more than 1 cm.

3. Slow pool comprises the large (> 8 cm) woody parts of trees; α_{ij} is the coefficient of the exponential model of decomposition and $T_{0.95}$ is time of decomposition of 95% of initial amount of organic.

Abbreviations: S & T—subarctic areas and tundra; FT, SpT & MdF—forest tundra, sparse taiga, and meadow forests; MxF, DF & FS—mixed forests, deciduous forests, and forest steppe.

Disturbances in 1990 (as an average for the period 1988–1992) caused a flux from the Russian forests of 193 Tg C • yr^{-1}. Forest fires are estimated for Forest Fund areas and northern unused land of the State Reserve, other disturbances for Forested Areas. This estimate does not include site restoration processes and regrowth.

4.3.3.3 Fire

Stand-replacing disturbances affect an area of some 0.8–0.9 million ha annually identified by the Russian forest inventory as burned areas and dead stands. The high correlation between this indicator and the intensity and severity of disturbance regimes means that they can also be used for some indirect estimates of the non-stand-replacing disturbances. The dynamics of burned and dead forests for the period 1961–1993 suggest a strong suppression over time of the extent of fire as a major factor of disturbances. Data for forests under state forest management (about 95% of all Russian forests) show that areas of burned and dead stands decreased from 70.6 million ha in 1961 to 68.4 million ha in 1966, 53.6 million ha in 1973, 43.9 million ha in 1978, 36.8 million ha in 1983, 34.9 million ha in 1988, and 30.6 million ha in 1993.

Our estimate of the area burned annually during 1988–1992 by carbon-important types of fires is 3.5 million ha (Shvidenko and Nilsson, 2000a, b). We estimate direct fire emissions and post-fire biogenic fluxes occurring annually between 1988 and 1992 to be 58 Tg C • yr^{-1} and 64 Tg C • yr^{-1} respectively (Table 33 and Table 34). The direct emissions during the year of the fire are estimated as 1.66 kg C • m^{-2} • yr^{-1}. If we exclude peat fire from this amount, the average is 1.08 kg C • m^{-2} • yr^{-1}.

Table 33. Yearly average direct forest fire carbon emissions (1988–1992), in Tg C.

Subject/Type of Fire	Area 10^6 ha	Emissions (Tg C • yr^{-1})		
		Total	Incl. Vegetation	Incl. soils
Forested area	1.4	18.1	16.6	1.5
Of which crown fire	0.24	5.1	4.8	0.3
on-ground fire	1.16	13	11.8	1.2
Unforested areas	0.48	6.5	6.1	0.4
Vegetative non-forest lands	0.9	5.7	5.4	0.3
Low-productive non-forest lands	0.39	1	0.9	0.1
Peat fires	0.35	23.5	3.1	20.4
Below-ground fires	0.012	3.2	0	3.2
Total	3.532	58	32.1	25.9

Table 34. Average annual post-fire emissions in 1988–1992 resulting from decomposition of die-back caused by fires of previous years (1800–1988), in Tg C.

Vegetation Zone	Average Input Organic Matter for Decomposition (1990), by Pool				Average Total Post-Fire Emissions from Previous Years (1990), by Pool				
	Fast	Medium-fast	Slow	Total	Fast	Medium-fast	Slow	Soil	Total
SA & T	1.6	0.1	–	1.7	2.2	0.1	–	0.7	3.0
FT & SpT & MdF	2.3	0.3	1.8	4.4	2.9	0.4	2.8	2.0	8.1
NT	3.2	1.0	5.4	9.6	4.1	1.2	8.1	2.1	15.5
MT	4.6	1.6	7.4	13.6	6.8	2.0	10.9	2.4	22.1
ST	3.2	0.7	4.6	8.5	7.0	1.0	6.1	1.1	15.2
MxF & DF & FS	0.6	0.3	1.7	2.6	2.1	0.4	2.1	0.2	4.8
S & SD & D	0.3	–	–	0.3	0.3	–	–	0.1	0.4
Total	15.8	3.9	20.9	40.6	25.4	5.1	30.0	8.6	64.1

4.3.3.4 Pest outbreaks, diseases, and other biotic factors

The total area affected by pest and disease outbreaks is estimated to be about 4 million ha annually (Isaev, 1991; Nilsson and Shvidenko, 1998). No comprehensive and detailed inventory of these disturbances exists for the Russian forests. Rough and approximate estimates, based on available statistics, publications, and fragmentary data from different surveys, give about 74 Tg C • yr^{-1} as an average annual flux caused by insects and diseases during the period studied. If we take into account other biotic factors (e.g., damage caused by recreation, unregulated forest grazing, wild animals, etc.) the probable estimate is about 91 Tg C • yr^{-1}. Of this amount 9 Tg C • yr^{-1} are classified as fire carbon emissions and 8 Tg C • yr^{-1} as harvested and destroyed wood. Therefore, the final estimate of the C flux to the atmosphere due to biotic disturbances is 74 Tg C • yr^{-1}.

4.3.3.5 Harvest.

In this section we only discuss the direct site-located impacts of industrial harvests. The components taken into account are decomposition of harvest residuals, post-harvest die-back, and soil respiration. The biospheric emissions caused by the harvest (based on average annual harvests for the period 1988–1992) are estimated to be 16 Tg C • yr^{-1} (Shvidenko and Nilsson, 1996). The fluxes from the forest products sector will be discussed later in this report.

4.3.3.6 Abiotic impacts

Industrial pollution, land-use changes and unfavorable climatic conditions are the most important factors in abiotic impacts. There are no complete surveys of the extent and intensity of these processes covering all of the Russian Forest Fund area. Based on data for specific regions and expert estimations, we obtained a rough estimate of the carbon losses in live vegetation caused by different abiotic factors; the findings varied between 43 and 65 Tg C • yr^{-1}, with an average of 54 Tg C • yr^{-1}. Of this amount 25 Tg C • yr^{-1} are accounted for as use of harvested wood, increased coarse woody debris pool, fires, and landfills. Thus, the total fluxes caused by abiotic factors are estimated to be 29 Tg C • yr^{-1} (Nilsson and Shvidenko, 1998).

We estimated the total efflux generated by disturbances of forest ecosystems to be 193 Tg C in 1990. It should be pointed out that these data do not consider any short-term changes occurring as part of post-fire recovery processes. The latter is accounted for by other parts of the FCA.

4.3.3.7 Disturbances of wetlands, grasslands and shrubs

Disturbances of wetlands include wildfires and the use of peat for fuel and agricultural purposes. Our estimate of the emissions in 1990 is 56 Tg C; 40 Tg C due to usage (peat extraction, of which 33 Tg C is considered a flux in the agriculture module and 7 Tg C in the other consumption module) and 23 Tg C • yr^{-1} due to wildfires (Shvidenko and Nilsson, 2000a, b).

Fluxes generated by disturbances of natural grasslands and shrubs are estimated to be 46 Tg C • yr^{-1}, emissions generated by wildfires to be 39 Tg C • yr^{-1}, and industrial transformation of these lands to be 7 Tg C • yr^{-1}. In addition, losses of carbon amounted to 65, 29 and 14 Tg C for consumption by domestic livestock (considered an animal husbandry flux), domestic use and wild fauna (considered another consumption flux), respectively. A summary of the above-ground fluxes into the atmosphere as a result of disturbances is presented in Table 35.

Table 35. Summary of above-ground fluxes into the atmosphere due to disturbances, 1990.

Disturbance Type	Emissions, Tg	Type totals, Tg	Group totals, Tg
Fire			
Forest fire emission	58		
Post-fire biogenic flux	64		
Forest Fund Total	122		
Minus area accounted in wetlands	-14		
Minus area account in dead wood dynamic	-3		
Minus area account in charcoal dynamic	-5		
Minus area accounted in grasslands and shrubs	-25		
Subtotal		*74*	
Pest outbreaks, diseases and other biotic; all areas	91		
Minus area accounted in Forest Fund as burned	-9		
Minus amount accounted in forest products	-8		
Subtotal		*74*	
Harvest	16		
Subtotal		*16*	
Abiotic impacts, all areas	54		
Minus amount accounted in forest products	-25		
Subtotal		*29*	
Forest Disturbances Total			**193**
Wetlands			
Fire	23		
Agricultural Usage	33		
Domestic Usage	7		
Subtotal		63	
Grasslands and Shrubs			
Fire	39		
Transformation	7		
Subtotal		*46*	
Non-Forest Disturbances Total			**102**
GRAND TOTAL	**302**	**302**	**302**

The total above-ground fluxes into the atmosphere due to disturbances in Russia in 1990 are assessed to be 302 Tg C. They are considered as fluxes in the modules from which they enter the atmosphere.

4.4 Agricultural Products and Animal Husbandry

4.4.1 Fluxes from products of land management sector

We assume that all biomass produced annually by cropland and pastures is utilized and either released into the atmosphere in the form of CO_2 from agricultural products and byproducts or humified into soils. We exclude the harvested portion of phytomass from the humification process. The assessed harvest of agricultural products in 1990 is presented in Table 36.

Table 36. Assessment of harvested products (1990), in million tons.

Statistical Data	
Grain	116.7
Sugar beets	32.2
Sunflower (seed)	3.4
Potatoes	30.8
Vegetables	10.3
Fruits and berries	2.4
Meat	9.4
Milk	51.9
Eggs ($x10^9$)	46.9

Source: Romanenko, 1995

The harvested portion of the pasture phytomass is most probably returned though livestock respiration, enteric fermentation and excreta (manure—see Section 4.3.2.). The pasture byproducts are decomposed and released into the atmosphere or enrich soil organics. The amount of vegetation organic material required for the support of livestock is presented in Table 37. The assessment is based on data derived from Agriculture of Russia (1995), Romanenko (1995), IPCC (1995), and Jonas (1997).

Table 37. Amount of fodder carbon needed for the support of the livestock and livestock CO_2-C respiration (1990).

Livestock	Number in 1990, in million livestock units	Basic Fodder requirement, in Mg C • LU^{-1} • yr^{-1}	Basic Fodder Requirement, in Tg C	Total Fodder to Achieve the Basic Livestock Fodder Requirement	Respiration, Tg C
Dairy Cattle	20.5	2.10	43.0	49.5	
Non-dairy cattle	36.5	1.95	71.2	78.2	
Sheep and goats	58.2	0.50	29.1	31.4	
Swine	38.3	1.74	66.6	69.9	
Horses	2.6	1.90	4.9	5.6	
Reindeer	2.3	2.5	5.8	5.8	
Poultry	659.8	0.0045	4.8	5.1	
Other			10.0	11.0	
Total			235.4	256.5	163

LU: livestock unit

The total fodder requirements for support of livestock in 1990 is 257 Tg C, which is considered a flux in the animal husbandry module, and the emissions from livestock in the form of CO_2-C respiration is estimated as 163 Tg C (Table 37). The emissions of CH_4 from livestock (expressed in CH_4) are shown in Table 38.

Table 38. Livestock CH_4 emissions, in Tg.

Livestock	Number in 1990, million head	CH_4 Enteric Fermentation		CH_4 Emission Due to Manure Management		Total, Tg CH_4
		Emission factor (kg CH_4· head^{-1} ·yr^{-1})	Total Tg CH_4	Emission factor (kg CH_4· head^{-1} ·yr^{-1})	Total Tg CH_4	
Dairy cattle	20.5	81	1.66	6	0.12	1.78
Non-dairy cattle	36.5	56	2.04	4	0.15	2.19
Sheep and goats	58.2	7	0.41	0.17	0.01	0.42
Swine	38.3	1.5	0.06	4	0.15	0.21
Horses	2.6	18	0.05	1.39	0.0	0.05
Reindeers	2.3	18	0.04	1.39	0.0	0.07
Poultry	659.8	1.5	n.a.	0.078	0.05	0.05
Total	–	–	4.26	–	0.48	4.74

Source: Data based on IPCC emission factors, 1995.

The emission of CO_2 from enteric fermentation is estimated as be about 65% of the CH_4 emissions (Vashkutina *et al*., 1985). The total CH_4-C emissions from livestock are estimated to have been 3.6 Tg C in 1990. This is close to the estimate by the Russian Country Study (RFCCCS, 1997).

4.4.2 Application of manure and liming

Conventional land management in Russia is heavily based on application of organic (mainly manure) fertilizers. One study (Krylatov *et al*., 1998) estimates that, on average, each hectare of cropland of Russia should receive about 12 ton per ha and year of organic fertilizers in order to maintain a positive humus balance of the cultivated soil. The recent decrease in application of organic matter to 3.5 tons per ha (Agriculture of Russia, 1995) does not meet this standard, and has seriously decreased national yields.

The average annual production of manure in Russia during 1986–1990 was 450–460 million tons (Krylatov *et al*., 1998). Manure has a dry matter content of 0.3–0.7, depending on the type of manure (Popov, 1988). The rate of humification is usually 0.2, with a high extent of mineral fertilizer application 0.4 (Djakonova and Buleeva, 1987). The total average application of organic fertilizers was 481.9 million tons • yr^{-1} during the same period. In 1991 the application amounted to 347.2 million tons • yr^{-1} (Romanenko, 1995, RFCCCS, 1997). The emissions of CO_2 from organic fertilizers vary significantly due to temperature conditions during the vegetation period (Dmitrochenko and Pshenichny, 1975). The Russian Institute of Agriculture Radiology and Agroecology of the Russian Academy of Agriculture Sciences estimates the average CO_2 emissions from soils due to manure application to be 0.36 kg CO_2 • kg of manure (RFCCCS, 1997) or 0.098 kg C • kg^{-1} of applied manure.

The total application of organic fertilizers amounted to 430 million tons (390 million in the public sector and an additional 40 million tons in the private sector) in 1990. This amount is divided between 395 million tons of manure and 35 million tons of peat. With an average dry matter content of 0.5, an emission factor of 0.8, and carbon content of 0.3, the emissions to the atmosphere due to manure application are assessed to be 47 Tg C • yr^{-1}. The input to the soil carbon pool is estimated as 12 Tg C • yr^{-1}. These fluxes are considered as parts of the agricultural module.

About 33% of the cultivated soils of Russia suffer from excessive acidity. Application of lime is one of the common ameliorative measures in Russian agriculture. According to statistics 31.5 million tons of limestone ($CaCO_3$) were applied in 1990. We assume that this amount reacts completely with the soil solutions and created emissions of about 4 Tg of CO_2-C into the atmosphere in 1990. This, too, is counted as part of the agricultural module.

4.5 Forest Products

FOR developed a model to calculate stocks and fluxes of the Russian forest products sector (Obersteiner, 1999). The core of the model describes the flows of industrial wood, its transformation into forest consumption goods and its resilience in the consumption sector. The fuelwood component (commercial and noncommercial) is considered separately from the industrial wood model. Residues from harvesting and losses that remain in the biosphere are discussed in Section 4.3.3.5. External energy inputs to the forest sector are considered in Section 4.6.

Building upon the knowledge gained from analysis of the fiber flow and detailed description of consumption, we derived carbon emissions from the forest industrial sphere. The fluxes of the forest products sector have a number of components, as shown in Figure 14.

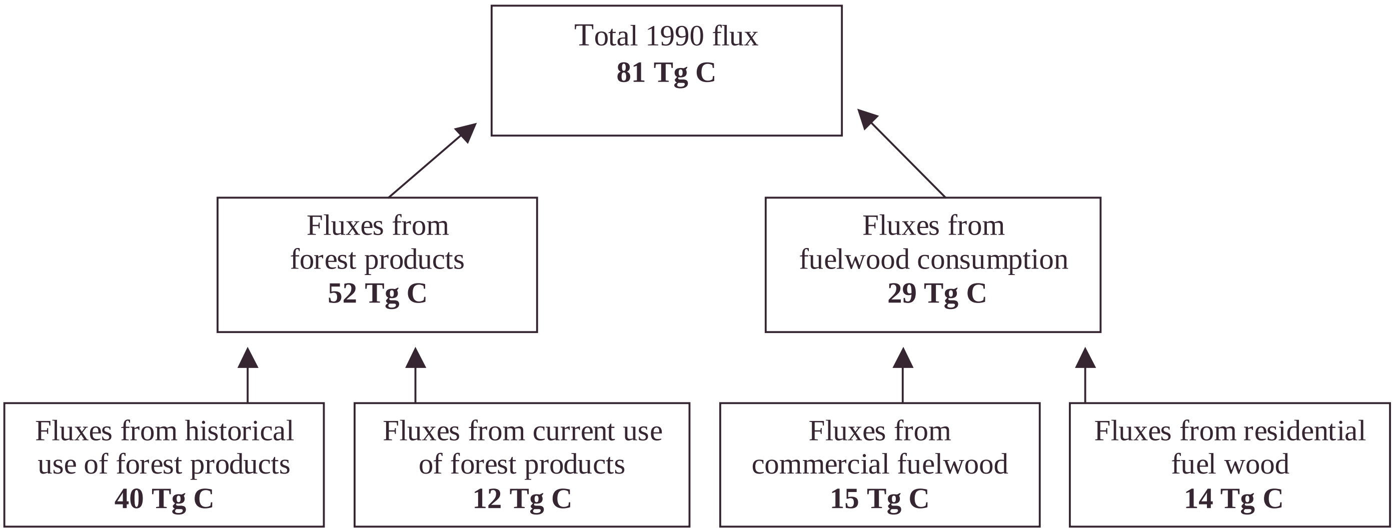


Figure 14. Composition of 1990 fluxes from the forest products sector, in TgC.

In total some 81 Tg C were emitted in 1990 due to current and past consumption of forest products. The major part of the emissions (52 Tg C) originates in the woodworking industry. Of this amount, 40 Tg C are due to past consumption of forest products (going back to 1928). Fuelwood accounted for a flux of 29 Tg C; half of the emissions stemming from commercial fuelwood and half from residential uses. These fluxes are considered in the biomass consumption module (see Table 46). For more details on the calculations see Obersteiner (1999).

4.6 Energy and Other Sector Fluxes

To estimate fluxes of the energy and other sectors of Russia, we relied on earlier work carried out by IIASA (Nakićenović *et al*., 1998). This work employed a number of different models. The starting point was population growth and per capita economic growth. This latter information is limited to a scenario generator, which combines extensive historical data on the national economy and the energy systems with empirically estimated equations of past economic and energy developments. Two other models were used interactively for testing the consistency of each scenario. For a more detailed description see Nakićenović *et al*. (1998).

Russia's emissions of carbon dioxide from combustion of fossil fuels amounted to 650 Tg C in 1990. On the basis of adjusted 1990 data presented by the International Energy Agency (1993), we estimated that Russia accounts for 63% of the Former Soviet Union emissions. The emission estimate is also consistent with historical data for the former Soviet Union compiled by Marland *et al*. (1994). For further details of the calculations see Nakićenović *et al*. (1998) and Victor *et al*. (1998).

4.7 Summary of 1990 Fluxes

Based on the assessments made in Section 4 we present a complete balance for 1990 in Table 39 to Table 46, corresponding to the modules identified in Figure 13. A detailed table of the fluxes in 1990 is presented in Appendix 5. This appendix also provides a comparison with other studies.

In the discussion below on the directions of different fluxes it should be underlined that throughout the discussion we assign a positive sign to fluxes going into the atmosphere and a negative sign to fluxes going out of the atmosphere. In a similar way we assign a negative sign to fluxes going out of a given subsystem to another subsystem and a positive sign to fluxes coming into a subsystem. We also present pool changes, which we consider as a "control" for our estimates of the total flux balances. For pool changes, however, a positive sign indicates an accumulation in a subsystem and a negative sign a decrease in the pool.

The agriculture sub-budget (Table 39) shows a total flux balance of –161 Tg C out of the sub-budget. At the same time, we find independently a net accumulation of 32 Tg C in the agricultural land pools.

Animal husbandry fluxes (Table 40) constitute only transfers from other modules equal to the fluxes into the atmosphere, and therefore a total flux balance into the atmosphere of 252 Tg C (source).

The human biomass consumption fluxes (Table 41) are made up of transfers from other modules equal to the fluxes into the atmosphere and amount to a total flux balance of 372 Tg C (source). Again we stress that there is a high degree of uncertainty in this module—products may be stored, imported or exported—but we consider this module a "filter" between other modules and the atmosphere.

The so-called horizontal fluxes (Table 42) we consider as pool changes of 264 Tg C. Thus, these fluxes are not taken into account in the atmosphere/ecosystem balance, but only in the balance for the pool changes. Horizontal fluxes are presented in this table only for purposes of illustration and can be found distributed among individual flux modules.

The forest fluxes (Table 43) constitute 1567 Tg C into the atmosphere and 1743 Tg C out of the atmosphere. Fluxes going out of the forest sub-budget amount to 81 Tg C in the form of consumption of forest products. At the same time there is an accumulation of the forest phytomass pools of 58 Tg C. This results in a total flux balance for the forest of -–95 Tg C (sink).

The wetland fluxes (Table 44) are 406 Tg C into the atmosphere and 498 Tg C out of the atmosphere. At the same time 40 Tg C is transferred out of the sub-budget and 38 Tg C is accumulated in the below-ground phytomass pools. This results in a total flux balance for the wetlands of –51 Tg C (sink).

The grassland and shrub fluxes (Table 45) are made up of 917 Tg C into the atmosphere and 1222 Tg C out of the atmosphere. At the same time there is a transfer out of the sub-budget of 108 Tg C and a net loss from the carbon pools of 3 Tg C. The total flux balance of the grasslands and shrubs module is –197 Tg C (sink).

Table 39. Agricultural land fluxes (1990).

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1
Above ground					Above ground NPP	545		
							Agricultural harvest to animal husbandry:	
							hay	-119
							grain	-50
							straw	-61
							grazing	-55
							residual to other consumption	-193
					Precipitation of C	10		
Below ground					below ground NPP	413		
			Erosion	-18				
							Manure from animal husbandry	59
							liming (emissions from 31.5 Tg)	4
							peat from wetlands	33
			humification of peat	2				
			humification of manure	12				
			humification	67				
	Soil C-CO2 respiration	664						
	Manure emission	47						
	Peat emission	31						
	Liming emission	4						
			Leaching	-17				
			Soluble SOC	-10				
			Surface runoff	-4				
	TOTAL FLUX	**746**		***32***		***967***		***-382***
	Total Flux Balance	161						

Note: Fluxes from imported grain and lime application are accounted separately from the modules although they are reported in the animal husbandry and agricultural modules.

Table 40. 1990 Animal husbandry fluxes.

Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1
						from agriculture	285
						from grasslands and shrubs grazed	65
Respiration	163						
Fermentation	5						
						meat (to other consumption)	5
						eggs (to other consumption)	5
Sub-products, wastes, etc.	19						
From grasslands and shrubs grazed	65						
						to other consumption	-29
						manure	-59
TOTAL FLUX	**252**						**252**
Total Flux Balance	0						

Table 41. 1990 Fluxes of human biomass consumption.

Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1
						Harvest from agriculture	193
						Residual from animal husbandry	48
						forest products	81
						Wetlands	7
						Land management & domestic consumption from grasslands and shrubs	29
						Wild fauna	14
Harvest from agriculture	193						
Residual from animal husbandry	48						
Forest products	81						
Wetlands	7						
Land management & domestic consumption from grasslands and shrubs	29						
Wild fauna	14						
TOTAL FLUX	**372**						***372***
Total Flux Balance	0						

Note: Fluxes from imported grain and lime application are accounted separately from the modules although they are reported in the animal husbandry and agricultural modules.

Table 42. 1990 Horizontal fluxes.

Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1
Erosion			-25				
Leaching			-136				
Soluble SOC			-73				
Surface runoff			-30				
TOTAL FLUX			-264				
Total Flux Balance							

Table 43. 1990 Forest fluxes

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1
Above ground					Above ground NPP	1,387		
	Disturbances							
	Fire	74						
	Pests	74						
	Harvest	16						
	Abiotic	29						
							Forest Products	-81
	Produced and Consumed NPP in year of dist.	7						
			phytomass	-43				
			CWD	94				
					precipitation of C	36		
Below ground					Below ground NPP	320		
			Humification	114				
			Charcoal	5				
	Soil C-CO2 respiration	1,363						
	Increase in soil respiration following drainage	4						
			Leaching	-64				
			Soluble SOC	-34				
			Surface runoff	-14				
	TOTAL FLUX	**1,567**		**58**		**1,743**		**-81**
	Total Flux Balance	-95						

Table 44. 1990 Wetland fluxes.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1
Above ground					Above ground NPP	307		
	Disturbances							
	fire	23						
							Peat usage to agriculture	-33
	Produced but consumed NPP	15						
							Domestic use	-7
					precipitation of C	10		
Below ground					Below ground NPP	181		
			Accumulation	46				
			Humification	25				
	Soil C-CO2 respiration	368						
			Leaching	-19				
			Soluble SOC	-10				
			Surface runoff	-4				
	TOTAL FLUX	**406**		**38**		**498**		**-40**
	Total Flux Balance	-51						

Table 45. 1990 Grassland and shrubs fluxes.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1	Description	Tg C•yr-1
Above ground					Above ground NPP	463		
	Disturbances							
	fire	39						
	transformation	7						
	Decomposition of above ground wood*	53						
	Produced but consumed NPP	20						
							Domestic livestock grazing	-65
							Land management & domestic consumption	-29
							Wild fauna	-14
			phytomass					
					precipitation of C	20		
Below ground					Below ground NPP	738		
			Erosion	-7				
			Humification	67				
	Soil C-CO2 respiration	798						
			Leaching	-36				
			Soluble SOC	-19				
			Surface runoff	-8				
	TOTAL FLUX	**917**		**-3**		**1,222**		**-108**
	Total Flux Balance	-197						

*includes wetland and perennial areas

Table 46. 1990 All module flux summary.

Module	Flux into Atmosphere, Tg C•yr^{-1}	Pool Change* Tg C•yr^{-1}	Flux out of Atmosphere, Tg C•yr^{-1}	Inter-module transfer from Modules, Tg C•yr^{-1}	Flux Balance into-out-Transfer, Tg C•yr^{-1}
Agriculture	751	32	967	-377	161
Animal husbandry	243			243	0
Biomass consumption	363			363	0
Forest	1,567	58	1,743	-81	-95
Wetland	406	38	498	-40	-51
Grassland & shrub	917	-3	1,222	-108	-197
Soil CH4-C Respiration	20				20
*Additional fluxes ** *	13			0	*13*
Atmosphere-ecosystems total	4,281	Accumulation 125	4,430	0	***-149***
Module	Flux into Atmosphere, Tg C•yr-1	Pool Change Tg C•yr^{-1}	Flux out of Atmosphere, Tg C•yr^{-1}	Inter-module transfer from Modules, Tg C•yr^{-1}	Flux Balance into-out-Transfer, Tg C•yr^{-1}
Energy and other sectors	676	0	0	676	0
Fossil fuel		-676		-676	0
GRAND TOTAL	**4,957**	**Loss -551**	**4,430**	**0**	***527***

Note: Fluxes from imported grain and lime application are accounted separately from the modules although they are reported in the animal husbandry and agricultural modules. With respect to the fossil fuels in the Pool Change assessment we assign a "zero pool" (no storage) for the fossil fuels and continue to use the expression "Pool Change."

5. Carbon Balances, 1990

In the course of this study, FOR produced two different carbon balances. Table 46 presents the total flux balance and what we call the "pool change balance." The total flux balance is the difference between the fluxes into the atmosphere, the fluxes out of the atmosphere, and the transfers of carbon (in the form of products) from the modules. The total flux balance (including energy and other industrial processes) shows Russia to be a net source of 527 Tg C emitted into the atmosphere in 1990. If only the total flux balance of the atmosphere and ecosystems are considered, the ecosystems served as a net sink of 149 Tg C in 1990.

The pool change balance (Appendix 5 and Table 46) shows a net accumulation (sink) of 125 Tg C in 1990 if only the atmosphere and ecosystems are considered. If the energy and other industries are taken into account the pool losses are 551 Tg C. Therefore, our study shows a rather good correspondence in the estimates between the total flux balance and the pool changes, with a difference of only 24 Tg C. Table 47 summarizes the different balances assessed in our study and in Table 46.

Table 47. Summary of Assessed Carbon Balances for 1990.

	Including ecosystems, energy and other industrial processes	Only ecosystem related fluxes excluding energy and other industrial processes
Total Flux Balance	Source of 527 Tg C	Sink of 149 Tg C
Pool Change Balance	Source of 551 Tg C	Sink of 125 Tg C

5.1 Comparison with Other Studies

While it is possible to make some comparisons between the results of other studies (e.g., Zavarzin, 1998) and our balances, these other studies reflect only partial accounting and not FCA. Previously reported studies also differ from our estimates because they used different classifications, geoinformatic sources, and approaches. In the following discussion, we will compare our results with other studies and by that also indicate the uncertainties in the results presented. Appendix 5 presents earlier studies by other research teams.

As shown in Table 46, our study found that the total fluxes into the atmosphere in the atmosphere/ecosystem balance amounted to 4957 Tg C in 1990 (including energy and other industrial processes). Studies carried out by other institutions, based on PCA, estimated these total fluxes at 635–875 Tg C in 1990 (see Appendix 5). However, these studies cover only parts of the FCA. For example, when energy and other industrial processes are included, these studies estimate Russia to be a net source of 584 Tg C in 1990. If only the ecosystem-related fluxes are considered, Russia is assessed to be a net sink of 94 Tg C in 1990.

We estimated the total fluxes out of the atmosphere in 1990 as 4430 Tg C (Table 46). The studies by other institutions, based on PCA, estimated these fluxes to be 157–185 Tg C. The vegetation-soil system and human use of biological products in 1990 caused emissions of 4281 Tg C. The major source was soil respiration with emissions of 3218 Tg C.

The average of 14 estimates on the global NPP, mainly based on different dynamic global vegetation models (Whittaker and Likens, 1973; Whittaker and Marks, 1975; Atjay *et al*., 1979; Goudriaan and Ketner, 1984; Olson *et al*., 1985; Esser, 1987, 1991; Box, 1988; King *et al*., 1992; Seino and Uchijima, 1992; Polgasse and Wang, 1992; Melillo *et al*., 1993; Potter *et al*., 1993; Goldwijk *et al*., 1994), is 0.398 ± 0.052 kg C • m^{-2} • yr^{-1}. These results exceed our data by about 1.5 times for the obvious reason that they include far more productive tropical vegetation in the global estimates. Recent estimates by IMAGE 2.0 for countries of the former USSR show 0.354 kg C • m^{-2} • yr^{-1} (Goldwijk *et al*., 1994).

There are very few estimates of NPP for all terrestrial vegetation of Russia, but many studies report on NPP of different zones, land classes and vegetation types. Here we present a short comparative analysis. Terrestrial vegetation NPP for all Russia, using the chlorophyll index method, has been estimated at 4409.7 Tg C • yr^{-1}; the uncertainty of the result is estimated at ±15–25% (Voronin *et al*., 1995; Mokronosov, 1998). This practically coincides with our result; the difference is about 1%.

For the tundra zone of Russia, Kolchugina and Vinson reported 109 g C • m^{-2} • yr^{-1} (1993a, b, c), and Karelin *et al*. and Zamolodchikov and Karelin (1998) reported estimates of 125 g C • m^{-2} • yr^{-1} on NPP (1995). The referenced sources above have not been included in our databases, and could be considered as an independent control of our estimate of 122 g C • m^{-2} • yr^{-1} for the tundra zone.

We estimated the average NPP for boreal forests by using 10 available sources (Whittaker and Likens, 1973; McGuire *et al*., 1993; Mellilo *et al*., 1993; Potter *et al*., 1993; Warnant *et al*., 1994; Woodward *et al*., 1995; Ruimy *et al*., 1996; Denning *et al*., 1996; Lloyd, 1999; Schulze *et al*., 1999), taking into account their estimate of areas of coniferous and deciduous species in Russia at 267± 89 g C • m^{-2} • yr^{-1}, which is about 12% more than our estimate. Significantly higher is the average NPP of the above references for temperate forests: –475 g C • m^{-2} • yr^{-1} versus 375 g C • m^{-2} • yr^{-1} in our estimate. These differences are not surprising, given the large variability among the referenced estimates (e.g., from 123 to 419 g C • m^{-2} • yr^{-1} for boreal coniferous forests).

For all (tall) grasslands, McGuire *et al*. (1996) estimate the average NPP density as 335 g C • m^{-2} • yr^{-1}, and the estimate by Whittaker and Likens (1973) is 225 g C • m^{-2} • yr^{-1}. We have a NPP density for grassland and shrubs of 279 g C $m^{-2}yr^{-1}$, and 453 g C $m^{-2}yr^{-1}$for agricultural land.

Several studies report NPP estimates for peatlands, which represent a unique type of land class that can provide a long-term record of C accumulation. The estimates of NPP of peatland vary significantly (Bazilevich, 1993a, b; Vompersky *et al*., 1994; Varlygin, 1998), as do estimates of the C accumulation rate. The average accumulation rate is estimated as 31.5 g C • m^{-2} • yr^{-1}, with variation from 12 g C • m^{-2} • yr^{-1} for polygonal mires to 72–80 g C • m^{-2} • yr^{-1} for fens and marshes (Botch *et al*., 1995). These studies further showed 22 g C • m^{-2} • yr^{-1} for all Russian bogs (Vompersky, 1994) and 14 g C • m^{-2} • yr^{-1} for deep bogs (Vompersky *et al*., 1998). Our estimate of C accumulation in the wetland land class is close to the Vompersky (1994) estimate, namely 21 g C • m^{-2} • yr^{-1}.

Other publications have defined a set of indicators of the FCA as net ecosystem production (NEP) and net biome production (NBP). We do not use this terminology.

Some data have been gathered for other boreal forests on net ecosystem exchange (NEE) of CO_2, which combines plant metabolics and soil activities. For mature spruce-lichen subarctic woodland (northern Quebec), the CO_2 exchange during the growing season was estimated as 0.065 kg C • m^{-2}, for Alaskan tundra and for temperate deciduous forest the estimate for the total year was 0.300 kg C • m^{-2} • yr^{-1} (Wofsy *et al*., 1991, 1993; Moore, 1996). The average NEE estimate from eight flux studies in temperate coniferous and deciduous forests is 272 g C • m^{-2} • yr^{-1}. The estimate for four boreal coniferous forests in the same study is 46 g C • m^{-2} • yr^{-1} (EEC, 1997). For the total growing season the NEE in a 200-year Siberian pine stand was estimated as a sink of 0.060 kg C • m^{-2}; two bogs in Siberia and European Russia were estimated as a sink of 60 g C • m^{-2} and summer (Schulze *et al*., 1999). By contrast, over the same period, a spruce forest in European Russia was estimated as a net source with a NEE of 0.084 kg C • m^{-2} and summer (Schulze *et al*., 1999).

The estimates referenced above present interesting information for comparison of indicators of production, measured and estimated by different methods for different sites. However, they are not reliable for aggregated estimates of large territories because (1) the number of sites measured was small, (2) the results depend strongly on site and seasonal weather conditions, and (3) the impacts of disturbances are not taken into account.

6. Scenarios

6.1 General Assumptions

To illustrate the possible future development of the pools and fluxes, and to study possible changes during the commitment period for the Kyoto Protocol (UNFCCC, 1998), FOR generated three different scenarios covering the period 1990–2010. The overall objective of these scenarios is to identify possible lessons to be learned from the Russian case study for the implementation of the Kyoto Protocol. However, in this process we do not follow the details of the Kyoto Protocol, but simply study the changes of the pools and fluxes during the relevant period. Within this framework it is important to point out that the biological systems of the carbon budget have a “warm start” in 1990; in other words, the 1990 conditions are a result of historical development.

In order to work with consistent scenarios for the system studied in the FCA, we built the scenarios around the possible economic development of Russia between year 2000 and year 2010. The current state of Russia is characterized by a deep economic, social and moral crisis (e.g., Glasiev, 1997; Council of Russian Federation, 1998; Nilsson, 2000). These sources identify a number of basic concerns with respect to future development: non-profitability of the majority of the branches of the Russian economy, destruction of existing capital (rent seeking), extremely low level of new investments, criminalization of economic activities, lack of functioning institutions, declining social services and networks, etc. These conditions in themselves create huge uncertainties about the future development of the Russian society and economy, yet these developments constitute some of the driving forces for the development of the carbon balance.

FOR created the scenarios based on figures used by Nakićenović *et al*. (1998) to generate long-term energy scenarios, as discussed earlier. The scenarios were reformulated into three scenarios, summarized in Table 48.

Table 48. GDP growth assumptions for Russia (GDP in 1990 = 100).

Scenario	Growth Rate	
Mean	1.054766	From 50% to 100% within 13 years
Lower	1.026220	From 50% to 70% within 13 years
Higher	1.069663	From 50% to 120% within 13 years

Economic development is assumed to be the driving force for the usage of terrestrial products and for land-use/land-cover dynamics, which in turn are assumed to be the major forces influencing carbon budget changes during the study period. The *lower* scenario leads to alterations of existing ecosystems that result in imbalances of the carbon cycle. However, there are not enough resources or time during the scenario period to try to bring the carbon balance back into equilibrium. The differences between the *mean* and *higher* scenarios are mainly determined by different economic possibilities for managing carbon-related issues connected with terrestrial vegetation and the different sectors of the national economy. The following discussion presents the major features and components of the three scenarios.

6.2 Land Use and Land-Cover Dynamics to 2010

The *mean* scenario (Table 49) is based on the assumption that land use change in the country would follow the trends identified for the period 1961–1995. Development during this period was not stable, and the latter years of the period were associated with a high rate of change in agricultural practices, economic decline, deterioration of natural resource use, etc. In following the general trend for the period indicated above, we used the dramatic changes of developments in 1990–1997 as a correction factor for the future.

In the *mean* scenario we assume a general reduction in the extent of cropland of about 2.2 million ha between 1995 and 2010, which will result in a total cropland area of about 128.0 million ha in 2010. Pasture is assumed to expand by about 30 million ha during the same period, and its total area is assumed to be about 120 million ha in 2010. This assumption is based on current trends of changes in both the land-use dynamics and the composition of feeding stocks for livestock. The latter factor is associated with reduction of grain imports for feeding purposes and increased use of domestically produced forage such as hay and silage. Following this assumption, we assume the increase of pasture area may occur at the expense of a reduction of such grassland and shrub areas as currently unmanaged pastures and meadows (about 36 million ha during 1995–2010).

The *mean* scenario also assumes an expansion of forests by about 8 million ha during the period 1995 and 2010, mainly due to natural regeneration. During 1961–1997 the average annual rate of increase of forested areas in European Russia was 0.54 million ha per year and 1.6 million ha per year in Asian Russia, mainly due to forest fire suppression. These rates were adjusted by taking into account the actual areas of forests in 1998 and an assumed decrease in the efficiency of forest fire protection during the coming years. Areas of forests planted annually are assumed to be at the level of the mid-1990s—about 0.25 million ha—and final harvests to be about 150 million m^3 per year.

Large uncertainties exist with respect to the dynamics of wetlands. The SLA (see Table 1) indicates a decrease of bogs at an annual rate that was about 0.6–0.7 million ha per year for the period 1985–1997. The decline may be caused by drainage and amelioration; about 6 million ha were drained during 1965–1990 (Shishov *et al*., 1991). By contrast, the SFA data do not support any decrease of wetlands: areas of treeless bogs in the State Forest Fund did not change during the period 1961–1993. However, we conclude that the extent of wetlands may change over time, as described in Table 49. It should be pointed out that the future of peat territories is of crucial importance for the future carbon budget of terrestrial ecosystems.

The *higher* scenario reflects a slightly smaller loss of cropland (about 1 million ha during 1995–2010), a more rapid expansion (37 million ha) of pasture areas, and further decrease of non-forest land. We assume the rate of forest protection, in particular against forest fires, will improve and will reach the state of the former Soviet Union for the period 1980–1990. The annual areas of plantations in 2001–2010 are estimated to be

0.5 million ha. Simultaneously, we assume that the total harvested area will increase to about 1 million ha annually, corresponding to a final harvest of about 190 million m^3 per year. This development is expected to result in an annual rate of increased forested areas of about 0.9 million ha annually. The amelioration of natural grasslands is assumed to be rather intensive (48 million ha during 1995–2010).

The *lower* scenario assumes a more rapid decline of cropland, by about 4 million ha during the period 1995–2010. This corresponds to development in the period 1996–1998. The improvement in the domestic feeding capacity is assumed to be limited (about 17 million ha for the period 1995–2010). We assume that the level of forest protection will continue to decline, and that areas of artificial reforestation will be 0.1–0.2 million ha annually. Harvested areas are also assumed to be small area and the final harvested will be about 100 million m^3 per year. The increase of forested areas for 2001–2010 is assumed to be only about 1 million ha, and the transformation of grassland into managed hayfields and pastures is assumed to be 17 million ha. The land use and land cover scenarios are summarized in Table 49.

Table 49. Land-use and land-cover dynamics in Russia according to the three scenarios (2010), in million ha.

Low		1995 Scenario Areas					
		Cropland	Pasture	Forests	Wetlands	Grasslands	Total
2010 scenario areas	Cropland	126					126
	Pasture		93			17	110
	Forests			771	1	1	773
	Wetlands				217		217
	Grasslands	4				400	404
	Total	130	93	771	218	418	1630
Mean		1995 scenario areas					
		Cropland	Pasture	Forests	Wetlands	Grasslands	Total
2010 scenario areas	Cropland	128					128
	Pasture		93			36	129
	Forests			771	0	8	779
	Wetlands				218		218
	Grasslands	2				374	376
	Total	130	93	771	218	418	1630
High		1995 scenario areas					
		Cropland	Pasture	Forests	Wetlands	Grasslands	Total
2010 scenario areas	Cropland	129					129
	Pasture		93			37	130
	Forests			771		14	784
	Wetlands				218	1	219
	Grasslands	1				366	367
	Total	130	93	771	218	418	1630

6.3 Soils and Agriculture

A considerable time span (about 10^2–10^3 years) is needed to achieve equilibrium of the soil carbon pools (Orlov and Biryukova, 1998). The intensity of carbon fluxes is related to the yearly and seasonal dynamics, which depend on temperature and precipitation (Kudeyarov, 1999; Raich *et al*., 1995).

Soils under management or utilization behave differently than natural soils. Changes in the soil carbon pool often occur rapidly, as a result of human impacts, and can even be catastrophic in the case of extreme events, such as water and wind erosion (Bouwman, 1990; Buyanovski and Wagner, 1997; Jeffrey *et al*., 1998). The most obvious changes in the soil carbon pools can usually be observed within 15–20 years (Shishov, 1984).

We assume that the content of carbon in soils under natural conditions, as well as the soil carbon pools of wetlands, will stay constant during the scenario period. To improve estimates of the dynamics of the carbon content, we need to model the interactions between vegetation and soils, and we also require a better understanding of the processes within permafrost. We also need further investigations of the dynamics of the carbon content of wetlands.

We assume that the content of carbon in cultivated soils will decline during the scenario period due to low application of organic and mineral fertilizers, decrease of plant density, and yield. These factors will cause the deterioration of carbon input into soils. We assume the rate of soil dehumification to be less in the future (as discussed earlier) compared to the situation in the 1990s. The humus decline in the future is estimated as be half of the current one.

In the scenarios we have assumed that the rate of soil erosion will remain constant. An assumed decrease of the crop density may enhance runoff and increase erosion, although these aspects have not been considered in this study. The assumptions regarding the development of agricultural production are connected with large uncertainties as demonstrated by Stroev (1997) identifying limited optimism about any recovery of the agro-industrial sector in the midterm. A basic assumption is that the yield will not exceed the yield level of 1990. Thus, all scenarios assume a decline of cropland production compared to 1990, as well as an increased area and production of phytomass for pastures.

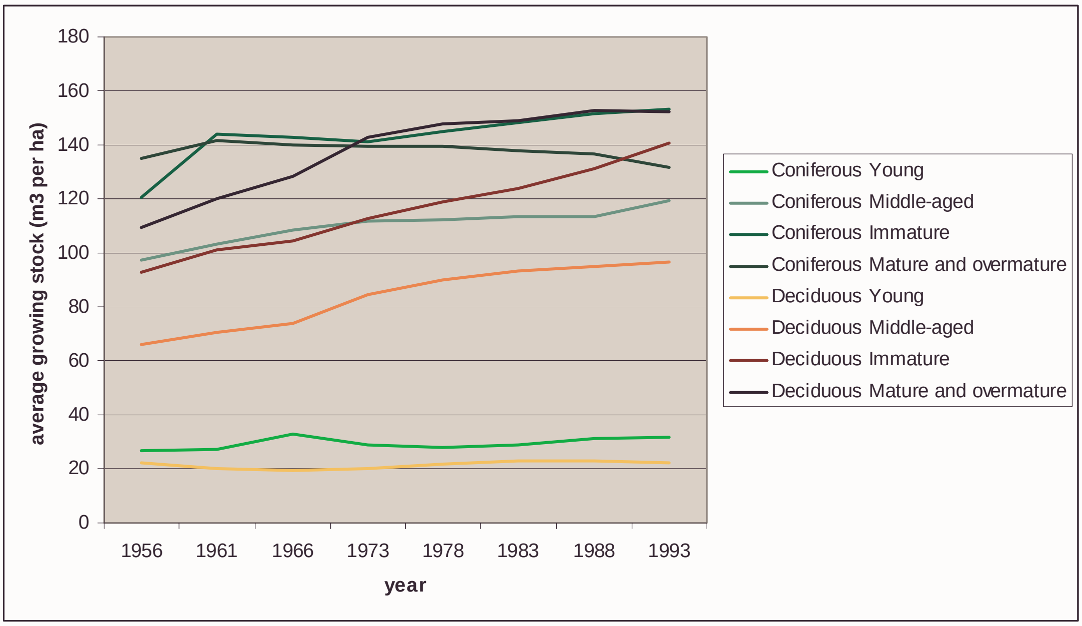
For the scenario period, we assume that Russia will return to the traditional (pre-1990s) practice of applying manure in agriculture. We therefore also assume that the amount of manure applied will be in proportion to the number of cattle, and that the application of liming will be in proportion to the cropland area.

Since 1990, there have been tremendous changes in Russia’s livestock production, with a considerable decline in the animal population. In the *mean* and *higher* scenarios we assume that cattle production will increase compared to 1997, which follows the increased feed potentials, although in none of the scenarios would the amount of cattle reach the 1990 level. We assume in the *mean* scenario that by 2010 the swine population will return to the 1990 level, and in the *higher* scenario that it will surpass the 1990 level. In the *lower* scenario we assume a slight population increase of cattle and swine compared to 1997. In all cases the gas emissions are assumed to be in direct proportion to the amount of animals.

6.4 Forests, Wetlands, and Grasslands and Shrubs

Many reports (e.g., Shvidenko *et al.*, 1987; Sedykh, 1999) indicate an increase in the productivity of the terrestrial vegetation in Russia during the last decades, which may be explained by changed climate, CO_2 and nitrogen fertilization, changed intensity of disturbances, etc. However, statistical evidence can be found only for forests. In Figure 15 the dynamics of the average growing stock by groups of dominant species and age groups in Russian forests are presented for the period 1956–1993 (Shvidenko *et al.*, 1999).

Figure 15. Dynamics of average growing stock of Russian forests (1956–1993), in m^3/ha.



Source: Shvidenko *et al.*, 1999.

From this time series we concluded that the annual increase of growing stock in coniferous species was about 0.5% for the studied period. For deciduous species the corresponding increase was 1%. Based on the above data, it is possible to define the net growth of stands, to recalculate this growth into gross growth, and to indirectly estimate trends of NPP and NEP as a basis for prolongation. However, there are large uncertainties in these calculations. To decrease the uncertainties we used as a starting point for the scenarios the latest available data of the SFA (as of January 1, 1998), the SLA for 1991–1998, distribution of disturbances for the period 1991–1998, etc. (see Table 1).

For vegetation of all land-use/land-cover classes used in the basic calculations the NPP, the increase was assumed to vary between 1.03 and 1.07 in the different scenarios. For forests, the *lower*, *mean* and *higher* scenarios assumed 1.03, 1.05 and 1.07, respectively, for the period 1998–2010. All scenarios for the period 1990-2010 assumed the rate of NPP increase for wetlands to be 1.05 and for grasslands to be 1.06.

We used a simple approach to estimate fluxes and pools originating from forest plant materials (phytomass and dead organic vegetation) over large territories. This approach encompasses calculation of the dynamics (by area) of major groups of forest-forming species, net and gross growth, annually harvested wood, and temporal and spatial distribution of disturbances.

For wetlands, the *higher* scenario assumes an increase of 50% in the agricultural consumption of peat compared to 1990; the corresponding increase for fuel consumption is assumed to 25%. The decrease of forest fire emissions is assumed to be 50% compared with the situation in 1990. In the *lower* scenario fire emissions are assumed to increase by 50% and the total peat consumption to decrease by 50%. The *mean* scenario reflects the situation in 1996–1998.

For grasslands and shrubs, the *higher* scenario assumes that the area disturbed by forest fires is the same as in 1990. The *mean* and *lower* scenarios assume an increase in disturbed areas of 10% and 30%, respectively. The factors for areas disturbed by industrial processes are assumed to be 1.0, 0.8 and 0.7 compared to 1990 in the *higher*, *mean* and *lower* scenario respectively.

FOR calculated the ameliorative effect of disturbances based on data reported by Sheshukov *et al.*, 1992; Sedykh, 1999; and Zimov *et al.*, 1999. According to these sources, post-fire productivity of terrestrial biota on permafrost increases 1.5- to 3-fold depending on the type of vegetation, latitude, type and severity of fire, etc. The data are presented in two forms, either as regional or ecosystem-specific aggregations or results of measurements on definite sites, and do not completely cover all the territories studied. For these reasons, we used productivity estimates corresponding to 50-60% of the reported data above.

6.5 Forest Products Sector

As discussed earlier, FOR undertook a substudy to model the forest products sector and to estimate the pools and fluxes resulting from production and consumption of forest products (Obersteiner, 1999). The consumption scenarios were driven by economic development and technological change.

6.6 Energy and Other Industry Sector Fluxes

Nakićenović *et al*. (1998) created energy sector scenarios that are especially well suited to long-term global-scale analysis. These scenarios treated Russia as a geographic subregion within the area of the former Soviet Union. The study grouped the individual scenarios into six alternative scenario sets. Our study aggregated these six alternatives into three scenarios, in line with the earlier descriptions in this chapter.

7. Carbon Pools, 2010

This section presents FOR's aggregate results for the scenarios with respect to the carbon pools for the year 2010.

7.1 Soil Pools

The changes in the soil carbon pools of cropland (0–0.3 m layer) according to the scenarios are presented in Table 50.

Table 50. Changes of soil carbon pools (0–0.3 m) in croplands of Russia, in Tg C.

	Pools
Year 1990	10838
Year 2010	
Lower	9638
Mean	9738
Higher	9838

The losses assumed in the scenarios are caused by tillage (45%) and by erosion (55%). The corresponding figures for 1990 were 85% and 15%, respectively.

7.2 Terrestrial Vegetation Pools

The scenarios for the phytomass carbon pool in 2010 are presented in Table 51.

Table 51. Carbon pools of phytomass according to the scenarios (2010), in Pg C.

Land-Use/Land-Cover Classes	1990 Pg C	Scenarios 2010, in Pg C		
		Lower	Mean	Higher
Cropland	0.65	0.58	0.60	0.62
Pastures	0.34	0.47	0.56	0.58
Total Agricultural Land	0.99	1.05	1.17	1.20
Forests	32.86	34.64	35.21	36.01
Swamps	1.33	1.36	1.40	1.43
Bogs	1.27	1.29	1.31	1.35
Total wetlands	2.60	2.65	2.71	2.78
Grassland & shrubs	3.49	3.20	3.03	3.02
Total	39.95	41.54	42.12	43.01

The scenarios show an increase in the terrestrial vegetation phytomass pool from about 40.0 Pg C in 1990 to 41.5, 42.1, and 43.0 Pg C in 2010 according to the *lower*, *mean* and *higher* scenarios respectively. This means that the live phytomass during the period 1990–2010 would sequester an additional 75, 100, or 150 Tg C • yr^{-1}, respectively, according to the three scenarios. The increased sink is provided mainly by forests. The total plant organic pools are presented in Table 52.

Table 52. Plant organic pools by different scenarios (2010), in Pg C.

Pool	1990 in Pg C	Scenarios for 2010, in Pg C		
		lower	mean	higher
Live phytomass	39.95	41.54	42.12	43.01
Coarse woody debris	4.96	6.15	6.15	5.96
Below-ground mortmass	8.84	9.85	9.68	9.51
Total	53.74	57.54	57.95	58.48

The total plant carbon pools for 2010 are 57.54, 57.95 and 58.48 Pg C for the *lower*, *mean* and *higher* scenarios respectively. The average annual sequestration by the total terrestrial vegetation in the three scenarios is 190, 210 and 237 Tg • C • yr^{-1} respectively.

7.3 Agricultural Products Sector Pools

The agricultural products pools according to the three scenarios are presented in Table 53. These pools are also included and discussed in the terrestrial vegetation pools (Table 51), but are highlighted separately in this section.

Table 53. Agricultural products sector pools (2010), in Tg C.

Pools	1990 in Tg C	Scenarios for 2010, in Tg C		
		Lower	Mean	Higher
Cropland phytomass	648.5	583.9	605.0	623.5
Pasture phytomass	338.4	469.1	561.1	576.2
Total Agriculture	986.9	1053.0	1166.1	1199.7

All scenarios show an increase in carbon of the total agricultural products sector in the period 1990–2010 in the range of about 65–215 Tg C.

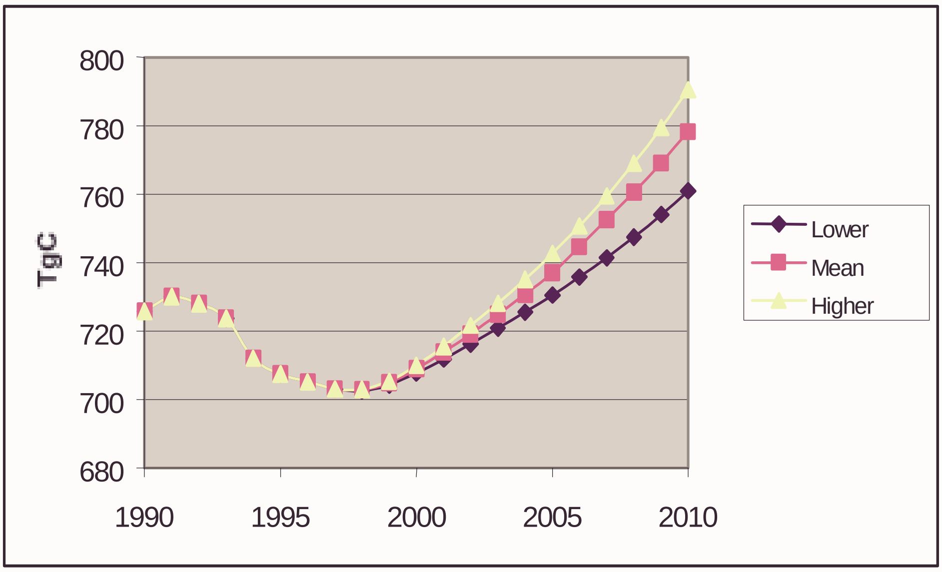
7.4 Forest Products Sector Pools

Table 54 shows the carbon pools calculated for the forest product sector according to the three scenario assumptions. All scenarios show an increase in the carbon pool. The exponential growth of the pool prior to 1990 was coming to an end in the post-Soviet era as a result of the output decline in the forest sector. The model results show that due to lagged emissions from prior production, the forest products pool changed from a net sink into a source of carbon in 1992 (Figure 16). The amounts of carbon emissions due to past consumption, i.e., from pools, of some 36 Tg C were not compensated by the current sequestration. A negative carbon balance for the forest industrial sector prevails until 1998 in all scenarios.

Table 54. Forest products pools (2010) according to the scenarios, in Tg C.

Scenario	Pools in Tg C	
	1990	2010
Lower	725.8	760.9
Mean	725.8	778.3
Higher	725.8	790.6

Source: Data are based on Obersteiner (1999).



Source: Obersteiner (1999).

Figure 16. Carbon Pools of the Forest Products Sector Over Time, in Tg C.

The declining development between 1990–1998 is due to the differential rate of decline of emissions caused by past and current sequestration. By 1998, fluxes due to past consumption declined to 36% of the level in 1990, whereas production of industrial wood declined to 28% of the 1990 level. According to the model calculations, Russia's carbon pool will reach the original size of the 1990 pool by 2003–2004, depending on the scenario used.

None of the computed scenarios take the implementation of sequestration strategies into account. In the model calculations, carbon emissions are a function of output growth; the model also considers such factors as technological improvements in production, changes in the type of production, quality and duration improvements in the lifecycle of forest products, and, finally, historical consumption and production. For a more detailed discussion of the forest products pool see Obersteiner (1999).

7.5 Summary of 2010 Pools

Table 55 summarizes the development of the carbon pools according to the scenarios. All scenarios show an increase in the total carbon pool compared to 1990. The increase for the *lower*, *mean* and *higher* scenarios is 2,634.5, 3,154.9 and 3,800.9 Tg C, respectively. This corresponds to an average annual net sequestration of 132, 158 and 190 Tg C • yr^{-1}, respectively. The total change between 1990 and 2010 is in the range of 0.8 to 1.0%.

Table 55. Carbon pools according to scenarios for 2010, in Tg C.

	1990		2010 Phytomass, Carbon, Tg C		
Land classes	Area, 10^6 ha	Carbon, Tg	Lower	Mean	Higher
Organic soil, 1.0 m layer	1,582.0	292,868.2	291,668.2	291,768.2	291,868.2
Terrestrial and products pools					
Croplands	130.3	648.5	583.9	605.0	623.5
Pasture	81.5	338.4	469.1	561.1	576.2
Total agricultural lands	211.9	986.8	1,053.1	1,166.1	1,199.7
Forests	763.5	32,861.9	34,640.0	35,210.0	36,010.0
Forest products		725.8	760.9	778.3	790.6
Swamps	105.8	1,334.3	1,360.0	1,400.0	1,430.0
Bogs	116.2	1,268.6	1,290.0	1,310.0	1,350.0
Total wetlands	222.0	2,602.9	2,650.0	2,710.0	2,780.0
Grasslands & shrubs	432.4	3,494.1	3,200.0	3,030.0	3,020.0
Total Phytomass	1,629.8	39,945.8	41,543.1	42,116.1	43,009.7
Coarse woody debris	1,629.8	4,955.9	6,150.0	6,150.0	5,960.0
Below-ground dead vegetation	1,629.8	8,841.9	9,850.0	9,680.0	9,510.0
Total plant	1,629.8	53,743.6	57,543.1	57,946.1	58,479.7
Non-vegetated land	79.6				
Total C	1,709.4	347,337.6	349,972.2	350,492.6	351,138.5

8. Fluxes, 2010

In describing the scenarios we have followed the same principles used to present the 1990 carbon budget. The different sub-budgets are given in Appendix 6 and the corresponding 1990 fluxes and budgets are given in Appendix 7 for the 2010 scenarios. We assume that the transfers among modules in 2010 followed similar patterns, though different rates, compared to those in 1990.

8.1 Soil Fluxes

Because of different, sometimes contradictory developments of different processes under all scenarios (Table 56), CO_2-C emissions are quite close to those estimated for 1990. As can be seen, the change for the *lower* scenario is some –3 Tg C.; the estimate for the *mean* and *higher* scenarios is about 6–8 Tg C • yr^{-1} higher than for 1990. The CH_4-C emissions of 20.0 Tg C remained unchanged during the scenario period as compared to 1990.

Table 56. Scenarios for CO_2-C emissions from soils and different land classes (2010), in Tg C.

C-CO_2 flux by land classes	1990		2010					
			Scenario Areas, Mha			Scenario fluxes, Tg C		
Land Class	Area, Mha	CO2-C, Tg C	Lower	Mean	High	Lower	Mean	Higher
Cropland	130	488	126	128	129	472	479	483
Pasture	82	176	110	129	130	237	279	281
Sub-Total Agriculture	212	664	236	257	259	710	758	764
Forest	764	1367	773	779	784	1,380	1,391	1,400
Swamps	106	76	45	95	45	74	75	75
Bogs	116	292	173	331	174	286	287	289
Sub-Total Wetlands	222	368	217	218	219	360	362	364
Grassland and shrubs	432	798	404	376	367	745	694	678
Total Country	1630	3198	1629.8	1629.8	1629.8	3,195	3,204	3,206

In general, our scenarios illustrate a close dependence of the gas emissions on the extent of the land-use changes. The largest changes in CO_2-C emissions are in the grasslands and shrubs, pasture, and forest land class groupings.

8.2 Terrestrial Biota Fluxes

Table 57 shows the NPP estimates according to the scenarios, based on the assumptions and approaches discussed earlier (Section 7). All scenarios show an increased uptake of carbon out of the atmosphere by the vegetation for the scenario period. The increase varies between approximately 130 Tg C (*lower* scenario) to 260 Tg C (*higher* scenario).

Table 57. Scenarios for NPP generated by vegetation (2010), in Tg C.

Land-use/land-cover classes	1990 Area	2010 Areas, Mha			1990 NPP, Tg C	2010 NPP, Tg C		
		Lower	Mean	Higher		Lower	Mean	Higher
Cropland	130.3	126.2	128.0	129.2	648.5	584	605	624
Pasture	81.5	109.7	128.7	129.7	308.8	428	512	526
Sub-Total Agriculture	211.9	235.9	256.7	258.9	957.2	1,012	1,117	1,149
Forest	763.5	772.8	778.8	784.3	1,707.3	1,780	1,829	1,877
Swamps	105.8	103.6	104.1	104.6	225.0	231	232	233
Bogs	116.2	113.8	114.3	114.8	262.2	270	271	272
Subtotal Wetlands	222.1	217.4	218.4	219.4	487.2	501	503	505
Grassland and shrubs	432.4	403.7	375.9	367.2	1,201.7	1,189	1,107	1,082
Total Country	1,629.8	1,629.8	1,629.8	1,629.8	4,353.4	4,482	4,556	4,613

Table 58 presents the scenarios for the aggregated fluxes caused by disturbances. All scenarios show increased fluxes in comparison with 1990. The increases are in the range of 28–73 Tg C. The aggregated fluxes stem from complicated interactions between different subcomponents of the total system; the table also illustrates these interactions.

Table 58. Calculation of fluxes from disturbances for 1990 and 2010 scenarios, in Tg C.

Disturbance Type	1990 Area (Mha)	1990 Rate (Tg/Mha)	2010 Scenarios*, Tg C		
			Lower	Mean	Higher
Forests					
Fire	764	0.10	83	83	84
Pests	764	0.10	75	75	76
Harvest					
Pests	764	0.02	16	16	16
Abiotic	764	0.04	53	60	76
Forest Disturbances Total	**764**		**226**	**235**	**252**
Wetlands					
Fire	222	0.10	30	25	23
Agricultural use			17	33	50
Domestic Use			4	7	11
Wetlands Disturbances Total	**222**		**50**	**65**	**83**
Grasslands and Shrubs					
Fire	432	0.09	47	37	33
Transformation	432		7	7	7
Grasslands and Shrubs Total	**432**		**54**	**44**	**40**
GRAND TOTAL	**1418**		**330**	**345**	**375**

8.3 Agricultural Sector Fluxes

In the scenarios for the agriculture sector fluxes we have tried to close the budgets for the subcomponents—agriculture, animal husbandry and consumption. The detailed scenarios are presented in Appendices 6 and 7. In this section we excerpt the major components of the budget from Appendix 6. Because the flux from perennials is negligibly small, the scenarios have not taken this amount into account.

8.3.1 Agricultural land

In Table 59 we present the scenarios for the fluxes of the agriculture subsystem within the atmosphere/ecosystem balance.

Table 59. Scenarios for the fluxes of the agriculture subsystem in the atmosphere/ecosystem balance, in Tg C.

Fluxes into Atmosphere	1990	2010		
		Lower	Mean	Higher
Soil CO_2-C respiration	664	710	758	764
Manure Emission	47	36	44	52
Peat Emission	31	15	31	48
Liming emission	4	4	4	4
Total	746	764	836	867
Fluxes out of atmosphere				
Above-ground NPP	545	562	615	633
Precipitation	10	10	10	10
Below-ground NPP	413	450	502	516
Total	967	1,022	1,127	1,159

In all scenarios for the agricultural land budget there is an increasing flux out of the atmosphere of about 55–192 Tg C — the highest increase being the *higher* scenario.

8.3.2 Animal husbandry

Appendix 6 gives the detailed balance for the animal husbandry subsystem. We assume that respiration from animals is directly related to the size of the livestock herd.

In all scenarios we assume an increase in livestock population relative to 1997 in the country. However, in the *mean* and *lower* scenarios we assume that in 2010 the number of cattle will not reach the level of 1990. As Table 60 shows, both the *mean* and the *higher* scenarios postulate that the swine population will again reach the 1990 level in 2010. Here we present only the balance dealing with the atmosphere/ecosystem interaction (Table 61).

Table 60. Projection of livestock population (10^3 head) in 2010.

Scenario	Cattle	Swine
1990	56073	37627
1997	31700	17300
Scenario		
Lower	46000	27000
Mean	50000	37000
Higher	56000	47000

Table 61. Scenarios for animal husbandry fluxes (2010), in Tg C.

Fluxes into Atmosphere	1990	2010		
		Lower	Mean	Higher
Respiration	219	1707	1998	226
Fermentation	5	4	5	5
Waste, etc.	19	19	19	19
Total Flux	243	201	223	250

In the *lower* and *mean* scenarios the fluxes are 42 and 20 Tg C below 1990 levels, corresponding to decreases in the animal population. In the *higher* scenarios the emissions are slightly higher than 1990 levels, as the animal population remains close to the 1990 levels.

8.3.3 Consumption

Most of the agricultural products produced are consumed by humans. Appendix 6 shows the total subsystem of human consumption. Here we present only the consumption fluxes from the agriculture sector (Table 62). All consumption fluxes in the agriculture scenarios show increases in the range of some 65–87 Tg C compared to 1990.

Table 62. Scenarios for Consumption of Agricultural Products (2010), in Tg C.

	1990	2010		
		Lower	Mean	Higher
Consumption of Agricultural Products	232	302	319	297

8.4 Scenarios of Land-Use and Erosion Effects

The carbon losses caused by land use and erosion of croplands under the different scenarios are presented in Table 63. These losses lead to changes in the soil pools (see Appendix 6).

Table 63. Scenarios for carbon losses by land use and erosion in croplands (0–0.3 m) by 2010, in Tg C.

Year	Soil Carbon Pools, 0–0.3 m, Tg C	Cumulative Losses of Soil Organic C, 1990–2010					
		Total		Caused by tillage		Caused by erosion	
		Tg C	% of initial pool	Tg C	% of total losses	Tg C	% of total losses
1990	10838	2634	24	2210	85	390	15
Scenarios 2010							
Lower	9638	1200	11	540	45	660	55
Mean	9738	1100	10	495	45	605	55
Higher	9838	1000	9	450	45	550	55

In all scenarios the cumulative loss of organic matter from cropland soils in Russia is about 1000–1200 Tg C. This result corresponds to the current rate of humus decline of about 0.5–0.7 t • ha^{-1} • yr^{-1} (Shishov, 1984). However, we assume that the role of erosion in the organic decline will be greater in the future than in 1990.

8.5 Forest Products Sector Fluxes

The scenarios for the fluxes in the forest products sector are presented in Table 64. The total fluxes in 2010 are some 40 to 50% lower than the 1990 levels. Fluxes due to current and past use of industrial wood are down to some 30–45% of the total in 2010 compared to 65% in 1990. This is due mainly to the decline in final consumption of forest products and an assumed increase in the technological efficiency of wood processing. A large share of the total flux is attributed to fuelwood consumption. Noncommercial fuelwood emissions account for a share in the range of 60 to 70% of the total fluxes, with the highest share in the *lower* scenario.

Table 64. Fluxes by the forest products sector (2010), in Tg C.

Scenario	Total Fluxes, Tg C	Fluxes due to Current and Past Industrial Use, Tg C	Fluxes of Commercial and Non-commercial Fuelwood, Tg C
1990	80.8	51.5	29.3
Scenarios for 2010			
Lower	41.2	13.2	28.0
Mean	42.5	16.2	26.2
Higher	47.2	20.4	26.8

8.6 Scenarios of Energy and Other Industry Sector Fluxes

As described in Section 7, the energy sub-scenarios used by Nakićenović *et al*. (1998) have been adjusted to be valid for the three alternative GDP developments used in this report. The scenarios for the emissions are presented in Table 65. The emissions of CH_4-C from the energy sector and emissions from other industrial processes, 26 Tg C in total, remain constant through the scenario period.

Table 65. Scenarios of emissions by energy and other industrial sectors (2010), in Tg C.

Scenario	1990	2010
Lower	650	402
Mean	650	535
Higher	650	642

The *higher* scenario shows hardly any difference compared with the 1990 energy emissions. But in the *mean* and *lower* scenarios the emissions by the energy sector are 115 and 248 Tg C • yr^{-1}, respectively, lower in 2010.

8.7 Summary of Fluxes in 2010

The total flux balances according to the three scenarios are summarized in Table 66 and are described in more detail in Appendices 6 and 7.

Table 66. Summary of all fluxes for 1990 and 2010 scenarios, in Tg C.

Flux into Atmosphere, Tg C	1990	2010 Scenarios		
		Lower	Mean	Higher
Agricultural land	746	765	836	867
Animal husbandry	252	210	232	259
Biomass consumption	363	385	405	392
Forest	1,567	1,617	1,637	1,664
Wetland	406	406	403	402
Grassland & shrub	917	874	812	792
Soil CH_4-C respiration	20	20	20	20
Additional fluxes (from imported grain & lime)	13	13	13	13
Total fluxes out of ecosystems	*4,272*	*4,276*	*4,345*	*4,396*
Energy and industrial sectors	676	428	561	668
Total into Atmosphere	**4,957**	**4,713**	**4,916**	**5,074**
Fluxes out of Atmosphere, Tg C				
Agricultural land	967	1,022	1,127	1,159
Animal husbandry				
Biomass consumption				
Forest	1,743	1,816	1,864	1,912
Wetland	498	511	513	516
Grassland & shrubs	1,222	1,209	1,127	1,102
Total out of Atmosphere	**4,430**	**4,558**	**4,632**	**4,689**
Flux Balance (excluding energy)	**–149**	**–272**	**–277**	**–283**
Flux Balance (including energy)	**527**	**156**	**284**	**385**
Pool Change (excluding energy)	**–125**	**–122**	**–124**	**–126**
Pool Change (including energy)	**551**	**306**	**437**	**542**

The *lower* and *mean* scenarios that include energy and other industrial processes show in 2010 lower emissions to the atmosphere of some 224 and 42 Tg C, respectively, compared to 1990. The *higher* scenario shows increased fluxes of 116 Tg C.

All scenarios show an increased total flux out of the atmosphere compared to 1990. The increase is in the range of 128–259 Tg C, with the largest increase in the *higher* scenario. The dominant part of the increase is due to increased sequestration and change in the area of forests and pastures.

In 1990 Russia (including energy and other industrial processes) was a net emitter of 527 Tg C to the atmosphere. All the scenarios for 2010 still show a net emission to the atmosphere in the range of 156–385 Tg C, with the lowest emissions in the *lower* scenario and the highest in the *higher* scenario. If only the atmosphere and ecosystem interactions (excluding energy and industry sectors) are taken into account, the *mean* scenario indicates that the net sink of the ecosystems will change from 149 Tg C in 1990 to about 277 Tg C in 2010.

9. Total Balances

9.1 Summarized Total Flux Balance

This section summarizes the total flux balances in a simplified form (Figure 17). The numbers without parentheses illustrate the net flux, including all fluxes (energy/industry and ecosystems). The numbers in parentheses illustrate only the total of all ecosystem-related fluxes (excluding energy sector and other industrial processes).

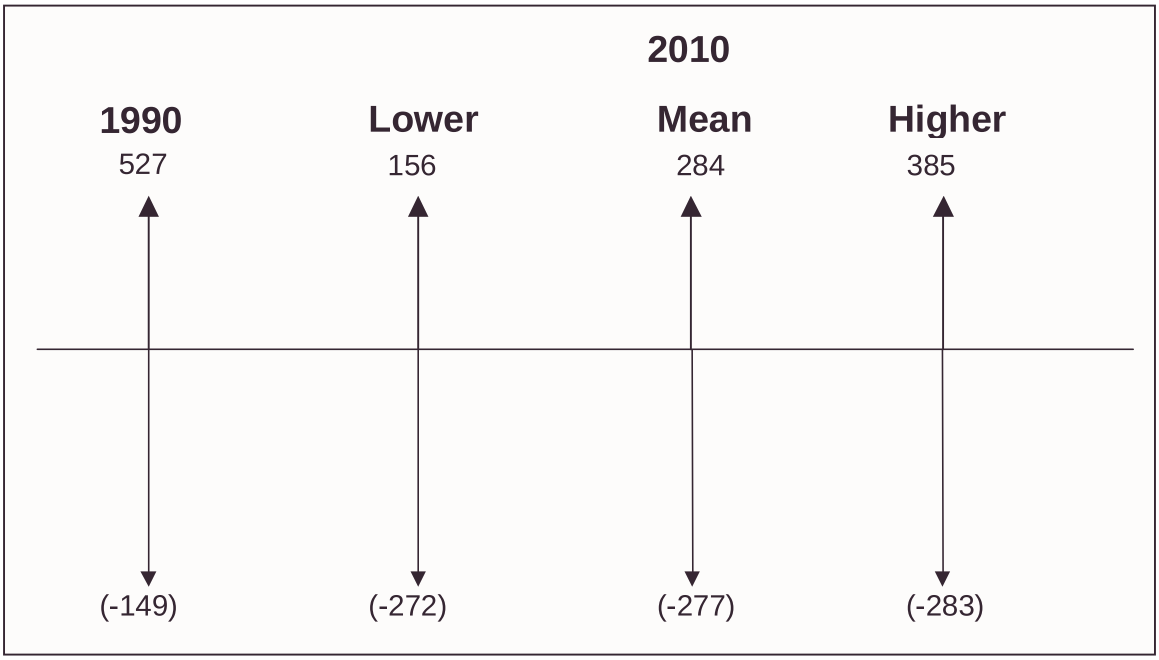


Figure 17. Net fluxes, in Tg C.

With respect to the total fluxes (including energy and other industrial processes), Russia is thus expected to continue to be a net source of emissions. The range of total net emissions to the atmosphere is 156–283 Tg C in the scenarios for 2010, with the highest emissions in the *higher* scenario. However, the net emissions according to the scenarios are less than the total net emissions in 1990 (527 Tg C).

In the case of net fluxes of ecosystems (excluding energy and other industrial processes), the *mean* scenario indicates that the net sink of 149 Tg C in 1990 will change to around 277 Tg C in 2010.

To reflect the requirements of the Kyoto Protocol, we also tried to determine the changes in the net fluxes during the commitment period 1990–2010. Figure 18 illustrates these changes for the total flux balances.

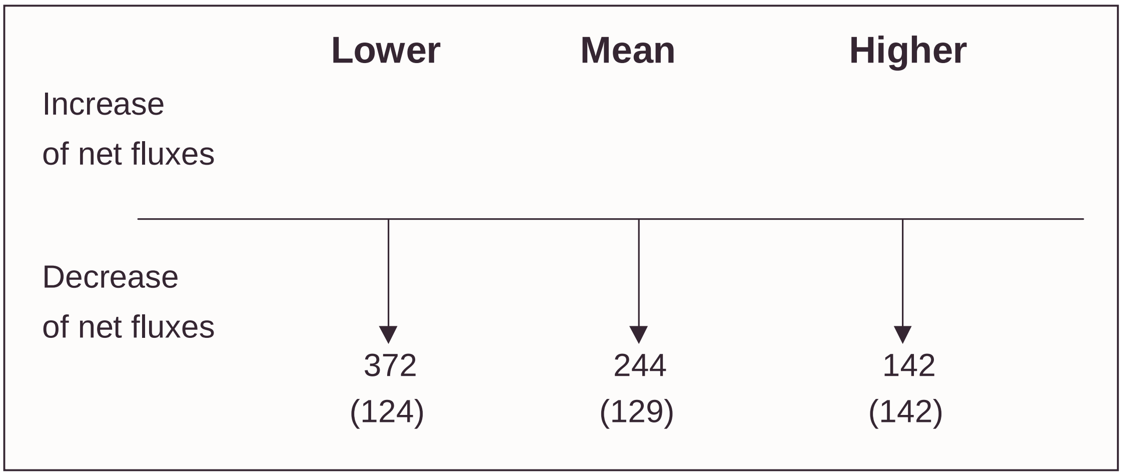


Figure 18. Changes of the net fluxes (1990–2010), in Tg C.

Our calculations show that the total carbon sink strength (including energy and other industrial processes) is assumed to increase by 142–372 Tg C during the period 1990–2010 depending on the scenario used, with the highest improvement in the *lower* scenario. If only the ecosystem fluxes are considered, the change is in the range of 124–142 Tg C for the same period, with the highest increase in the *higher* scenario.

9.2 Other Balances

In Section 5 we presented balances other than the total flux balance for year 1990. Table 67 presents the total flux balance and the pool changes for the three scenarios. The information underlying these balances is given in Appendix 6.

The total flux balance shows small variations between the different scenarios when energy and other industrial processes are excluded. In the scenarios the sink varies from 272 to 283 Tg C from *lower* to *higher*, respectively. If the energy sector and other industrial processes are included, however, the scenarios vary more significantly. In the *lower* scenario the total flux is a net source of 156 Tg C; in the *mean* and *higher* scenarios it is a net sources of 284 and 385 Tg C, respectively, in 2010.

FOR's assessment of the pool changes corresponds to the trend in the flux balance, showing a maintained accumulation of the sink capacity around 124 Tg • yr^{-1} in all scenarios if the energy and industry sectors are excluded. If the latter sectors are included, the pool changes show a loss that ranges between 306–542 Tg C in 2010 depending on the scenario employed.

Table 67. Summary of Balances for the 2010 Scenarios, in Tg C.

	Including Energy and Other Industrial Processes			Excluding Energy and Other Industrial Processes		
	Lower	Mean	Higher	Lower	Mean	Higher
Total Flux Balance	Source 156	Source 284	Source 385	Sink 272	Sink 277	Sink 283
Pool Changes	Source 306	Source 437	Source 542	Sink 122	Sink 124	Sink 126

10. Comparisons with Other Estimates

As discussed earlier, there are difficulties in making direct comparisons between this study with other studies, primarily because this study follows the FCA concept and other available studies of Russia, to our knowledge, have been based on some form of PCA. Another reason is that there are big differences between data and methodologies used in this study and other studies. In the earlier text, where it was possible, we made comparisons with other studies on partial results. These comparisons will not be repeated here.

Two studies report aggregate estimates of the carbon emissions for all Russia, although they did not follow the FCA methodology. The first study is the Russian Country Study (1994–1997), and is reported in a number of publications. The second aggregate estimate is reported by the Second National Communication (SNC) of the Russian Federation (NCR, 1998). Because the latter contains more recent data (we use a 1998 Russian version of this report) and to a large extent refers to the Country Study results, the comparisons we present in this section refer to the SNC estimates.

The SNC reports the CO_2-C emissions to the atmosphere by agriculture to equal zero, i.e., fluxes to and out of the atmosphere cancel each other out, for different reasons. Methane emissions by livestock are estimated to be 4.93 million tons of CH_4 for 1990 and 3.62 million tons for 1995. Cattle generate about 85% of total methane emissions. The SNC does not take into account the grasslands, shrubs and wetlands outside Forest Fund areas.

Thus, according to the SNC, forests define all C-CO_2, sinks/sources of the Russian terrestrial ecosystems. For the Forest Fund areas (1.18 billion ha, including the majority of wetlands and peat soils), the carbon *sink* in phytomass was estimated as 262 Tg C in 1990, of which 242 Tg C were contained in phytomass of forest ecosystems. The SNC reported two types of forest disturbances: forest fires and harvests. Forest fire emissions were estimated to be in the range of 24–66 Tg C • yr^{-1}, of which about 58% were direct fire emissions and 42% post-fire biogenic fluxes. This fire emission estimate is less than 50% of the results FOR reported for Russia (Shvidenko and Nilsson, 2000a, b), while the average rate of emission (kg C • ha^{-1} • yr^{-1}) is about one third of the reported results for boreal forests of the American continent (Kasischke *et al*., 1995; Stocks *et al*., 1998). The SNC estimated the emissions caused by harvests and by use of forest products to be 109 Tg C in 1990, about 35% higher than our estimate.

The conclusion of the SNC report is that Russian forests served as a net sink of 107 million tons of carbon in 1990, with an uncertainty of about 30% around this mean value. Drawing on long-term data of forest inventories, FOR estimated this flux to result in a sink of 176 Tg C • yr^{-1} (average for 1992–1998).

The reason for the disparity is methodological. Analysis of the publications used as input by the SNC study (e.g., Isaev *et al*., 1993; Isaev and Korovin, 1998) shows that the data in the SNC report were calculated based on a snapshot of the forest inventory of 1988, using average growing stock by age groups *a priori*. The product of areas times change of average growing stock by age groups results in a net sequestration or net sink of carbon if the areas increase during the studied period. This means that the dynamics of the forest ecosystem/atmosphere carbon exchanges in the referenced studies were replaced by a "static picture" for 1988. Such an approach would be relevant if (1) the extent and severity of fire and other natural disturbances were relatively stable for different years, and (2) the average growing stock by age groups were stable during the last decades, but this is not the case with respect to the Russian forests. Yearly variations in disturbance regimes are evident (approximately 10-fold with respect to the disturbed areas monitored during the period 1985–1998), and the average growing stock of young, middle-aged and immature forests increased by 20–50% during the period 1956-1993. Obviously, the method used in the above-mentioned Russian publications can present only average results for a long and indefinite period of time, but does not have high accuracy for the year 1990, for which the results were reported.

11. Uncertainties in the 1990 Full Flux Balance

Valentini *et al*. (2000) point out that the carbon balance is in principle a delicate equilibrium between the two large fluxes of photosynthesis and respiration, especially in boreal ecosystems. The same authors studied the net carbon exchange in 15 European forests during 1996 and 1998 and found that the annual carbon balances range from an uptake of 6.6 ton C • ha^{-1} • yr^{-1} to a release of nearly 1 ton C • ha^{-1} • yr^{-1}. High-latitude forests show more variable carbon sequestration values than low-latitude forests. Old high-latitude forests tend to change from sinks to sources of carbon during mild winters (Valentini *et al*., 2000). Thus, the carbon exchange in the forest ecosystem varies greatly.

In earlier sections of this report we have illustrated that the soil provides huge pools and fluxes of carbon. Schlesinger (1999) illustrates the great variation of carbon sequestration and carbon fluxes in agricultural soils that results from different management regimes. Post and Kwon (2000) state that, "... there is a large variation in the length of time for and the rate at which carbon may accumulate in soil, related to the productivity of the vegetation, physical and biological conditions in the soil, and the past history of soil organic inputs and physical disturbance." Lal *et al*. (1998) estimate an uncertainty range of ±40% of the existing flux estimates for U.S. agricultural soils. Subak (2000) claims that there is a consensus that a "convincing ability" to estimate carbon content and fluxes for agricultural soils does not exist yet and no country has yet demonstrated the ability to adequately assess carbon fluxes from agricultural soils at a national level. Under these conditions it is extremely important to try to assess the uncertainty of the carbon balances we have presented.

In Section 2.5 we introduced a discussion on uncertainty. In that section, and in Appendix 4, we also illustrate an example of how the precision calculations were carried out for forest phytomass. We attempted to carry out these precision calculations for the major components of the total flux balance. These precision calculations were used as a platform for uncertainty assessments in the form of expert estimates for some of the components of the Russian FCA in 1990. Appendix 8 illustrates this type of expert assessment (estimate) of the uncertainties for fossil fuel emissions . It should be underlined that the assessments *do not* deal with *all aspects* of the carbon account and do not assume *any bias* in the estimates.

The *expert* column of Table 68 shows FOR's expert estimates of the uncertainties in some components of the Russian FCA for the atmosphere/ecosystem balance. These, together with estimates of other uncertainties (*Other* columns), have been used for quantitative estimates on the impact of the uncertainties on the 1990 carbon account in Table 68. Additional uncertainties identified related to disturbances (15%, according to Shvidenko and Nilsson, 2000b), soil and litter dynamics interaction for soil C respiration (3%; set by IIASA experts), conversion factors for forest volume to mass balance (13.5%; SSF, 1992), the carbon content of wood (5%; personal communication from Prof. Hakkila, Finland, March 2000), and uncertainties in the Russian forest inventory information (10%; European Commission, 1997; personal communication from Prof. Päivinen, EFI, Finland, May 2000). In addition, our analysis shows that the contribution of uncertainty that results from merging GIS databases of different spatial scales and thematic classes amounts to 10%. In Table 68, we have also identified the components for which the IPCC (1995) identified an overall uncertainty. Our estimate shows substantially lower uncertainties than the IPCC for similar biological components.

We are also carrying out analysis on the uncertainties of the carbon balance for Austria. Preliminary results show an uncertainty assessment of the Austrian wood balance (part of the total Forest Products Sector for Russia in Table 68) of –13 to 19%, which is in line with our results presented for Russia.

Even though we do not have an expert estimate for several components, the resulting uncertainty range for the 1990 flux balance of Russia is huge, as shown in the bottom row of Table 68: from –155 (sink) to +1209 (source) Tg C. The uncertainty of the assessed averaged balance of 527 Tg C is estimated to be 129%.

The approach used to illustrate the uncertainty of the 1990 total flux balance is to apply the uncertainty propagation (NIST, 1994) on the numbers presented in Table 68. This can also be regarded as a control method for the uncertainty range of the resulting carbon balance for 1990 (the lower box of Table 68). This uncertainty propagation calculation gives a total flux balance of 527 ± 682 Tg C for 1990; there is no efficient method available to estimate the uncertainties in the presented scenarios. Therefore we used the assessed uncertainties for the 1990 total flux balance for all scenarios. Given that the scenario projections introduce additional uncertainties, it can only be concluded that the uncertainties are at least as large as the scenarios for the balance for year 2010 compared with uncertainties of the balance for year 1990. This means that the assumed changes of the Russian total flux balance between 1990 and 2010 of 142 to 371 Tg C (depending on the scenario) are completely within the uncertainty range estimated for the total flux balance.

As stated above, several components of the carbon account are still missing from the estimates of the uncertainty range. In addition, the estimates do not take biases into account. To our knowledge, some limited analysis is available on estimates of biases of the major components of the carbon account. One example of biases appears in the forest inventory system. Gertner and Köhl (1993) found that national forest inventory systems are very sensitive to random or systematic errors, which cause substantial biases in the results.

Thus, we have illustrated that substantial uncertainties exist in the carbon budget, even though we have not been able to estimate the uncertainty of all the components of the FCA. We have only been able to give an illustration for the case year 1990 and not for the scenario period, for which the uncertainties are bound to be larger. In addition, our uncertainty estimates have not taken biases into account, even though there are indications that biases in the FCA can be substantial. All of this leads us to conclude that the uncertainty ranges exceed and fully absorb the estimated balances for 1990 and 2010, as well as the changes of the carbon balance between 1990 and 2010.

Table 68. Impact of Uncertainties (*sans bias*) on 1990 Carbon Balance of Russia (Total Flux Balance).

Flux Category	Sub-flux	Uncertainties (%)						Fluxes into the Atmosphere				Fluxes out of the Atmosphere				Balance		
		expert	Area	additional [1]			total	1990	uncertainty, Tg C	low	high	1990	uncertainty, Tg C	low	high	mean	low	high
Energy Sector		**17**					**17**	**665**	**113**	**552**	**778**							
Other Sectors		**17**					**17**	**11**	**2**	**9**	**13**							
Total Soil Respiration		**7**	**10**	**3**	**10**		**16**	**3,218**	**517**	**2,701**	**3,734**							
Disturbances	Fire	15	10	15			23	74	17	57	91							
	Abiotic	15	10	15			23	29	7	22	36							
	Harvest	15	10	15			23	16	4	12	20							
	Pests	15	10	15			23	74	17	57	91							
	Wetland fire	15	10	15			23	23	5	18	29							
	Grasslands and Shrubs	15	10	15			23	46	11	35	57							
	Total							**262**		**262**	**262**							
Other consumption		**40**					**40**	**363**	**145**	**218**	**508**							
Agricultural Land Management	Manure	5					5	56	3	53	59							
	Peat			20			20	31	6	25	37							
	Liming	0					0	0	0	0	0							
	Total							**87**		**87**	**87**							

Flux Category	Sub-flux	Uncertainties (%)						Fluxes into the Atmosphere				Fluxes out of the Atmosphere				Balance		
		expert	Area	additional [1]			total	1990	uncertainty, Tg C	low	high	1990	uncertainty, Tg C	low	high	mean	low	high
Animal Husbandry	Respiration	13					13	219	29	191	248							
	Fermentation	13					13	5	1	4	5							
	Production	17					17	19	3	16	22							
	Total							**243**		**243**	**243**							
Produced and consumed NPP					**15**		15	**42**	**6**	36	48							
Decomposition of phytomass					**15**		15	**53**	**8**	45	61							
Additional Fluxes	Grain imports and liming						5	**13**	**1**	**12**	**14**							
NPP	Agriculture				15	10	18					957	173	785	1,130			
	Forest		10		14	5	18					1,707	299	1,408	2,007			
	Wetland		10	20	15		27					487	131	356	618			
	Grasslands & shrubs		10		15		18					1,202	217	985	1,418			
	Total											**4,353**		**4,353**	**4,353**			
Deposition and Precipitation												76	0	76	76			
TOTAL							**83.6**	**4,957**	**530.7**			**4,430**	**428**			**527**	**-155**	**1,209**
Range +/-									**11%**				**10%**			**129%**		

[1]. Notes: soil-litter interaction (SCP) IIASA experts 3%), forest carbon content, 5% (Hakkila, 2000), forest dry matter, 13.5% (SSF, 1992), agricultural land-use pattern , 10% (IPCC, 1995), wetland carbon storage 20% (Efremov et al. 1996), forest NPP, 15% (Alexeyev *et al.* 1996), carbon soil storage, 20% (Shugalei *et al.*, 1996).

12. Implications for the Kyoto Protocol

Based on this study and related studies by IIASA, we conclude that the Kyoto Protocol will only be meaningful and implementable if it is based on *full carbon accounting* at all levels (i.e., project, regional, national, and continental) and not on partial accounting. However, we recognize that such an accounting involves many uncertainties, given today's technology and methods. We have made substantial efforts to illustrate the uncertainties connected with measurements for a single nation by calculating the current account for Russia. Our results illustrate that the changes in the carbon balance for Russia during the period 1990–2010 (mimicking the Kyoto Protocol) are small in relation to the uncertainties involved in the accounting (Figure 19). Admittedly, our study focused on Russia, which covers a huge land area, but a parallel FCA for Austria, a small country, shows similar trends (see Jonas, 1997; Jonas *et al*., 1998).

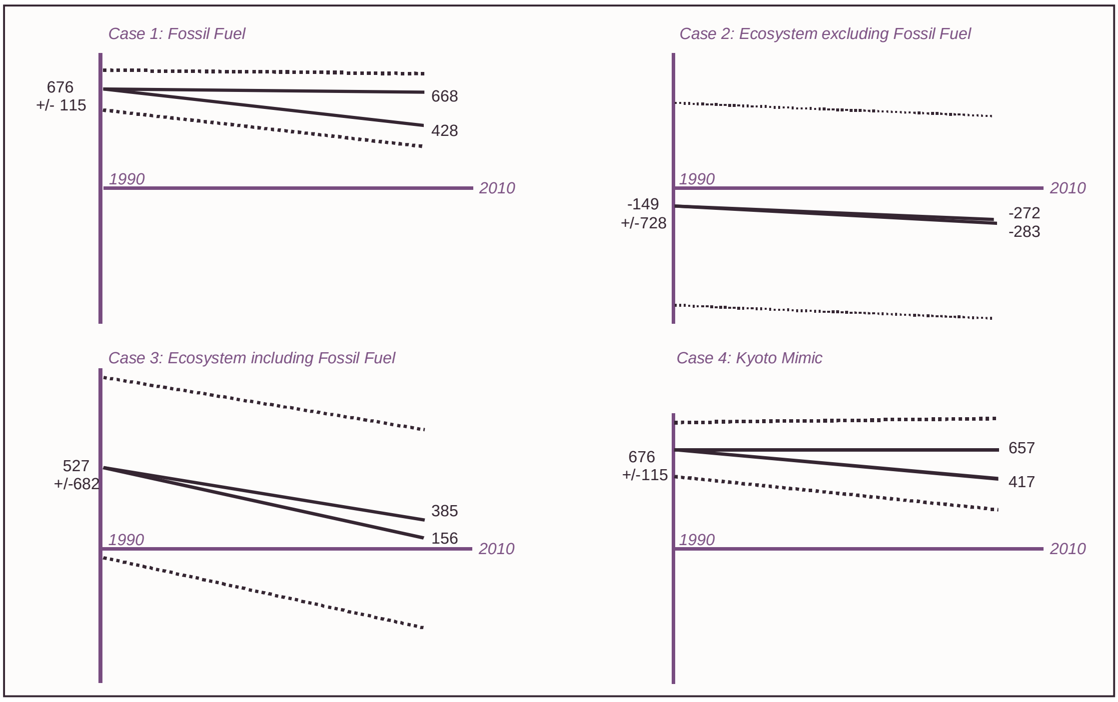


Figure 19. Changes in total flux balances (solid lines) and uncertainty ranges (dotted lines) for the Kyoto Protocol commitment period (1990–2010), in Tg C.

The huge differences between changes in different components of the total flux balance over time and the uncertainties generate severe problems with the verification of the Kyoto Protocol.

Here we make use of the "verification time" concept described in Jonas *et al*. (1999b). This concept links the temporal changes of net carbon emissions with the temporal changes of the underlying uncertainties. At present, the concept considers only the physical characteristics of the temporal changes for methods of carbon reduction (which means that the verification times for the Kyoto Protocol are only discussed from a purely physical point of view), and does not consider any impacts over time associated with the implementation of emission reduction measures. However, we have developed a first cut approach on this issue based on verification constraints (see Obersteiner, *et al*., 2000).

Based on this methodology, we have estimated the verification times for the changes of the carbon balance for four types of accounts, namely:

- Case 1: Fossil Fuels Account;
- Case 2: Atmosphere and Ecosystem Balance (excluding fossil fuels);
- Case 3: Total Flux Balance (including fossil fuels); and,
- Kyoto Protocol Mimic (fossil fuels plus ABCs; in other words, LUCF activities permitted under the Kyoto Protocol).

The estimated verification times for the scenario range are presented in Table 69. The calculations are based on the incomplete estimates of the uncertainties discussed in Section 11.

Table 69. Verification time for different types of accounts for Russia and the scenario range.

Type of Account	Verification Time, in years
Case 1: Fossil Fuels	9 to 287
Case 2: Atmosphere and Ecosystem Balance (excluding fossil fuels)	108 to 118
Case 3: Total Flux Balance (including fossil fuels)	37 to 96
Case 4: Kyoto Mimic (Case 1 with Anthropogenic Biosphere Changes)	
• 0% uncertainty	9 to 121
• 50% uncertainty	9 to 170
• 100% uncertainty	9 to 288
• 150% uncertainty	9 to 920

From the estimates of the verification times shown in Table 69, it can be seen that the fossil fuel balance shows the greatest temporal variations over time (9–287 years) for the basic cases (cases 1–3). The total flux balance (excluding fossil fuels) case has dramatically slower dynamics, as the biosphere reacts more slowly to change than does the fossil fuel system. The total flux balance (fossil fuels and ecosystems) is consequently an average for cases 1 and 2.

The Kyoto mimic case, illustrated through different uncertainty rates for Kyoto measures (Table 69), shows that taking the uncertainties into account increases the verification times substantially: from 9 to 121 years if one assumes 0% uncertainty to 9 to 920 years for 150% uncertainty.

In the fossil fuels and Kyoto mimic cases, it can be concluded that the verification times depend heavily on the uncertainties connected with the estimation of the ABCs.

Based on this study and the following FOR studies – Jonas *et al*., 1998; Jonas *et al*., 1999a, b; Obersteiner *et al*., 2000 – we conclude:

- With no uncertainties included in the accounting, no verification can take place with respect to changes in the net emissions in 2010 (the commitment period according to the Kyoto Protocol).

- With no verification tool available, which follows from the above, we cannot compare the effectiveness of fossil fuel or land-use change and forestry activities with respect to reduced emissions.

- There is no possible way to conduct top-down verification (atmospheric measurements) for individual biosphere components.

- There is no possible way to verify that so-called Kyoto measures do not influence the non-Kyoto biosphere from the carbon balance viewpoint.

- The reductions of emissions are small during the commitment period and the uncertainties are large.

- From the above it follows that FCA with uncertainty estimation is essential for all carbon accounting.

The overall policy conclusion based on this study and adjunct FOR studies is that given the uncertainties in place most of the so-called Annex 1 countries of the Kyoto Protocol will not be able to verify their Kyoto targets at the country level.

13. Conclusions

Developing the first FCA for Russia has enabled FOR to understand the atmospheric balance better under current conditions. FOR also compared the results of FCA and PCA, and identified the sources of various discrepancies. We have concluded that the full carbon account is not any simple physical mass balance, but is driven by deep transformations with inputs not always equal to outputs. In our mean scenario we assume Russia will remain a net source of some 284 Tg C • yr^{-1} in 2010.

One of FOR's goals in conducting the Russian case study was to illustrate the uncertainties connected with an FCA. Many of these uncertainties stem from a lack of data and from insufficient methods for analyzing even the data available. Below we identify some of the needs for data and methodology that would permit future research efforts to refine our results and develop a more complete and accurate FCA.

13.1 Data

With respect to data and the FCA for Russia, the first problem confronting the investigator is that different data sources use different classifications and definitions, which makes data compilation highly demanding in terms of time and human resources. The amount and detail of data required for the FCA are huge. In addition, most of the available data required for carbon accounting are not collected for that purpose.

This study used new and more comprehensive input data than that presented in earlier studies of the carbon account for Russia. We also used new and consistent classifications and definitions of the data employed in this study compared to earlier studies. In spite of these efforts, there are still many shortcomings connected with the basic data used in this study. Our experience in preparing the FCA identified the following data requirements to support future carbon accounting analysis:

- Improved consistency and compatibility of classifications and definitions used.
- More comprehensive data covering all aspects of the carbon account, including data that accurately describe the dynamics of disturbances as well as knowledge and data about several ecological processes, in order to reduce the uncertainties of the FCA.
- Longer historical data series (not available today) in order to cover many important components of the full carbon budget.
- Efficient remote sensing data collection, especially to cover the data series and disturbances aspects, as well as for reliable verification of possible implementation of the Kyoto Protocol.
- Systematic sensitivity analysis of input data used in the FCA in order to identify the needs for improvements of existing inventory methods.
- Completely new data systems for carbon accounting.
- An integrated land information system containing a multi-layer GIS on relevant scales with connected attributive databases.

- Information systems capable of describing interactions among different land classes and adjoined landscapes.

13.2 Methodology

We believe that we have carried out consistent and transparent estimates of the FCA for Russia. However, there are clearly significant uncertainties connected with the existing estimates that cannot be evaluated without considering the overall uncertainty issue. Other aspects that must be addressed in any evaluation are the importance of individual components of the FCA and management of the components in carbon-directed regimes. Formal methods of mathematical statistics to estimate accuracy can only be applied to parts of the FCA. Therefore, there is a need for new and more complete approaches to assess the uncertainties connected with the FCA process. Reliable policy recommendations in the future require that the uncertainties in the FCA be dramatically reduced.

This study used an integrated GIS framework based on integrated soil/vegetation units. To our knowledge, none of the earlier studies of the Russian carbon account used this approach. However, we did not work with any comprehensive vegetation-soil-modeling environment; such an environment should be developed in the future.

Based on the experience gained in conducting this study and comparisons with other existing studies, we conclude that the methodologies currently available are not satisfactory for carbon accounting. Thus, substantial work is required to develop new and more comprehensive methods. Linked to the methodology are the scaling and connected impacts on the estimates of the FCA. Given the current state of the art, it seems plausible that our approach has exhausted the possibilities of decreasing the uncertainties in the aggregate carbon account for total Russia for some time.

To complete the FCA for Russia we were forced to perform a huge number of system calculations. From these calculations it can be seen that the results are very sensitive to how the boundaries of the system are set. Therefore, any future analysis of carbon accounts should be accompanied by clear illustrations of the boundaries of the overall system and the subsystems used in the analysis.

13.3 New Research Directions

The next step in improving the FCA for Russia requires that a number of new investigations be carried out. Examples are studies of fire in remote areas, anthropogenic transformation of forests, and fluxes from permafrost and wetlands, as well as comprehensive integration of the vegetation-soil-modeling environment, and efficient modeling of the dynamics of terrestrial ecosystems. All of these activities will take substantial time to finalize.

In this situation, two new research directions seem especially promising. The carbon balance is only one component of the total greenhouse gas balance for Russia. A logical next step would be to start from the carbon budget presented here and to add data on the other greenhouse gases for which information is available in order to come up with an estimate of the total greenhouse gas balance for Russia and connected uncertainties and verification times.

FOR carried out its analysis of the carbon account for Russia without any consideration of targeted carbon management. Other IIASA studies (e.g., Shvidenko *et al.*, 1996, 1997) show a large potential for increasing carbon sequestration through changed management of terrestrial ecosystems. Another valuable research direction would be to take the current carbon analysis as a platform and investigate how targeted carbon management (e.g., land management, as presented by Smith *et al.*, 2000) could improve Russia's current carbon balance.

13.4 Overall Policy Conclusion

The overall policy conclusion based on this study and adjunct FOR studies is that, given the uncertainties in place, most of the so-called Annex 1 countries of the Kyoto Protocol will not be able to verify their Kyoto targets at the country level.

Appendix 1. Selection Criteria Used in Creation of Land Class Map and Land Class Balance for 1990.

Table A1.1 shows the decision steps used to create the LCM. The input maps used were the VEG, SOIL, CAT, ECO, ADM, LND and PHYS maps described in Section 2.2 (see Table 1). The order of the listing of land classes indicates the order in which areas were assigned. For each administrative unit we attempted to match the area distribution of land classes in the SLA as closely as possible.

Table A1.1: Selection criteria used in creation of land class map for RFCB.

Land Class and Definition	Selection Criteria
Non-Vegetation. Areas without vegetation considered in the FCA.	All non-vegetated classes from *all* input maps.
Swamps. Wetlands, often with a woody substrate, well decomposed peat or a mixture of mineral & organic material.	Shallow peat soil types selected from Soil Map.
Bogs. Wetlands isolated from mineral rich soil waters, strongly acid & extremely nutrient poor, peat usually >50cm deep, usually covered with *Sphagnum* spp.	Deep peat soil types selected from Soil Map.
Cropland. Areas under cultivation.	Primary cropland land use areas (selected from Land Use Map) occurring on soil types (from Soil Map) considered most likely to support cultivation.
Pastures. Areas not cultivated and used for grazing.	Primary cropland land use areas (selected from Land Use Map) occurring on soil types (from Soil Map) considered most likely to support cultivation.
Forest. By definition, forests have relative stocking greater than or equal to 10 for young age groups and greater than or equal to 30 for all other age groups.	Forest land classes were selected from the Vegetation Map. Using information from the Soil Map, areas were assigned to species, stocking and site index classes to match the State Forest Account as closely as possible.
Non-Forest Vegetation.	All remaining vegetated classes were assigned to this class.

Table A1.2 presents the 1990 land class balance for Russia.

Table A1.2: Land-class areas by bioclimatic zones (1990), in 10^6 ha.

Bioclimatic Zone	Agricultural Land				Forest	Wetlands			Grass and Shrub	Total
	Total	Including				Total	Including			
		Crop	HLP	PER			Swamp	Bog		
Polar desert	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7
Tundra	1.8	0.0	1.8	0.0	3.8	62.3	53.4	8.9	199.0	266.9
Forest tundra, sparse & northern taiga	1.5	0.3	1.3	0.0	141.2	64.7	28.2	36.5	25.5	233.0
Middle taiga	14.6	5.3	9.2	0.1	455.0	62.0	21.2	40.8	152.0	683.6
Southern taiga	35.3	24.2	10.5	0.7	126.5	30.1	1.6	28.5	19.5	211.5
Temperate forests	29.4	21.2	7.2	1.1	26.4	1.8	0.6	1.2	2.6	60.3
Steppe	111.7	75.0	36.1	0.6	9.3	0.7	0.5	0.2	26.7	148.4
Semi-desert & desert	17.3	4.3	12.9	0.1	1.3	0.4	0.3	0.1	6.5	25.5
Non-vegetated land										79.6
Total	211.9	130.3	79.0	2.6	763.5	222.0	105.8	116.2	432.5	1709.5

Appendix 2. Auxiliary Models

A2-1. Forest Phytomass Models

FOR developed a system of multidimensional nonlinear regression equations to estimate major forest phytomass fractions for main forest-forming species at the subregional level. Drawing on a database that includes roughly 2700 sample plots from more than 200 regional studies, we estimated equations for species covering 94% of the Russian forested areas and concluded that (1) indicators reported in the aggregated SFA covering age, site index and relative stocking over dominant species could be used as input variables in nonlinear regression equations, (2) the ratio $R_f = M_f / GS$, where M_f is mass of a fraction, and *GS* is growing stock volume is especially informative. The most adequate equations were selected from eight examined analytical types in the form of:

$$R_{fr} = M_{fr} / GS = c_0 \, SI^{c_1} A^{(c_2 + c_3 RS + c_4 RS^2)}, \text{ or } R_{fr} = c_0 \, A^{c_1} \, SI^{c_2} \, RS^{c_3} (c_4 + c_5 RS) \quad \text{(A2.1)}$$

where *A*, *SI*, *RS* are, respectively, age, site index and relative stocking of stands, and c_0, c_1, c_2, c_3, c_4, c_5 are regression coefficients.

The theoretical background for the modeling, experimental data, analytical forms and accuracy of the models are discussed in Shepashenko *et al*. (1998) and Shvidenko *et al*. (1999).

A2-2. Models of Growth and Productivity of Russian Forests

A system of models for growth and productivity of Russian forests was developed based on roughly 200 different growth and increment models and yield tables. The modified Richard-Chapman equation was used as an analytical basis for the system. It comprises models of more than 1500 dynamic rows. The system is designated for the evaluation of gross and net growth and mortality of forests. A detailed description of the system and results of its application are given in Shvidenko *et al*. (1995, 1997), and Venevsky and Shvidenko (1997).

A2-3. Models of Agricultural Productivity

The system includes crop and livestock production and soil degradation development. It comprises linear and non-linear regression equations of productivity change depending on projections of land use dynamics. The system has been used for the assessment of the productivity in agriculture, above and below-ground by-products and phytomass and the assessment of the major carbon fluxes associated with the harvest, organic mineralization, humification and erosion.

Appendix 3. The Theory of Error Propagation

The formulation used below deviates from the role of aggregation recommended by the IPCC (1999) with respect to inclusion of correlations among variables, which are of high importance for biological systems. The following steps are necessary for a relevant application of the theory of propagation. The *first* prerequisite is that the summarized error of any initial variable used should be estimated either in the classical sense (e.g., precision of measurements), or based on reported direct and indirect evidences (e.g., historically known absolute or relative errors (precision) or confidential limits of a definite method (value), for instance average soil organic carbon content in an estimated horizon of a definite soil type). Sometimes it is inevitable to base such conclusions on expert estimates. The latter leads to the obligatory use of *a priori* or *personal probabilities*. The *second* prerequisite requires the availability of an explicit algorithmic form for the carbon accounting. In its general form, the FCA is presented as a consecutive chain of recurrent functionals, for instance,

$$U = f(V_i),\ V_i = \phi(Q_{ij}),\ \ldots,\ Y_{ij\cdots k} = \varphi(X_{ij\ldots 1}, X_{ij\ldots 2}, \ldots, X_{ij\ldots n}), \qquad \text{(A3.1)}$$

where U is a final result (carbon flux or pool), V_{ij} are intermediate results of the top aggregation level, e.g., for a process i and(or) aggregation unit j, etc., and at the lowest (finest) level of a set $X\ldots \in \{X\ldots_1, X\ldots_2, \ldots, X\ldots_n\}$ is a part of initial variables.

Then, if m_{Xk} is introduced above the summarized error of initial variables $X\ldots. \in \{X\ldots_1, \ldots, X\ldots_n\}$, and under the assumption that all functionals in the above equation are differentiated by all variables (what is true for all analytical expressions of the carbon account), the precision of all intermediate and final results could be estimated (*cf*. Kendall and Stuart, 1966) in an explicit form, e.g., for the first level of modeling (calculation)

$$m_y^2 = \sum_{i=j} \left(\frac{\partial y}{\partial x_i} mx_i\right)^2 + 2\sum_{i \neq j} \left(\frac{\partial y}{\partial x_i}\right)\left(\frac{\partial y}{\partial x_j}\right) r_{ij} mx_i mx_j + \ldots \qquad \text{(A3.2)}$$

what can be easily transformed to relative errors (in percentage) too, as $P_y^2 = m_y^2/Y^2$. If variables $X\ldots \in \{X_1, X_2, \ldots, X_k\}$ are independent, the last equation is simplified in an evident way (r_{ij}=0), but as a rule it is not the case for the FCA.

Usually m_y is interpreted based on the normal frequency distribution theory that is hypothetical for many cases, but it could be shown that the use of this assumption does not change the sense and magnitude of the summarized error comparatively with more common approaches, e.g., Tschebishev's theorem. The important practical limitation pertains to the requirement that all variables could have a bias (systematic component of the summarized error), which must not exceed 10–15% of the absolute value. In our calculations we used the above described approach (confidential probability was in the range 0.85–0.90) for the following goals:

1) for calculations of standard errors of intermediate results if estimates of precision of initial (previously used) data were known;
2) for estimations of summarized errors if personal (a priory) probability were used due to either lack or statistical insufficiency of data and results, and
3) for examination of sensitivity of final results to the variability (uncertainties) of initial and intermediate indicators in the framework of the accounting schemes used.

Appendix 4: Derivation of Precision and Uncertainty Estimates of Forest Phytomass by the State Forest Account (SFA)

A4-1. Assumptions

The following assumptions were used in the calculations:

- Data of the SFA do not have any systematic errors (bias) at an accepted level of significance.
- Regression equations of forest phytomass do not generate any bias.

A4-2. Designations

A4-2.1 Indexes used

i is phytomass fraction, $i = 1, ..., 7$;
ρ is dominant species (DS), $\rho = 1, ..., 27$;
m is ecoregion, $m = 1, ..., 141$;
k is number of stands (primary inventory units) inside the initial information matrix (see Section 2), $k = 1, ..., l_{m\rho}$.

A4-2.2 Variables

M	is dry mass of fraction, Tg;
GS	is growing stock volume, m^3;
A, SI, RS	is age, site index and relative stocking, respectively;
δ	is content of carbon in phytomass.

A4-3. Initial Data

The initial information matrix has the following form:

Ecoregion	FIT	DS	Variables	Age Classes				SI	RS
				A_1	A_2	...	A_q		
m_1	r_{m_1}	ρ_1	S	S_{11}	S_{12}	...	S_{1q}		
			GS	GS_{11}	CS_{12}	...	GS_{1q}	SI_{ρ_1}	RS_{ρ_1}
		ρ_2	S	S_{21}	S_{22}	...	S_{2q}		
			GS	GS_{21}	GS_{22}	...	GS_{2q}	SI_{ρ_2}	RS_{ρ_2}

Forest inventory type (FIT) is used for the approximate estimation of SE_{GS}-summarized error of growing stock (see Section 4); five forest inventory types are used:

1–3: Three levels of forest inventory and planning (in Russian: razrjad lesoustroistva).
4: Remote sensing inventory.
5: So-called aerotaxation.

SI and RS are used as averages for species ρ of an ecoregion m.

A4-4. Algorithm

The phytomass of fraction i, dominant species ρ, ecoregion m is calculated as

$$M_{i\rho m} = \delta_i \cdot \sum_{A=1}^{q} (R_{i\rho mA} \cdot GS_{\rho mA}) \tag{A4.1}$$

where

$$R_{i\rho mA} = c_0 SI^{(c_1 A^{c_2 + c_3 RS + c_4 RS^2})} \tag{A4.2}$$

c_0, c_1, c_2, c_3, c_4 are regression coefficients.

Then, the total phytomass of forest ecosystem vegetation is

$$M = \sum_{m=1}^{147} \sum_{\rho=1}^{27} \sum_{i=1}^{7} M_{i\rho m} \tag{A4.3}$$

A4-5. Estimation of Precision (in terms of summarized errors)

A4-5.1 Summarized errors (SE) of initial variables

For age $A = A_t$ (of ecoregion m, dominant species ρ) an approximate number of primary inventory units is defined as

$$n_{A_t} = int[S_t \cdot \bar{S}_R^{-1}] \tag{A4.4}$$

where $int[S_t \cdot \bar{S}_R^{-1}]$ is an integral part of the number in brackets, and $\bar{S}_R$ is an average area of a primary inventory unit of a given forest inventory type.

Thus, the SE of initial variables, with probability 0.9, are defined by

$$SE_{GS_{A_t}} = \frac{\alpha GS_{A_t}}{\sqrt{n_{A_t}}}, \quad \alpha = 0.12 \tag{A4.5}$$

$$SE_{SI_\rho} = \frac{1}{\sqrt{n_{A_t}}} \tag{A4.6}$$

$$SE_{RS_\rho} = \frac{\beta}{\sqrt{n_{A_t}}}, \quad \beta = 0.15 \tag{A4.7}$$

There are about 60 million primary inventory units in Russia, 141 ecoregions, about 10 (major) dominant species in an ecoregion, and some 10 age classes per species. The average n_{A_t} is about 4000.

A4-5.2 Precision of intermediate and final results

The SE of phytomass $M_{i\rho m}$ is defined by equation (A4.7), and

$$SE^2_{M_{i\rho m}} = \left(\frac{\partial M_{i\rho m}}{\partial \delta_i} \cdot SE_{\delta_i}\right)^2 + \sum_A \left[\left(\frac{\partial M_{i\rho m}}{\partial R_{i\rho mA}} SE_{R_{i\rho mA}}\right)^2 + \left(\frac{\partial M_{i\rho m}}{\partial GS_{\rho mA}} \cdot SE_{GS_{\rho mA}}\right)^2\right] \tag{A4.8}$$

where $\partial M_{i\rho m}/\partial x_i$, $x_i = \delta_i, R_{i\rho mA}, GS_{\rho mA}$ are partial derivatives of the above variables, which are expressed as

$$\begin{aligned} \frac{\partial M_{i\rho m}}{\partial \delta_i} &= \sum_{A=1}^{q} (R_{i\rho mA} \cdot GS_{\rho mA}) \\ \frac{\partial M_{i\rho m}}{\partial R_{i\rho mA}} &= \delta_i GS_{\rho mA} \\ \frac{\partial M_{i\rho m}}{\partial GS_{\rho mA}} &= \delta_i R_{i\rho mA} \end{aligned} \tag{A4.9}$$

Errors $SE_{R_{i\rho mA}}$ in equation (A4.8) depend on errors in parameters c_j, $j = 0, ..., 4$ and variables SI, A, RS, and values of the corresponding partial derivatives of phytomass ratio $R = R_{i\rho mA}$ in regression equation (A4.2), which is presented in the following table.

Variables	Partial Derivatives	Relative value
$\frac{\partial R}{\partial c_0}$	$SI^{c_1} A^{(c_2+c_3RS+c_4RS^2)}$	$\frac{1}{c_0}$
$\frac{\partial R}{\partial c_1}$	$c_0 SI^{c_1} lnSI \cdot A^{(c_2+c_3RS+c_4RS^2)}$	$lnSI$
$\frac{\partial R}{\partial c_2}$	$c_0 SI^{c_1} A^{c_2} lnA \cdot A^{(c_3RS+c_4RS^2)}$	lnA
$\frac{\partial R}{\partial c_3}$	$c_0 SI^{c_1} lnA \cdot RS \cdot A^{(c_2+c_3RS+c_4RS^2)}$	$lnA \cdot RS$
$\frac{\partial R}{\partial c_4}$	$c_0 SI^{c_1} \cdot A^{(c_2+c_3RS+c_4RS^2)} \cdot lnA \cdot RS^2$	$lnA \cdot RS^2$
$\frac{\partial R}{\partial SI}$	$c_0 \cdot c_1 SI^{(c_1-1)} A^{(c_2+c_3RS+c_4RS^2)}$	$\frac{c_1}{SI}$
$\frac{\partial R}{\partial A}$	$c_0 SI^{c_1} (c_2 + c_3RS + c_4RS^2) A^{(c_2+c_3RS+c_4RS^2-1)}$	$\frac{(c_2+c_3RS+c_4RS^2)}{A}$
$\frac{\partial R}{\partial RS}$	$c_0 SI^{c_1} A^{(c_2+c_3RS+c_4RS^2)} lnA \cdot (c_3 + 2RSc_4)$	$lnA \cdot (c_3 + 2RSc_4)$

The $SE^2_{R_{i\rho mA}}$ could be expressed in the form of the relative error $SE_{R_{i\rho mA}}$

$$\begin{aligned} SE^2_{R_{i\rho mA}} &= \left[\frac{1}{c_0} SE_{c_0}\right]^2 + [lnSI \cdot SE_{c_1}]^2 + [lnA \cdot SE_{c_2}]^2 + \\ &+ [RS \cdot lnA \cdot SE_{c_3}]^2 + \left[RS^2 \cdot lnA \cdot SE_{c_4}\right]^2 + \left[\frac{c_1}{SI} SE_{SI}\right]^2 + \\ &+ \left[\frac{c_2 + c_3 RS + c_4 RS^2}{A} SE_A\right]^2 + [lnA(c_3 + 2RS \cdot c_4) \cdot SE_{RS}]^2 \quad \text{(A4.10)} \end{aligned}$$

Finally, the summarized error of total phytomass of Russian forests is

$$SE^2_M = \sum_m \sum_\rho \sum_i SE^2_{M_{i\rho m}} \quad \text{(A4.11)}$$

The calculations are provided over fractions and species inside ecoregions, and are later summarized for ecoregions.

The simplified calculations, employing ecoregions, indicate that the summarized error for total forest phytomass is in the range of 2.5–3.3%, which gives about 4% for forest phytomass in Russia. This means that the confidence limits are 66.45 ± 2.65 Pg of dry matter. Precision of the carbon stock estimate depends upon whether δ_i is considered as an exact or an approximate value. We used the expert estimate $SE_{\delta_i} = 2.5\%$ (i.e., $SE_{\delta_i} = 0.0125$ for woody parts and $SE_{\delta_i} = 0.00111$ for green parts), which resulted in the summarized error of total phytomass carbon of about ±4.7%, or confidence limits of $32.9 \pm 1.55 PgC$ (confidence probability 0.9).

A4-6. Validation of Possible Biases

Estimating the uncertainties involves examining the assumptions and imperfections of the models used, which could be used to help to illustrate possible biases.

We realize that our assumption that the SFA data have no biases is not true; in the 1990s the bias of the officially reported total growing stock is estimated at –5.1% (Shvidenko and Nilsson, 1997). Nevertheless, there are indications that this bias should not be taken into account for forest phytomass estimation. In 1990, about 46% of Russian forests by area and 59% by growing stock were composed of mature, overmature, and uneven-aged stands. The major forest forming species in these stands have a significant amount of trunk and root decay: up to 10% in forest stands (Alexeyev and Birdsey, 1994) and up to 15–17% in larch stands of Central Jakutia. Our conservative calculations gave a very rough estimate of the biases of about 2.4% for total growing stock. The latter should be increased about two times due to the method used. Thus, the bias indicated above is completely compensated.

We verified the forest phytomass regression equations by the standard analysis of residual distribution, and concluded that (with respect to the data used) the equations have no significant bias.

We provided a comparison of our estimates with independent estimations from other sources. From eight available estimates of forest phytomass in Russia during the last two decades we could select only three, after careful control. The rest of the studies had evident gaps in information or methodology. To these three estimates we added the GIS-based estimate produced in this study. The comparison was carried out with respect to carbon densities.

	$kgC \cdot m^{-2}$
Isaev *et al.* (1995)	4.549
Isaev and Korovin (1998)	4.506
Alexeyev and Birdsey (1994)	3.632
IIASA–GIS method (in this report)	4.403

The average of these estimates is 4.272 $kgC \cdot m^{-2}$, or –0.75 compared to our main estimate (4.304 $kgC \cdot m^{-2}$). Standard statistical analysis leads to the conclusion, with probability close to 1.0, that our estimate belongs to the analyzed set.

Nevertheless, there are a number of assumptions and simplifications unaccounted for in the analysis. This is the reason for analyzing the sensitivity of the variability of initial data, models, and assumptions.

Under reasonable assumptions of the increase of uncertainties of initial data and assumptions the sensitivity analysis leads to increased SE of the total phytomass to 6–7%.

Appendix 5. Total Flux Balance of 1990 (with and without energy and industrial sectors)

Item	Flux	This Study		Other Studies		
		Tg C	Reference/Remark	Tg C	Range	Reference/Remark
Fluxes into Atmosphere (I)						
All Energy (Fuel Combustion + Fugitive)				**All Energy (Fuel Combustion + Fugitive)**		
Energy CO_2-C	I			640		NCR (1995): Including: bunker fuels [≈ 45.8 Tg C accd'g. to CS1 (1997)] and gas combustion at oil fields
				625		CS1 (1997): Including: 'coal dump burning', release from underground coal mines and flaring of natural gas. Excluding: losses due to leaks etc. [≈ 36.2 Tg C] and bunker fuels [≈ 45.8 Tg C]
		650		**650**	**585–715**	ECS (1998): Including fugitive emissions; reduced by reinjection/ scrubbing and non-energy use; Victor *et al.* (1998): The 1990 C emissions data are probably uncertain by as much as ± 10%.
Energy CH_4-C	I			14.7		NCR (1995): Including: gas production, transportation and consumption; coal production; and oil production and transportation
		14.5		**14.5**	**11.3–22.5**	CSSR (1997), CS1 (1997): Including: fugitive emissions from coal mining and handling activities; from oil and natural gas; and from fuelwood burning
Industrial Processes & Solvent and Other Product Use				**Industrial Processes & Solvent and Other Product Use**		
Industrial Processes	I	11		11		NCR (1995): Excluding emissions from fuels used for cement production; CSSR (1997), CS1 (1997): 11.31 Tg C in 1991
Total: Energy + Industrial Processes	**I**	**676**		**676**	**607–749**	

Item	Flux	This Study		Other Studies		
		Tg C	Reference/Remark	Tg C	Range	Reference/Remark
Fluxes into Atmosphere (I)						
Soil CO_2-C Respiration, Incl. Past LUC Changes				**Soil CO_2-C Respiration, Incl. Past LUC Changes**		
Cropland (incl. land-use management)	I	488		30	20-40	CSSR (1997): Average annual humus-C loss over 32 years (1950-82); CS2 (1997): Value unknown. The relevant pages, 50-58, are missing and not retrievable.
Pasture	I	177		n.a.		
Forest	I	1367	Values have been created by multiplying daily emissions (Kudeyarov *et al.*, 1996; Kudeyarov, 1999) with calculated number of days with temperature >0°C (based on Leemans and Cramer, 1991) and soil area.	n.a.		
Wetlands	I	368		n.a.		
Grasslands & Shrubs	I	798		n.a.		
Soil CH_4 –C Respiration, Incl. Past LUC Changes				**Soil CH_4 –C Respiration, Incl. Past LUC Changes**		
All soils	I	20	Values for the emission are taken from Rozanov (1995) and Zelenev (1996).	18.0	4.1–82.3	Zelenev (1996): Methane emitted from soils minus methane consumed by soils
Total: Soils (CO_2-C + CH_4-C)	**I**	**3218**		**48**	**24–122**	
Disturbances				**Disturbances**		
Forest disturbances	I	193	For details on the carbon budget of forest disturbances see (Nilsson and Shvidenko, 1998) and forest products see (Obersteiner, 1999). The area data come from Forest State Account and Land State Account and soil degradation database (Stolbovoi and Fischer, 1998) and Integrated Land Cover Database (this study).	n.a.		CS2 (1997), (CSSR (1997): Consider also direct CO_2-C emissions from fires; these emissions are included in Russia's forest sink strength reported below and, unfortunately, are not reported separately for 1990.
Wetland fires	I	23		n.a.		Recalling: IPCC (1997) assumes CO_2-neutrality [except for: (1) changes in forest and other woody biomass stocks; (2) forest and grassland conversion; and (3) abandonment of managed lands].
Grasslands & Shrubs disturbances (fire & transformation)	I	46		n.a.		
Total: Disturbances	**I**	**262**		n.a.		
NPP Produced and consumed in disturbance year	**I**	**42**		**n.a.**		
Decomposition of above ground wood	**I**	**53**		**n.a.**		

Item	Flux	This Study		Other Studies		
		Tg C	Reference/Remark	Tg C	Range	Reference/Remark
Fluxes into Atmosphere (I)						
Agriculture: Land Management				**Agriculture: Land Management**		
Manure application	I	56	Data come from agricultural statistic (Agriculture, 1995) referenced by oblasts. Transformation rates derived from IPCC 1997.	n.a.		
Peat application	I	31	Taken from wetland disturbances - peat humification	n.a.		
Total: Agriculture: Land Management	I	**87**		n.a.		
Agriculture: Livestock				**Agriculture: Livestock**		
Respiration	I	219	The respiration rate is taken from Jonas *et al.*, (1997). The number of animals originates from agricultural statistics. Also included is emission from grazing on grasslands and shrubs (65)	n.a.		
Livestock enteric fermentation + Manure management	I			3.7		NCR (1995): Reports only the sum of the two emission sources
Livestock enteric fermentation	I	5		**3.20**		CSSR (1997), CS2 (1997)
Manure management	I		Manure storage is not proposed. Calculation is based on agricultural statistics (Agriculture, 1995) that have been georeferenced by oblasts.	**0.37**		
Sub-products and wastes	I	19	Taken from agricultural statistics	n.a.		
Total: Agriculture: Livestock	**I**	**243**		**4**		
Other Consumption of Biomass	**I**	**363**	Includes agricultural products, forest products and biomass from grasslands and shrubs.	**n.a.**		
Additional Fluxes						
Imported grain	**I**	**9**				
Liming emission	**I**	**4**				
Grand Total: Into Atmosphere	**I**	**4957**	Sum of all fluxes (i.e., including energy/industry-related fluxes)	**755 (728)**	**635–875**	
Ecosystem Total: Into Atmosphere	**I**	**4281**	Sum of all ecosystem-related fluxes	**77 (52)**	**28–126**	

Item	Flux	This Study		Other Studies		
		Tg C	Reference/Remark	Tg C	Range	Reference/Remark
Fluxes out of Atmosphere (O)						
Net Primary Production (NPP)				**Forest, Peat and Tundra Pool (F, P, T) Sink Strengths**		
Cropland	O	649		n.a.		
Pasture	O	309		n.a.		
Forest	O	1707		107		CS2 (1997), CSSR (1997): Direct CO_2-C emissions from forest fires are included; NCR (1995): Reports a total forest sink strength of 160 Tg C yr^{-1} (incl. fires), but with reference to the year 1993
Wetlands	O	487		24	9.5–38.0	CSSR (1997), CS2 (1997): Report this CO_2-C tundra sink strength with reference to "present times". [CH_4-C emissions in the order of (0.31-1.25) Tg C yr^{-1} are not included here.]
Grasslands & Shrubs	O	1202		40		NCR (1995), CSSR (1997): Report this net peat CO_2-C sink strength (carbon accumulation minus emissions from peat use) with reference to "present times"
Total: NPP and FTP (Non-dist. Areas)	**O**	**4353**		**171**	**157–185**	
Deposition: Atmospheric Precipitation				**Deposition: Atmospheric Precipitation**		
HCO_3 with precipitation	O	77		n.a.		
Total Deposition	**O**	**77**		**n.a.**		
Grand Total: Out of Atmosphere	**O**	**4430**	**Sum of all fluxes**	**171**	**157–185**	
Balances						
Atmospheric Balance: Into Atmosphere ↔ Out of Atmosphere (I-O)		**527**	Net flux, considering all fluxes (i.e., including energy/industry-related fluxes): directed into the atmosphere	**584 (557)**	**450–718**	
Atmosphere-Terrestrial Ecosystem Balance: Into Atmosphere ↔ Out of Atmosphere (I-O)		**-149**	Net flux, considering all ecosystem-related fluxes: directed into Russia's terrestrial ecosystem	**-94 (-119)**	**-(31–157)**	

Appendix 6. Modular Budgets for 2010 Scenarios

Table A6.1. 2010 Lower Scenario, Agriculture Sub-Budget.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
Above ground					Above-ground NPP	562		
							Agricultural harvest to animal husbandry	
							hay	-175
							grain	-31
							straw	-57
							grazing	-94
							residual to other consumption	**-139**
					Ppt	10		
Below ground					below ground NPP	450		
			Erosion	-18				
							manure	53
							liming (emissions from 31.5 Mt)	4
							peat from wetlands	17
			humification of peat	2				
			humification of manure	9				
			humification	67				
	Soil C-CO2 respiration	710						
	Manure emission	43						
	Peat emission	15						
	Liming emission	4						
			Leaching	-17				
			Soluble SOC	-10				
			Surface runoff	-4				
	TOTAL FLUX	**768**		**29**		***1,022***		***-426***
	Atmosphere-ecosystems exchange	-254						
	Flux balance	172						

**Fluxes from imported grain and lime application are accounted separately from the modules although they are reported in the animal husbandry and agricultural modules.

Table A6.2. 2010 Lower Scenario, Animal Husbandry Sub-Budget.

Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
						harvest from agriculture	356
						from imported grain	9
						grazed from grasslands and shrubs	61
Respiration	127						
Fermentation	4						
						meat (to other consumption)	-4
						eggs (to other consumption)	-4
Sub-products, wastes, etc.	19						
Respiration from grasslands grazed	61						
						residual (to other consumption)	-156
						manure to agriculture	-53
TOTAL FLUX	**201**						201
Atmosphere-ecosystems exchange	0						
Flux balance	0						

**Fluxes from imported grain and lime application are accounted separately from the modules although they are reported in the animal husbandry and agricultural modules.

Table A6.3. 2010 Lower Scenario, Other Consumption Sub-Budget.

Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
						from agriculture	139
						from animal husbandry	163
						forest products	41
						wetlands	4
						Land management & domestic consumption	27
						Wild fauna	13
Residual from agriculture	139						
Total from Animal Husbandry	163						
Forest products	41						
Wetlands	4						
Land management & domestic consumption of grasslands	27						
Wild fauna	13						
TOTAL FLUX	**387**						***387***
Balance	387						
Flux balance	0						

Table A6.4. 2010 Lower Scenario, Forest Sub-Budget.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from outside Sub-budget	
	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
Above ground					Above ground NPP	1,446		
	Disturbances							
	fire	83						
	pests	75						
	harvest	16						
	abiotic	53						
							Forest Products	-41
	NPP produced and consumed in year of dist.	7						
			phytomass	-43				
			CWD	94				
					ppt	36		
Below ground					Below ground NPP	334		
			Humification	114				
			Charcoal	5				
	Soil C-CO2 respiration	1,380						
	Increase in soil respiration following drainage	4						
			Leaching	-64				
			Soluble SOC	-34				
			Surface runoff	-14				
	TOTAL FLUX	1,617		58		1,816		-41
	Atmosphere-ecosystems exchange	-199						
	Flux balance	-157						

Table A6.5. 2010 Lower Scenario, Wetlands Sub-Budget.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
Above ground					Above ground NPP	315		
	Disturbances							
	fire	30						
							Peat usage to agriculture	-17
							Domestic use	-4
	Produced but consumed NPP	16						
					ppt	10		
Below ground					Below ground NPP	186		
			Accumulation	46				
			Humification	25				
	Soil C-CO2 respiration	360						
			Leaching	-19				
			Soluble SOC	-10				
			Surface runoff	-4				
	TOTAL FLUX	406		38		511		-20
	Atmosphere-ecosystems exchange	-105						
	Flux balance	-85						

Table A6.6. 2010 Lower Scenario, Grasslands and Shrubs Sub-Budget.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
Above ground					Above ground NPP	459		
	Disturbances							
	fire	47						
	transformation	7						
	Decomposition of above-ground wood***	53						
	Produced but consumed NPP	21						
							Domestic livestock grazing	-61
							Land management & domestic consumption	-27
							Wild fauna	-13
			phytomass					
					ppt	20		
Below ground					Below ground NPP	730		
			Erosion	-7				
			Humification	67				
	Soil C-CO2 respiration	745						
			Leaching	-36				
			Soluble SOC	-19				
			Surface runoff	-8				
	TOTAL FLUX	874		-3		1,209		-101
	Atmosphere-ecosystems exchange	-336						
	Flux balance	-235						

Table A6.7. 2010 Lower Scenario, Summary of Sub-Budgets.

Module	Flux into atmosphere Tg C•yr^{-1}	Pool Change* Tg C•yr^{-1}	Flux out of Atmosphere Tg C•yr^{-1}	Inter-module Transfer from modules Tg C•yr^{-1}	Flux Balance into-out-transfer Tg C•yr^{-1}
Agriculture	768	29	1,022	-426	172
Animal husbandry	201			201	0
Biomass consumption	387			387	0
Forest	1,617	58	1,816	-41	-157
Wetland	406	38	511	-20	-85
Grassland & shrub	874	-3	1,209	-101	-235
Soil CH4-C Respiration	20				20
*Additional fluxes ** *	*13*			*0*	*13*
Atmosphere-ecosystems total	**4,285**	**122**	**4,558**	**0**	**-272**
Module	Flux into atmosphere Tg C•yr^{-1}	Pool Change Tg C•yr^{-1}	Flux out of atmosphere Tg C•yr^{-1}	Inter-module transfer from modules Tg C•yr^{-1}	Flux Balance into-out-transfer Tg C•yr^{-1}
Energy and other sectors	428	0	0	428	0
Fossil fuel		-428		-428	0
GRAND TOTAL	**4,713**	**-306**	**4,558**	**0**	**156**

Table A6.8. 2010 Mean Scenario, Agriculture Sub-Budget.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
Above ground					above ground NPP	615		
							Agricultural harvest to animal husbandry	
							hay	-178
							grain	-31
							straw	-57
							grazing	-91
							residual to other consumption	-191
					ppt	10		
Below ground					below ground NPP	502		
			Erosion	-18				
							manure	63
							liming (emissions from 31.5 Mt)	4
							peat from wetlands	33
			humification of peat	2				
			humification of manure	11				
			humification	67				
	Soil C-CO2 respiration	758						
	Manure emission	52						
	Peat emission	31						
	Liming emission	4						
			Leaching	-17				
			Soluble SOC	-10				
			Surface runoff	-4				
	TOTAL FLUX	**840**		31		1,127		-452
	Atmosphere-ecosystems exchange	-286						
	Flux balance	166						

**Fluxes from imported grain and lime application are accounted separately from the modules although they are reported in the animal husbandry and agricultural modules.

Table A6.9. 2010 Mean Scenario, Animal Husbandry Sub-Budget.

Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
						from agriculture	357
						from imported grain	9
						from grasslands and shrubs grazed	56
Respiration	152						
Fermentation	5						
						meat	4
						eggs	4
Sub-products, wastes, etc.	19						
Respiration from grasslands grazed	56						
Residual						to other consumption	-137
						manure	-63
TOTAL FLUX	***223***						**222**
Atmosphere-ecosystems exchange	0						
Flux balance	0						

**Fluxes from imported grain and lime application are accounted separately from the modules although they are reported in the animal husbandry and agricultural modules.

Table A6.10. 2010 Mean Scenario, Other Consumption Sub-Budget.

Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
						from agriculture	191
						from animal husbandry	128
						forest products	43
						wetlands	7
						Land management & domestic consumption	25
						Wild fauna	12
Residual from agriculture	191						
Total from Animal Husbandry	128						
Forest products	43						
Wetlands	7						
Land management & domestic consumption of grasslands	25						
Wild fauna	12						
TOTAL FLUX	**406**						**406**
Balance	406						
Flux balance	0						

Table A.6.11. 2010 Mean Scenario, Forest Sub-Budget.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
Above ground					Above ground NPP	1,486		
	Disturbances							
	fire	83						
	pests	75						
	harvest	16						
	abiotic	60						
							Forest Products	-43
	Produced and Consumed NPP in year of dist.	7						
			phytomass	-43				
			CWD	94				
					ppt	36		
Below ground					Below ground NPP	343		
			Humification	114				
			Charcoal	5				
	Soil C-CO2 respiration	1,391						
	Increase in soil respiration following drainage	4						
			Leaching	-64				
			Soluble SOC	-34				
			Surface runoff	-14				
	TOTAL FLUX	1,637		58		1,864		-43
	Atmosphere-ecosystems exchange	-227						
	Dlux balance	-184						

Table A6.12. 2010 Mean Scenario, Wetlands Sub-Budget.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
Above ground					Above ground NPP	317		
	Disturbances							
	fire	25						
							Peat usage to agriculture	-33
							Domestic use	-7
	Produced but consumed NPP	16						
					ppt	10		
Below ground					Below ground NPP	187		
			Accumulation	46				
			Humification	25				
	Soil C-CO2 respiration	362						
			Leaching	-19				
			Soluble SOC	-10				
			Surface runoff	-4				
	TOTAL FLUX	403		38		513		-40
	Atmosphere-ecosystems exchange	-111						
	Flux balance	-71						

Table A6.13. 2010 Mean Scenario, Grasslands and Shrubs Sub-Budget.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
Above ground					Above ground NPP	427		
	Disturbances							
	fire	37						
	transformation	7						
	Decomposition of above ground wood***	53						
	Produced but consumed NPP	21						
							Domestic livestock grazing	-56
							Land management & domestic consumption	-25
							Wild fauna	-12
			phytomass					
					Atmosphere-ecosystems total	20		
Below ground					Below ground NPP	680		
			Erosion	-7				
			Humification	67				
	Soil C-CO2 respiration	694						
			Leaching	-36				
			Soluble SOC	-19				
			Surface runoff	-8				
	TOTAL FLUX	**812**		**-3**		**1,127**		-94
	Atmosphere-ecosystems exchange	-315						
	Flux balance	-221						

Table A6.14. 2010 Mean Scenario, Summary of Sub-Budgets.

Module	Flux into Atmosphere	Pool Change*	Flux out of Atmosphere	Inter-module Transfer	Flux Balance
	Tg C•yr^{-1}	Tg C•yr^{-1}	Tg C•yr^{-1}	Tg C•yr^{-1}	Tg C•yr^{-1}
Agriculture	840	31	1,127	-452	166
Animal husbandry	223			222	0
Biomass consumption	406			406	0
Forest	1,637	58	1,864	-43	-184
Wetland	403	38	513	-40	-71
Grassland & shrub	812	-3	1,127	-94	-221
Soil CH4-C Respiration	20				20
*Additional fluxes ** *	*13*			*0*	*13*
Atmosphere-ecosystems total	***4,355***	***124***	***4,632***	***0***	***-277***
Module	Flux into atmosphere	Pool Change	Flux out of atmosphere	Inter-module Transfer	Flux Balance
	Tg C•yr^{-1}	Tg C•yr^{-1}	Tg C•yr^{-1}	Tg C•yr^{-1}	Tg C•yr^{-1}
Energy and other sectors	561	0	0	561	0
Fossil fuel		-561		-561	0
GRAND TOTAL	**4,916**	**-437**	**4,632**	**0**	**284**

Table A6.15. 2010 Higher Scenario, Agricultural Sub-Budget.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
Above ground					above ground NPP	633		
							Agricultural harvest to animal husbandry	
							hay	-183
							grain	-32
							straw	-59
							grazing	-94
							residual to other consumption	-199
					ppt	10		
Below ground					below ground NPP	516		
			Erosion	-18				
							manure	75
							liming (emissions from 31.5 Tg)	4
							peat from wetlands	50
			humification of peat	2				
			humification of manure	13				
			humification	67				
	Soil C-CO2 respiration	764						
	Manure emission	62						
	Peat emission	48						
	Liming emission	4						
			Leaching	-17				
			Soluble SOC	-10				
			Surface runoff	-4				
	TOTAL FLUX	*873*		*33*		*1,159*		*-442*
	Atmosphere-ecosystems exchange	-286						
	Flux balance	156						

**Fluxes from imported grain and lime application are accounted separately from the modules although they are reported in the animal husbandry and agricultural modules.

Table A6.16. 2010 Higher Scenario, Animal Husbandry Sub-Budget.

Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
						from agriculture	368
						from imported grain	9
						from grasslands and shrubs grazed	55
Respiration	180						
Fermentation	5						
						meat	5
						eggs	5
Sub-products, wastes, etc.	19						
From grasslands and shrubs grazed	55						
Residual						to other consumption	-109
						manure	-75
TOTAL FLUX	**250**						249
Balance	0						
Flux balance	0						

**Fluxes from imported grain and lime application are accounted separately from the modules although they are reported in the animal husbandry and agricultural modules.

Table A6.17. 2010 Higher Scenario, Other Consumption Sub-Budget.

Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
						from agriculture	199
						from animal husbandry	99
						forest products	47
						wetlands	11
						Land management & domestic consumption	25
						Wild fauna	12
Residual from agriculture	199						
Total from Animal Husbandry	99						
Forest products	47						
Wetlands	11						
Land management & domestic consumption of grasslands	25						
Wild fauna	12						
TOTAL FLUX	**392**						***392***
Balance	392						
Flux balance	0						

Table A6.18. 2010 Higher Scenario, Forest Sub-Budget.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
Above ground					Above ground NPP	1,525		
	Disturbances							
	fire	84						
	pests	76						
	harvest	16						
	abiotic	76						
							Forest Products	-47
	Produced and Consumed NPP in year of dist.	7						
			phytomass	-43				
			CWD	94				
					ppt	36		
Below ground					Below ground NPP	352		
			Humification	114				
			Charcoal	5				
	Soil C-CO2 respiration	1,400						
	Increase in soil respiration following drainage	4						
			Leaching	-64				
			Soluble SOC	-34				
			Surface runoff	-14				
	TOTAL FLUX	1,664		58		1,912		-47
	Atmosphere-ecosystems exchange	-248						
	Flux balance	-201						

Table A6.19. 2010 Higher Scenario, Wetlands Sub-Budget.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
Above ground					Above ground NPP	318		
	Disturbances							
	fire	23						
							Peat usage to agriculture	-50
							Domestic use	-11
	Produced but consumed NPP	16						
					Atmosphere-ecosystems total	10		
Below ground					Below ground NPP	187		
			Accumulation	46				
			Humification	25				
	Soil C-CO2 respiration	364						
			Leaching	-19				
			Soluble SOC	-10				
			Surface runoff	-4				
	TOTAL FLUX	**402**		**38**		**516**		-60
	Atmosphere-ecosystems exchange	-113						
	Flux balance	-53						

Table A6.20. 2010 Higher Scenario, Grasslands and Shrubs Sub-Budget.

	Flux into Atmosphere		Pool Change		Flux out of Atmosphere		Transfer to/from Outside Sub-budget	
	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}	Description	Tg C•yr^{-1}
Above ground					Above-ground NPP	417		
	Disturbances							
	fire	33						
	transformation	7						
	Decomposition of above ground wood***	53						
	Produced but consumed NPP	21						
							Domestic livestock grazing	-55
							Land management & domestic consumption	-25
							Wild fauna	-12
			phytomass					
					Atmosphere-ecosystems total	20		
Below ground					Below ground NPP	664		
			Erosion	-7				
			Humification	67				
	Soil C-CO2 respiration	678						
			Leaching	-36				
			Soluble SOC	-19				
			Surface runoff	-8				
	TOTAL FLUX	**792**		**-3**		**1,102**		-92
	Atmosphere-ecosystems exchange	-310						
	Flux balance	-218						

Table A6.21. 2010 Higher Scenario, Summary of Sub-Budgets.

Module	Flux into atmosphere	Pool Change*	Flux out of atmosphere	Inter-module transfer	Flux Balance
	Tg C•yr^{-1}	Tg C•yr^{-1}	Tg C•yr^{-1}	Tg C•yr^{-1}	Tg C•yr^{-1}
Agriculture	873	33	1,159	-442	156
Animal husbandry	250			249	0
Biomass consumption	392			392	0
Forest	1,664	58	1,912	-47	-201
Wetland	402	38	516	-60	-53
Grassland & shrub	792	-3	1,102	-92	-218
Soil CH4-C Respiration	20				20
*Additional fluxes ** *	*13*			*0*	*13*
Atmosphere-ecosystems total	**4,406**	**126**	**4,689**	**0**	**-283**
Module	Flux into atmosphere	Pool Change	Flux out of atmosphere	Inter-module transfer	Flux Balance
	Tg C•yr^{-1}	Tg C•yr^{-1}	Tg C•yr^{-1}	Tg C•yr^{-1}	Tg C•yr^{-1}
Energy and other sectors	668	0	0	668	0
Fossil fuel		-668		-668	0
GRAND TOTAL	**5,074**	**-542**	**4,689**	**0**	**385**

Appendix 7. Total Flux Balance for 1990 and Projections to 2010

Accounting Units	Flux	Projections (Tg C)				
		1990	Lower (L)	Mean (M)	Higher (H)	Assumptions/Remarks
Fluxes into Atmosphere (I)						
All Energy (Fuel Combustion + Fugitive)						
Energy CO_2-C (combustion)	I	650	402	535	624	
Energy CH_4-C (combustion)	I	15	15	15	15	
Industrial Processes & Solvent and Other Product Use						
Industrial processes	I	11	11	11	11	
Total (Energy + Industry)	**I**	**676**	**428**	**561**	**668**	
Soil CO_2-C Respiration, Incl. Past LUC Changes						
Cropland (incl. land-use management)	I	488	472	479	483	M: Based on projected LUCC; L: 10% decrease compared with current LUCC rate; H: 10% increase compared with current LUCC rate
Pasture	I	177	237	279	281	
Forest	I	1367	1384	1395	1404	
Wetland	I	368	360	362	364	
Grasslands & shrubs	I	798	745	694	678	
Total	I	**3198**	**3199**	**3208**	**3210**	
Soil CH_4 –C Respiration, Incl. Past LUC Changes						
All soils	I	20	20	20	20	M: Based on projected change of wetland area; L: 10% decrease compared with projected change of wetland area; H: 10% increase compared with projected change of wetland area
Total Soils (CO_2-C + CH_4-C)	**I**	**3218**	**3219**	**3228**	**3230**	

Accounting Units	Flux	Projections (Tg C)				
		1990	Lower (L)	Mean (M)	Higher (H)	Assumptions/Remarks
Fluxes into Atmosphere (I)						
Disturbances						
Forest disturbances	I	193	*226*	*235*	*252*	Fire emissions based upon 10% increase and area change, pests on area change and abiotic based upon area change and factors 0.7, 0.8 and 1.0 for L, M and H respectively.
Wetland fires	I	23	*30*	*25*	*23*	
Grassland & shrub disturbances	I	46	54	44	40	
Total	**I**	**262**	**310**	**305**	**315**	
NPP produced and consumed in disturbance year	**I**	**42**	**44**	**44**	**44**	
Decomposition of above-ground wood	**I**	**53**	**53**	**53**	**53**	
Agriculture: Land management						
Manure application	I	56	43	44	52	M: Based on projected change of animals population: L: 10% decrease compared with projected real scenario; H: 10% increase compared with projected real scenario
Peat application	I	31	15	31	48	Peat consumption from wetlands increased by 50% in the high scenario remained unchanged in the mean and decreased by 50% in the low scenario
Total	**I**	**87**	**58**	**75**	**99**	

Accounting Units	Flux	Projections (Tg C)				
		1990	Lower (L)	Mean (M)	Higher (H)	Assumptions/Remarks
Fluxes into Atmosphere (I)						
Agriculture: Livestock						
Respiration	I	219	179	199	226	M: Based on projected change of animals population: L: 10% decrease compared with projected mean scenario H: 10% increase compared with projected mean scenario
Livestock enteric fermentation	I	5	4	5	5	
Subproducts and wastes	I	19	19	19	19	
Total	I	**243**	**202**	**223**	**250**	
Other Consumption of Biomass	**I**	**363**	**387**	**406**	**392**	
Additional Fluxes						
Imported grain	**I**	**9**	**9**	**9**	**9**	
Liming Emissions	**I**	**4**	**4**	**4**	**4**	
Grand Total: into Atmosphere	**I**	**4957**	**4713**	**4916**	**5074**	Sum of all fluxes (i.e., including energy/industry fluxes)
Ecosystem Total: into Atmosphere	**I**	**4281**	**4295**	**4355**	**4406**	Sum of all ecosystem-related fluxes
Fluxes out of Atmosphere (O)						
Net Primary Production (NPP)						
Cropland	O	649	584	605	624	Cropland yield decreased in all scenarios -- in the high scenario the decrease was assumed to be 3%, 5% in the mean and 7% in the low scenario. In addition the effect of decreasing cropland area further contributed to the change on total yield.
Pasture	O	309	428	512	526	Pasture yield increased in all scenarios -- in the high scenario the increase was assumed to be 7%, 5% in the mean and 3% in the low scenario. The effect of increasing pasture area further contributed to changing total yield.
Forest	O	1707	1,780	1,829	1,877	Forest NPP was adjusted according to changes in land cover dynamics and the following factors 1.07, 10.5 and 1.03 for high, mean and low scenarios respectively)
Wetlands	O	487	501	503	505	Wetland NPP was adjusted according to changes in land cover dynamics and a factor of 1.06 for all scenarios
Grasslands & Shrubs	O	1202	1,189	1,107	1,082	Grassland and shrub NPP was adjusted according to changes in land cover dynamics and a factor of 1.06 for all scenarios
Total	O	**4353**	4,482	4,556	4,613	

Accounting Units	**Flux**	**Projections (Tg C)**				
		1990	**Lower (L)**	**Mean (M)**	**Higher (H)**	**Assumptions/Remarks**
Fluxes into Atmosphere (I)						
Deposition: Atmospheric Precipitation H_CO_3 with precipitation		76	76	76	76	
Grand Total: Out Atmosphere	O	**4430**	**4558**	**4632**	**4689**	Sum of all fluxes
Atmosphere and Ecosystem Balance (excluding energy)	O	**-149**	**-272**	**-277**	**-283**	
Total Flux Balance (including energy)	O	**527**	**156**	**284**	**385**	
Pool Change (excluding energy)	O	**-125**	**-122**	**-124**	**-126**	
Pool Change (including energy)	I	**551**	**306**	**437**	**542**	

Appendix 8. Assessment of Uncertainty of Fossil Fuel Consumption in Russia

Providing an *ex post* full assessment of uncertainties of fossil fuel emissions in Russia is a very difficult task. Here we will try to discuss briefly some uncertainty components and to illustrate their sensitivity on a total hypothetical uncertainty range of fossil fuel emissions.

The IPCC (1997) states that energy activity data and emission factors are both subject to wide variations through uncertainties in basic data, identification of fuel qualities, calorific values and measurements in emissions. Furthermore, the uncertainties in estimates of fugitive emissions can be larger than those from fuel combustion, as wider ranges in natural resource conditions and operations practice exist for fuel extraction and processing. The latter is especially true for Russia in 1990 and beyond.

The major sources of uncertainty in the assessment of fossil fuel emissions are related to

1. inappropriate use of conversion factors;
2. apparently fraudulent consumption statistics; and
3. unmonitored losses during extraction, transportation and storage.

Global uncertainty ranges for fossil fuel emissions are reported to be ±10% (see IPCC, 1997). According to Victor (1998), the Nakićenović *et al*. (1998) emission data are probably uncertain by as much as 10%, but are consistent with other sources. Consider, for example, the comparison for 1990 (Table A7.1) of the Nakićenović *et al*. (1998) study with the First and Second Communication of the Russian Federation (NCR, 1995, 1998), Russian Federation Climate Change Country Study (CS1, 1997), and the Russian Energy Picture (REP, 1997). The Nakićenović *et al*. (1998) study is based on British Petroleum statistics for output estimation, whereas the others are based on different national statistics. All emission statistics are based on comparable apparent consumption definitions. The simplest and most naïve way to assess uncertainties is to multiply the lower and upper bounds of the conversion factors with the reported Russian output figures (see Table A7.1). Under these assumptions a first-cut approximation of the uncertainty range is ±17%. However, based on this simple computation it is difficult to judge whether the uncertainty range has been assessed correctly.

Table A8.1: Comparing conversion factors, apparent consumption[1] and resulting CO_2 emissions based on Nakićenović *et al*. (1998), the First and Second Communications of the Russian Federation (NCR 1995, 1998), Russian Federation Climate Change Country study (CS1, 1997), and Russian Energy Picture (REP 1997).

	IIASA (1998)			NCR (1995, 1998)			CS1 (1997)			REP (1997)		
	tC/toe	M toe	Tg C	tC/toe	M toe	Tg C	tC/toe	M toe	Tg C	tC/toe	M toe	Tg C
Coal	1.08	181	195	1.08	195	210	0.986	158	156	1.08	176	190
Gas	0.641	378	242	0.64	372	238	0.586	403	236	0.64	370	237
Oil	0.838	250	210	0.837	223	187	0.7	333	233	0.837	258	216
Total		809	647		790	635		894	625		804	643

A8-1 Conversion Factors

Uncertainties arise from the inappropriate use of conversion factors. For instance, the difference between the upper and lower bound relative to the mean value of the recommended heat value for oil is 12%, for coal 7.4%, and for natural gas 11.8% (see IPCC, 1996[2]). Computing the weighted uncertainty for Russia we find an 11% uncertainty range for fossil fuel emissions, which are exclusively attributed to the inappropriate use of heat values.

In addition, the IPCC product classifications are based on US classifications that do not coincide with Russian classifications. This is especially true for the Russian classification system for coal. This gives rise to additional biases in the use of heat values.

A8-2 Output / Apparent Consumption Estimate

Because of the political and economic disintegration of Russia, the uncertainty of the reported total output and apparent consumption figures also increased after 1990. For 1990 the CS1 (1997) claims that the two main factors influencing the accuracy of calculating apparent consumption are:

1. Incomplete data on exports/imports of fuels from Russia to other republics of the FSU; and
2. Lack of data of fuels consumed by military forces.

A closer investigation of such uncertainty factors is beyond the scope of this analysis.

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[1] The definition of apparent consumption also includes losses during extraction (excluding flackering), transportation and storage.

[2] At p. 80 IPCC (1997) in table B-2 the heating values (kgC/GJ) of crude oil are reported as follows:
  (1) OECD (1991, 1995 (cit. IPCC, 1997)) 20 kg C/GJ and
  (2) the literature range (Grubb, 1989, Marland and Rotty 1984 (cit. IPCC (1997)) for the higher heating value (HHV) is 19.0-20.3 kg/GJ and lower heating value is 20.0-21.4 kg C/GJ.
Whereas, the IPCC (1997) recommends for Russia a net calorific value of 48.08 TJ/kt, i.e., 23.76 kg/GJ.

A8-3 Losses

A8-3.1 CO_2 - C

In the past, oil and gas production practices in Russia have largely ignored international environmental standards (Sagers, 1998). Little is known about real total emissions of greenhouse-active gases associated with losses in production, transportation, storage, and consumption of fossil fuels. Losses from flaring, spills and leakage are still unknowns in the carbon account of Russia.

An interesting feature of the losses from oil spills is that they should actually decrease the emission figures. CS1 (1997) estimates some 36.2 Tg C of fuel leaks and other losses, which are not considered by the IPCC methodology and should be deducted from the net emissions, since spilled oil is stored in the terrestrial and aquatic ecosystems. However, it must be taken into account that spills alter the metabolism of terrestrial and aquatic ecosystems possibly leading to increased emissions of other GHGs (Scott, 1994).

A8-3.2 CH_4 - C

Despite large uncertainties, losses of methane can be considered an important factor contributing to global climatic change. According to the First National Communication (NCR, 1995), anthropogenic CH_4 emissions from mining, transportation and consumption of natural and accompanying gas emissions make up to 60% of total anthropogenic methane emissions in Russia. The share of methane in CO_2 equivalents is estimated to be 20% of total anthropogenic emissions. The major source of methane is emission from oil and gas activities. Rabchuk *et al*. (1991) (cit. IPCC 1997, p. 1.128) report that emissions from gas production and transportation in the former USSR were very high, about 3–7% of total gas production. In this respect, the IPCC (1997) concludes: “However, a better quantitative evaluation is needed to validate the current emissions estimates”—an activity that has not been undertaken so far. By applying the emission factors recommended by the IPCC the CS1 (1997) obtains a total fugitive emission of methane to be in the range of 11.8-26.5 Tg[3].

Following IPCC’s revised regional emission factors for methane from oil and gas activities, the Second National Communication (NCR, 1998) derives a flux of the fugitive share of emissions of 16 Tg methane, which is in line with the CS1 (1997) figure. This amount is considered a conservative estimate and the uncertainty of fugitive methane emissions is assessed to be “not lower” than ±30–40% for the reported data. However, the bias and total uncertainty can potentially be much higher. The CS1 (1997) considers an emission level of 30.6 Tg methane as the upper theoretically possible limit of emissions due to gas transportation and storage only. Leakages from oil fields are probably also largely underestimated. Reshetnikov *et al*. (2000) present a recent evaluation of the methane emissions from the Soviet gas industry for the late

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[3] (1) Production: a) routine maintenance emission 4.9 (3-6.8 Tg CH_4/yr); b) venting and flaring 0.4 (0.1–0.7 Tg CH_4/yr; (2) transportation, storage, processing and distribution 9.9 (6.2–13.6 Tg CH_4/yr) (3) consumption: a) leakage at industrial plants and power stations 3.8 (2.4–5.2 Tg CH_4/yr); b) leakage in the residential and commercial sector 0.17 (0.1–0.23 Tg CH_4/yr).

1980s/early 1990s. The probable annual emissions of methane in Russia during this period are 25–35 Tg CH_4. One-half to two-thirds may have been caused by long and aging pipelines.

Airborne measurements of atmospheric methane over oil fields in Western Siberia confirm high leakages from oil fields (Tohjima *et al.*, 1996).

A8-3.4 Issues related to oil consumption

The quality of fuels produced by the petroleum industry and the efficiency of combustion has a large impact on the composition of greenhouse gas emissions from fossil fuels. Thus, there is considerable, but unknown, uncertainty related to the potentially increased total radiative forcing potential from fossil fuel combustion emissions. It is well known that the bulk of Russia’s refined products are well below international quality levels. Assessments indicate that only 10% of AI-93 gasoline meets international quality criteria, and the corresponding figure for lubricating oil is 30%. The exception is diesel fuel, where 60% of Russia output is considered to meet world quality levels (Sagers, 1998). Therefore, a GHG emission calculation that is based on the apparent consumption of crude oil might not, at least in the case of Russia, represent the true picture in terms of its contribution to global warming. We are not aware of any study that has tackled this question with respect to Russia.

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