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Phytomass, Increment, Mortality and Carbon Budget of Russian Forests

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Foreword

The carbon balance of the Russian forests has gained a lot of international interest over the last 10 years. IIASA has over the years put in substantial efforts, through the Forest Resources Project, in trying to contribute to the knowledge about the carbon budget of the Russian forests.

This report, produced by Professors Anatoly Shvidenko and Sten Nilsson of the core-team of IIASA's Forest Resources Project, is an effort to summarize IIASA's current understanding of the carbon budget of the Russian forests.

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1. Introduction

The Kyoto negotiations on climate change placed increased emphasis on the role of the forests in the greenhouse gas debate. The protocol includes a statement that "net changes in greenhouse gas emissions from sources and removals by sinks resulting from direct human-induced land use change and forestry activities, limited to afforestation, reforestation, and deforestation since 1990, measured as verifiable changes of stocks in each commitment period shall be used to meet the commitments…on agreed reductions of emissions" (Bolin, 1998). The protocol also states that the signatory parties to the agreement may transfer, or acquire from other signing parties, emission reductions resulting from projects aimed at reducing anthropogenic emissions by sources or enhancing anthropogenic removals by sinks of greenhouse gases in any sector of the economy (Bolin, 1998). The OECD countries look upon Russia as one of the main targets for such economic instruments in order to achieve set targets.

Russian forests comprise some 22% of the world's total closed forests, including plantations (3.5 billion hectares in 1995; SOFO-1997). Intensive scientific debates over the years (e.g., Melillo *et al*., 1988; Sedjo, 1992; Dixon *et al*., 1993; Krankina and Dixon, 1994; Kolchugina and Vinson, 1993a, 1993b; Isaev *et al*., 1993, 1995, Krankina *et al*., 1996; Kokorin and Nazarov, 1994; Kokorin *et al*., 1996; Lelyakin *et al*., 1997) have focused on the interactions between the Russian forests and the global carbon budget. The cited publications and others estimate the Russian forests to be a net sink of carbon (C) between 0.02 and 450 Tg carbon/year in the early 1990s. Researchers cannot be satisfied with such huge variations in estimates, even if we take into account the diversity of methods used and the level of inevitable uncertainties.

The publications listed above and others reveal two major reasons for these uncertainties. First, estimates of the most important parameters influencing the carbon balance (e.g., phytomass, detritus (mortmass), net primary productivity (NPP), net ecosystem productivity (NEP), impact of primary types of disturbances, etc.) vary by a factor of two or more. Second, the carbon budget is by nature a stochastic process that depends strongly on current net ecosystem productivity, as well as on actual and historical regimes of disturbances. This is widely recognized, but the process is not implemented to any large extent in the model approaches used.

At least five important features of the interaction between forest ecosystems and the global carbon budget must be discussed explicitly in this respect:

1. Numerical estimates of fluxes without identification of a definite year or period have limited meaning;
2. An adequate evaluation of the current carbon fluxes requires historical reconstructions (up to 200 years for boreal forests);
3. All models used so far are deterministic either by sense or by applications, and can present only an average line of "mathematical expectations," while the real annual fluctuations of carbon in the boreal zone can differ 3–10 times the amount of the average fluxes, mainly due to interseasonal variations of natural disturbances;
4. Analyses of the models and approaches used reveal that most of them cannot present any estimates for a given year or shorter period (2–3 years), but only estimate average magnitude and tendencies for a rather uncertain period of time, and
5. Current global vegetational models have little in common with the actual carbon budget because they only consider the potential vegetation. The real productivity of boreal forests is only about 50% of the potential productivity defined by climatic and soil capacities of different sites.

A "bookkeeping" approach avoids the above shortcomings, but has others. The two most important shortcomings are:

1. The reliability of the bookkeeping approach is defined by the accuracy of the stocks of the carbon pools at the beginning and at the end of the period considered, and the carbon fluxes are very small compared to the sizes of the pools. Therefore, accurate measurements of the differences between the approximated pools and fluxes are crucial; and
2. The bookkeeping approach is best applied to historical developments, although it can also be used for simulations of future developments. Nevertheless, the bookkeeping approach is probably the best current method for validating the reliability of large-scale carbon budget models for short periods.

The basic interactions between forests and the global carbon cycle can be estimated by the following approximate equation (we use the annual time step).

$$F(t) = [dC/dt]_t = \sum_I C_{j,t} - \sum_j C_{j,t-1} \approx (NPP - WM - GPM - \Delta D - \Delta SOM)_t =$$
$$= (\Delta PH - \Delta D - \Delta SOM)_t = NPP^*(t) - NM(t) - \sum_p (TCF)_p(t) \qquad (1)$$

In equation (1), $F(t) = [dC/dt]_t$ is the summarized carbon flux during a given year t; $C_{j,t}$ and $C_{j,\,t\text{-}1}$ are carbon pools j=1,2, …, n, at the beginning and the end of the year t. The right-hand portion of the function depends on time and forest ecosystem characteristics; where *NPP* is net primary productivity generated by vegetation; *WM* and *GPM* are mortality (die-back) of woody and green parts, respectively; and ΔD and ΔSOM are change of carbon in dead vegetational organics (detritus) and soil organic matter, respectively. $NPP - WM - GPM = \Delta PH$ is the annual change of the phytomass storage, i.e., *NEP* generated by vegetation. In the absence of big regimes of nonstand-replacing disturbances, more than 95% of ΔPH is generated by the increment of wood, and the impacts of ΔD andΔSOM on the final flux are relatively small. The latter form of the equation could be used if we assume that in undisturbed areas the annual changes of carbon in detritus and soils are negligibly small; *NPP*(t)* is net primary productivity, *NM(t)* is natural mortality in undisturbed forest ecosystems, and $\sum_p (TCF)_p(t)$ is the total carbon flux generated by different types of disturbances *p*. The explicit form of the equation can be complicated depending upon methods and models used, the structure of carbon pools of forest ecosystem organics, availability of data, etc. This short description reveals the crucial role that reliable estimates of increment (gross and net growth), phytomass dynamics, and impact of disturbances play in estimates of the interactions between forest ecosystems and the carbon budget.

We have tried to apply the methodology described above, based on the IIASA Forest Resources Project's systems approach on the state and productivity of the Russian forests including increment, phytomass, disturbances and their impact on the carbon budget. These data are probably the most detailed and accurate that exist with respect to this topic.

All inventories and initial calculations were made for individual ecological regions (ecoregions) of Russia. These regions are territorial units, where the terrestrial biota have an impact on the global carbon budget of compatible magnitude, and are homogeneous with respect to climate, soil characteristics, basic features of disturbance regimes, extent and intensity of the transformation of natural vegetation (forest) cover, forest associations, and productivity (Shvidenko *et al*., 1996a). We have established 142 ecoregions for Russia, of which 78 are for European Russia and 63 are for Asian Russia.

We carried out our calculations for the Russian forest lands (886.5x10^6 ha in 1993, or some 52% of total Russian lands) which are divided into: (1) forested areas (763.5 x10^6 ha); i.e., high forests (and shrubs for territories in which high forests are unable to grow due to severe climatic conditions; the latter covers about 8.0% of the total Russian forested area); (2) unclosed forest plantations (3.8 x10^6 ha); and (3) unforested areas that are designated for forests but are temporarily without forests (119.2 x10^6 ha, of which 59% consist of sparse forests (open woodlands), 28% burned areas, 8% unregenerated harvested areas, and 5% grassy glades). The impact of nonforest lands (294.4 x10^6 ha of bogs, rocks, sands, tundra, etc., basically unsuitable for forest production) on the carbon budget is also discussed.

2. Estimates on Productivity: Methods, Initial Data and Results

This section deals with estimates on increment and mortality, the extent of phytomass and carbon in woody debris and soil, and disturbances.

2.1 Increment and Mortality

Gross growth *dTV(A)* and net growth *dGS(A)* play a crucial role in estimating potential and current productivity of forests, as well as in evaluating the interactions between forests and the global carbon budget. The two descriptors are defined respectively as $dTV(A) = f'(A)$ and $dGS(A) = g'(A)$, where *TV(A)* is total volume (total production) at age *A* (i.e., the total volume of all stemwood over bark produced by a stand up to age *A*), and *GS(A)* is the *growing stock* at age *A* (i.e., the total volume of stemwood over bark of all living trees in a stand at age *A*). Clearly, the derivatives *dTV(A)* and *dGS(A)* are respectively the (stem) woody part of the net primary productivity and the net ecosystem productivity of forest ecosystems.

The expression $dM(A) = dTV(A) - dGS(A)$ gives the *actual mortality* per year at age *A*. Actual mortality includes *natural* mortality (a result of self-thinning, e.g., competitive interaction among trees and death of overmature trees), as well as *pathological* and *mechanical* (e.g., wind and snowbreak) mortality. In managed forests, most of the *dM(A)* portion is removed in the form of thinnings (a kind of mechanical mortality). Impacts due to other factors are negligible. In unmanaged forests, most of the *dM(A)* portion is caused by disturbances. For boreal forests, these include forest fire, pests, diseases, pollution (pathological mortality), selective harvests, and windfall (mechanical).

In order to estimate *dTV(A)*, *dGS(A)* and *dM(A)* for the Russian forests we used a modeling system specially developed at IIASA. The system comprises a set of about 1,200 unified models for stand dynamics of the individual ecological regions of Russia and main forest forming species, forest types, site indexes, stocking (densities) and types of age stand structure. Most of the modeling system is generated by empirical growth functions for actual stands of a specific ecoregion and models for productivity at a variable growing stock. We used the Richard-Chapman growth function as the basic model concept, but modified this basic function to enable us to describe the destructive stage of overmature stands. (For a detailed description of the system, see Shvidenko *et al*. 1995a, and for the model calculations, see Shvidenko *et al*. 1996b, 1996c; Venevsky and Shvidenko, 1997.)

The indicators enumerated above present the maximum possible information that can be extracted from the State Forest Account (SFA) data—the only source that contains data on all Russian forests as of a definite date (the account is compiled every 5 years). In our analyses, we used State Forest Account data for the period 1961–1993, and estimated the percentages of net growth by main forest forming species ($P_{GS}(A,SI,D) = 100dGS(A,SI,D) / GS(A,SI,D)$, where *SI* is site index, *D* is density (stocking)), and percentage of mortality ($P_M = 100dM/GS$). We then calculated the ratio $P_{TV} = 100dTV/GS$, which is equal to $P_{TV} = P_{GS} + P_M$. Our estimates of mortality, and for net and gross growth in 1993 for aggregated ecological regions are presented in *Table 1*.

Table 1. Gross, net growth and mortality in Russian forests (1993)

Ecological regions	Forest Areas (thousand ha)	Growing stock (million m^3)	Net growth (million m^3/ year)	Mortality (million m^3/ year)	Gross growth (million m^3/ year)
European part					
Prebaltic (PRI)	271.9	46.6	1.31	1.00	2.30
Northern (NOR)	75742.4	7935.4	114.52	119.24	233.77
Northwestern (NW)	10105.7	1583.9	29.22	26.48	55.70
Central (CEN)	20834.5	3109.6	77.46	61.08	138.55
Volgo-Vjatsky (VOV)	13426.5	1862.7	48.28	40.00	88.28
Central-Chrnozemny (CEC)	1487.3	213.8	7.14	5.62	12.75
Povolshsky (POV)	4781.0	596.8	17.19	15.31	32.50
Northern Caucasus (NOC)	3735.8	662.3	13.06	11.68	24.74
Uralsky (URA)	35838.6	5099.4	108.90	93.67	202.57
Total	166223.7	21110.9	417.08	374.08	791.16
Asian part					
West Siberia (WES)	90011.5	10950.3	112.98	118.04	231.02
East Siberia (EAS)	227836.0	27658.2	250.07	227.13	477.20
Far East (FEA)	279429.6	20957.0	185.27	188.90	374.17
Total	597277.1	59565.5	548.32	534.08	1082.39
Russia					
Shrubs			0.91	5.30	6.21
Total	763500.8	80676.4	966.31	913.45	1879.76

At the beginning of the 1990s, the gross growth of stemwood of the Russian forests was about 1880 million m^3, the net growth (*dGS*) comprised 52.2% (966.3 million m^3) and mortality (due to nonstand-replacing disturbances) was 47.8% (913.5 million m^3). This means that on average for all Russian forests *dGS*, *dM* and *dTV* are 1.27; 1.20 and 2.47 m^3/ha, respectively. These data differ significantly among the various regions of the country; for example, they are 2.50, 2.25 and 4.75, respectively, for European Russia versus 0.92, 0.90 and 1.82 m^3/ha for Asian Russia. This indicates that the average actual productivity (per hectare) of Russia's Asian forests is about 38% of the forest productivity in the European zone. More severe climatic conditions beyond the Urals, different age structures of the forests, a more significant share of uneven-aged forests in Siberia, and especially a much higher intensity of disturbances (fires, insects and diseases) in the forests of Asian Russia explain these large differences.

The so-called main forest forming species (965.4 million m^3 of a total of 966.3 million m^3) essentially generate the net growth of the Russian forests. These species are divided into three groups: coniferous species (larch, pine, spruce, fir and two Russian cedars — *Pinus sibirica* and *P. korajensis*), hard deciduous species (oak, beech, ash, stone birch, etc.) and soft deciduous species (mainly white birches and aspen). Forests dominated by coniferous species generate 69.2% of the net growth, hard deciduous 3.4%, and soft deciduous 27.4%. Young stands contribute 36.6% to the total net growth, middle-aged stands 38.2%, immature stands 10.4%, and mature and overmature forests 15% (as a comparison, the areas covered by forests of the above age groups are respectively 18, 24, 10 and 48% of total forested areas). The method that the Russian forest inventory uses to identify age of maturity explains the rather high increment in mature forests: the definition relates to technical (industrial) maturity, which can be followed by significant net growth during several age classes.

In order to estimate the dynamics of net growth, actual mortality and gross growth for the period 1961–1993, we applied the system of equations described above to regional data of the State Forest Account for 1961, 1966, 1973, 1978, 1983, 1988 and 1993 (the latest available inventory). *Table 2* presents aggregated data for these years. From 1961 to 1993, the Russian forests produced 55.4 billion m^3 of stemwood, of which net growth comprised 29.4 billion m^3 and mortality 26.0 billion m^3.

Among other applications, these data can be used to estimate the balance of production and consumption of wood during 1961–1993. We estimate the net growth in European Russian forests to be 12.6 billion m^3. The difference in the total growing stock (see *Table 6*) for the 32-year period considered is +5.8 billion m^3. During this period, 6.9 billion m^3 of commercial wood (which corresponds to some 7.7 billion m^3 of growing stock) were harvested. Thus, the discrepancy in the wood balance is some +0.9 billion m^3, which leads us to conclude that the losses in the European forests due to disturbances were low during 1961–1993. The Asian part presents a completely different picture: the net growth is estimated to 16.8 billion m^3, the harvest was 4.8 billion m^3 (of the growing stock), and the change in the growing stock was +4.2 billion m^3. This indicates that “defined” losses comprise 7.8 billion m^3 or about 240 million m^3 per year. If we consider the period 1983–1993, the losses of growing stock in Asian Russia were twice as great.

Table 2. Dynamic of net growth (*dGS*), actual mortality (*dM*) and gross growth (*dTV*) (expressed in million m^3) in Russian forests during 1961–1993.

Indicators	1961	1966	1973	1978	1983	1988	1993	AC[1]
European part								
dGS	345.3	356.7	383.8	406.0	426.5	422.4	417.1	12624
dM	248.0	254.2	271.2	292.1	323.2	353.5	374.1	9552
dTV	593.3	610.9	655.0	698.1	749.7	775.9	791.2	22175
Asian part								
dGS	483.1	493.2	506.8	528.3	555.2	557.4	549.2	16785
dM	474.8	484.8	498.2	519.2	545.7	547.9	539.4	16497
dTV	957.9	978.0	1005.0	1047.5	1100.9	1105.3	1088.6	33283
Russia total								
dGS	828.4	849.9	890.6	934.3	981.7	979.8	966.3	29409
dM	722.8	739.0	769.4	811.3	868.9	901.4	913.6	26049
dTV	1551.2	1588.9	1660.0	1745.6	1850.6	1881.2	1879.8	55458

[1] AC are accumulated values for the period 1961–1993.

2.2 Phytomass Estimates

Data from the 1993 State Forest Account for individual ecological regions, covering growing stock by dominant species, age, site indexes and relative stocking (density), provided the basis of the phytomass inventory. As our primary tools, we used multidimensional regression equations for basic phytomass fractions — stemwood over bark, bark, crownwood (over bark), foliage (leaves and needles), roots, understory (undergrowth, bushes, green forest floor) — in the form of the ratio:

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

where M_{fr} is the mass of a definite fraction in Tg (of dry matter), *GS* is (green) growing stock in m^3, *A*, *SI*, *RS* are respectively average age, site index and relative stocking of stands, and c_0, c_1, c_2, c_3, c_4 are regression coefficients. Then, the mass of the phytomass fractions is defined as $M_{fr} = R_{fr} \cdot GS^*$, where GS^* is growing stock from the State Forest Account data. The use of multidimensional equations allowed us to take into account the geographical diversity of forests for species covering large areas.

We developed a special database to generate the regression equations, based on published biomass measurements; a total of 2040 sample plots and some 200 regional studies were used to generate the models. Given the vast amount of available experimental data and the huge areas studied, we regionalized some multidimensional models for individual species on a zonal principle. A description of the approach, including characteristics of initial data used to develop regression equations, etc., is presented by Lakida *et al*., (1997) and Shepashenko *et al*., (1998).

Table 3 gives summary data on the phytomass estimates for aggregated ecological regions. In order to calculate the carbon content, we used the following conversion coefficients (carbon to dry matter): 0.45 for green parts and 0.5 for wood in European Russia, and 0.5 for the total vegetation of the Asian forest ecosystem (Matthews, 1993; Alexeyev and Birdsey, 1994; Vedrova, 1995).

Table 3. Phytomass and carbon in Russian forests in 1993.

Ecological regions[1]	Forests ecosystems phytomass component , Tg, dry matter Stem-wood over bark	Crown wood	Roots	Foliage	Under-story	Total[2]	Phyto mass density kg/m^2	Carbon content Total, Tg	Density kg C/ m^2
European part									
PRI	21.8	3.5	6.6	1.5	1.4	35.0	12.86	17.4	6.40
NOR	3660.6	721.3	1263.4	548.9	526.9	6721.1	8.87	3306.7	4.37
NW	700.2	86.2	213.1	47.2	49.8	1096.4	10.85	543.4	5.28
CEN	1355.7	166.8	431.1	93.0	99.0	2145.6	10.30	1063.2	5.10
VOV	816.9	105.9	256.2	61.6	64.1	1304.7	9.72	646.0	4.81
CEC	106.1	20.8	25.6	5.3	6.7	164.4	11.05	80.6	5.42
POV	284.6	39.1	74.2	14.2	18.4	430.3	9.00	213.6	4.47
NOC	361.2	107.2	86.4	14.3	16.5	585.6	15.68	291.3	7.80
URA	2245.9	308.8	705.0	194.9	181.1	3635.6	10.14	1799.0	5.02
Total	9553.0	1559.6	3061.6	980.9	963.9	16118.7	9.70	7961.2	4.79
Asian part									
WES	5062.6	898.2	1329.6	365.9	706.4	8374.6	9.30	4187.3	4.65
EAS	13044.3	1792.4	3969.0	768.2	1384.3	21241.5	9.32	10620.7	4.66
FEA	10441.0	1394.3	3576.6	509.7	1609.2	18637.7	6.67	9318.9	3.33
Total	28547.9	4084.8	8875.3	1643.8	3699.8	48253.8	8.08	24126.9	4.04
Russia									
Total	38100.9	5644.4	11936.9	2624.7	4663.7	64372.5	8.43	32088.1	4.20
Additionally phytomass on unforested areas[3]									
Total	783.1	141.5	269.1	57.0	724.5	1975.2	1.61	967.8	0.79

[1] Abbreviations of the aggregated ecological regions are given as in *Table 1*.
[2] Total for the Asian part of Russia includes, in addition to biomass of closed forests, biomass of shrubs: in WES this amounts to 11.9 Tg of dry matter, in EAS 283.3 Tg, in FEA 1106.9 Tg. Most of the shrub phytomass is represented by biomass of ecosystems dominated by dwarf pine *(Pinus pumila)*.
[3] Data are given for unforested areas (sparse forests, harvested areas, burned areas and dead stands, grassy glades) and nonstocked forest plantations

As can be seen from *Table 3*, the total biomass of the Russian forests (for all forested areas) is estimated to be 64,372.5 Tg of dry matter or 32,088.1 Tg carbon in 1993, of which European forests contain 24.8% of the forest carbon and Asian Russia 75.2%. The distribution of the basic biomass fractions is: stemwood over bark comprises 59.2% of total biomass, roots 18.5%, crownwood 8.8%, understory including green forest floor 7.2%, and foliage 4.1%. Shrubs, as a separate category of forested area where closed forests are unable to grow, contain 2.2% of the total biomass.

Above-ground biomass constitutes 81.5% of the total. The structure of the biomass is similar in both parts of Russia, although Asian forests have more understory (7.7% versus 6.0%) and less foliage (3.4% versus 6.0%), but these figures are additionally impacted by differences in the general biomass structure (biomass of shrubs in European forests is negligibly small). The average carbon density D = total forest phytomass/ forested area for the whole country, European and Asian Russia is estimated to be 4.20, 4.79 and 4.04 kg C/m^2, respectively. The ratio R = total phytomass in megagrams (Mg)/growing stock in m^3 is 0.398; 0.377 and 0.405 Mg C/m^3, respectively.

Due to the significant zonal variation of forest productivity, the density *D* depends strongly on forest vegetational zones. The average density for northern and sparse taiga ecoregions is about 2.0 kg C/m^2; forests of subzones of southern taiga and mixed coniferous/broadleaf forests have the highest values (5.7 and 5.9 kg C/m^2, respectively). The phytomass density varies tremendously among administrative units, especially in Asian Russia (e.g., from 1.24 kg C/m^2 in Magadan oblast to 6.98 kg C/m^2 in Primorski kray, Russian Far East). Unforested areas contain about 3% of the vegetation phytomass of closed forests.

2.3 Estimates of Carbon in Coarse Woody Debris and Soil Organic Matter

Coarse woody debris (CWD), or detritus, comprises dead woody residuals that have a top diameter of more than 1 cm and have not lost their initial morphological structure. We further divided coarse woody debris into above ground (dry standing trees, dry branches of living trees, on-ground pieces of wood, etc.) and below ground (mostly roots of dry or selectively harvested trees). The amount and dynamics of such debris depend strongly on the forest structure and on forest management regime, specifically on the previous history of disturbances.

The Russian forest inventory identifies above-ground coarse woody debris in each inventoried stand, but Russia has never reported any aggregated data on detritus storage. Nevertheless, many publications describe research on biological productivity, as well as results of surveys of some forest formations or some types of disturbances. Thus, available information for the total Russian forests suffices only for approximate estimates.

In order to calculate carbon in coarse woody debris, we used the IIASA Forest Resources Project's database, which contains average volume (m^3/ha) of dry standing trees and on-ground coarse woody debris by ecoregions; Russian data from phytomass/mortmass inventories; relevant Russian publications; and samplings from data of forest inventories carried out by Russian forest enterprises. The total carbon content of the coarse woody debris was estimated to be 6,285 Tg C (or 19.6% of the phytomass of closed forests) of which above-ground carbon comprised 5,385 Tg (85.7% of total) and below ground 899 Tg (14.3%). European forests contain only 14% of the total amount of coarse woody debris (amounts for total, above-ground and below-ground coarse woody debris for European Russia are 889, 744 and 145 Tg C, respectively, and 5,395, 4,641 and 754 Tg C for Asian Russia; see *Table 5*).

We made indirect estimates of coarse woody debris for the beginning of the period 1961–1993 by two approaches. Based on the linear feedback theory (Olson, 1963), the dynamic of coarse woody debris can be described as:

$$dM/dt = L(t) - \alpha M(t), \qquad (3)$$

where $M(t)$ is CWD mass, $L(t)$ is CWD input, and α reflects decomposition coefficients by the different decomposition pools. The function $L(t)$ can be approximated to the interval $[32 \geq t \geq 1]$ based on the balance of production (using estimates of increment and mortality) and data on wood consumption. $L(t)$ was approximated as a polynomial of the second power. The integral of equation (3) is $M = 1/\alpha\ [a + bt(1\text{-}1/\alpha) + ct\ (t\text{-}\ 2/\alpha + 1/\ \alpha2)] + C_1$, where C_1 is defined by M[32]; *a, b,* and *c* are empirical coefficients of $L(t)$, and α is given in *Table 4*, which contains α for two decomposition pools of coarse woody debris (medium-fast and slow pools). We made calculations for the geographical zones presented in *Table 4*. The results lead us to conclude that the total amount of coarse woody debris increased during 1961–1993 by some 540 Tg C.

Table 4. Rate of organic matter decomposition by different decomposition pools.

	Fast (litter) pool (1)		Medium-fast pool (2)		Slow pool (3)	
Zone	α	*T0*.95	α	*T0*.95	α	*T0*.95
SA&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
NT	0.16	18.7 (15–35)	0.075	39.9	0.027	111
MT	0.32	9.4 (5–20)	0.097	30.9	0.03	100
ST	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
S&SD&D	4.0	0.75 (0.2–1.5)	0.37	8.1	0.13	23

Vegetational zones: SA&T – subarctic + tundra; FT&SpT&MdF – forest tundra + sparse taiga + meadow forests; NT, MT, ST – northern, middle, and southern taiga, respectively; MxF&DF&FS – mixed forests + deciduous forests + forest steppe; S&SD&D – steppe + semidesert + desert.

The second approach used is based on comparative analysis of the structure of the Russian forests during 1961–1993 and the basic types of disturbances during this period. From 1961–1993, forested areas in Russia increased by 69.0 million hectares, areas of burned areas and dead stands decreased from 70.6 to 31.9 million ha, and unregenerated clearcut areas decreased from 14,0 to 8.5 million ha. Simultaneously, areas covered by mature and overmature forests decreased by about one-fourth (from 437.1 million ha in 1961 to 340.1 million ha). We applied relative data from our inventory of coarse woody debris in 1993 to both the structure of forest land categories and distributions of forests by types of transformation (virgin, natural and anthropogenic forests were considered), dominant species, age groups and types of age stand structures (including different types of uneven-aged forests).

The results achieved are rather consistent with the results of the first approach. For 1961, carbon in coarse woody debris is estimated at 5,604 Tg and the increase during the next 32 years was 680 Tg. This result may seem surprising, taking into account a much higher occurrence of forest fires before the 1960s. We explain this result by complicated interactions of several, to a large extent contradictory, processes in the Russian forests: (1) a high level of harvest (about 1.6-1.8 million ha annually), which was accompanied by huge amount of wood losses (from 20–50% in different estimates and surveys); (2) decreased forest health due to pollution and other types of industrial pressure; (3) significant areas influenced by industrial transformation related to oil and gas exploration and extraction (West Siberia) or coal and diamond production (Jakutija); and (4) several years of big fires in Russia (especially in 1972 and 1987). The average estimate of the increase of carbon in coarse woody debris is 610 Tg for the period 1961–1993.

The most difficult problem in the framework of the methodology used is the estimation of the dynamics of soil organic carbon (SOC). We performed a special analysis of the soil organic carbon content for all Russian soils (Rojkov *et al.*, 1996) and for different categories of forest land. Digitized soil maps were used as a basis: the first compiled by the V.V.Dokuchaev Soil Institute at the scale of 1:2.5 million, and the second map at the scale of 1:4 million. The generalization of the carbon map was based on a map of soil-geographical regions produced at the scale of 1:4 million (Dobrovol'skii *et al.*, 1984). The soil carbon content was estimated based on soil profiles of 160 soil types, sampled across the country.

We estimated carbon reserves for the basic pedogenic horizons (0–5, 0–20, 0–50 and 0–100 cm) and carbon of carbonates in the top 1 m layer of soils. For the calculations, we used a set of key parameters, such as soil density and content of stony materials. In addition, the carbon of organogenic horizons (defined as topsoil (peat) layers with a carbon content greater than 15%) was assessed separately. Taking into account the important role of litter in the carbon budget, we independently estimated amount of (forest) litter on forested areas. The calculations were done by overlaying several digitized maps of which the major ones were: (1) a map of litter in Russian forests that IIASA produced based on measurements; (2) several different maps of land-use descriptions; and (3) a map of forest enterprises. Some additional calculations were based on data from the latest State Forest Account of 1993. Aggregated results are presented in *Table 5*.

Table 5. Carbon in soils, coarse woody debris and litter in forested areas of Russia. Stocks are expressed in Tg C, averages – in kg/m^2.

Ecological Region	Organic soil carbon, Tg			Carbon of carbonates	Detritus, Tg	Mortmass, Tg	Litter, Tg	Organic carbon density, kg/m^2	
	0-20 cm	0-50 cm	0-100 cm	0-100 cm				0-100 cm	Litter
NOR	6878.2	10672.2	13064.1	12.5	480	2364.8	1000.9	17.2	1.32
NW+PRI	648.7	969.5	1164.5	0	42	171.6	99.4	11.2	0.91
CEN	972.6	1437.6	1722.9	2.3	86	370.0	134.8	8.28	1.14
VOV	796.5	1269.7	1592.8	29.0	53	200.2	184.3	7.66	1.37
CCH	84.4	161.4	224.8	37.6	3	1.4	2.1	15.1	0.1
POV	210.3	403.5	571.2	225.0	9	2.2	15.8	12.0	0.33
NCA	256.5	477.9	504.4	95.9	15	2.8	6.1	12.6	0.16
URA	2084.8	3266.9	4808.3	567.5	202	232.9	487.2	13.4	1.36
Total ER	11932.0	18658.7	23653.0	943.7	889	3346.0	1925.6	14.2	1.16
WES	7657.1	12850.0	17670.4	2439.7	976	4040.2	1210.1	19.6	1.35
EAS	15053.1	25788.7	34638.2	7852.0	2361	6501.5	2825.5	15.2	1.24
FAE	23725.4	40485.5	53628.0	18894.3	2058	9797.7	2758.5	19.2	0.99
Total AR	46435.6	57795.0	105936.6	29186.0	5395	20339.4	6794.1	17.7	1.14
Total forests of Russia	58367.6	76453.7	129589.6	30129.7	6284	23685.4	8719.7	17.0	1.14
Average	7.64	10.0	17.0	3.95	0.21	3.10	1.14	-	-
All Russian lands	146624.3	255055.3	342088.5	111278.8	-	62841.0	-	20.0	-

From *Table 5*, it follows that the soils of forested areas of Russia are estimated to sequester 129.6 Pg of organic carbon and 30.1 Pg of carbon of carbonates in the 1 m top layer; the total amount of carbon is 159.7 Pg (±10%). The average carbon density is 17.0 kg/m^2. Thus, Russian forests (forested areas), which cover 44.7% of all Russian lands, contain 37.9% of all soil organic carbon. Such a result seems reasonable taking into account: (1) the significant amount of carbon in peat (118.4 Pg C according to the latest estimate; Rojkov *et al*., 1997), of which the largest part is located in treeless wetlands; and (2) vast areas of shallow mountain and permafrost soils. The surface 0–20 cm layer contains nearly half (45%) of the organic carbon in the top 1m layer, which underlines the significant role of disturbances (specifically fire) on soil organic carbon dynamics.

The total amount of carbon in litter (on forested areas) is estimated at 8.72 Pg C, or 11.4 Mg C per ha. Geographic variation of the litter extent is very high—from about 50–80 Mg C per ha in bogged forests of the north to about 0 in the steppe zone. The total amount of coarse woody debris (6.28 Pg C) is equal to the amount of C in litter. It supports the importance of taking the carbon of coarse woody debris into account in all forest carbon calculations.

In *Table 5* we present data on carbon in mortmass (defined as all dead organic residuals that have not lost their morphological structure; Bazilevich, 1993) on forested areas, calculated from the digitized map of Bazilevich. A simple comparison of these data with statistics on other parts of dead organics in forest ecosystems demonstrates that Bazilevich's data significantly overestimate the mortmass.

The carbon content of soils of unforested areas is somewhat less than in forests, primarily due to decreased storage of litter. Significant differences occur for burned areas and unregenerated harvested areas, where the carbon content decreased during the relatively short post disturbance period. The most significant differences relative to forested areas were observed for lands on which new forests were planted. Totally, the organic carbon content of the 1 m topsoil layer of unforested areas (123.0 million ha) is estimated to 17.9 Pg C, or a density of 14.6 kg C/m^2.

2.4 Disturbances

Five basic types of disturbances play a crucial role with respect to successional dynamics, productivity, state and structure of Russian forests and forest carbon: forest fires, pest and disease infestations, harvests, land-use changes, and, in some regions, industrial pollution. Disturbances of different types impact 10–15 million ha of the Russian Forest Fund annually. Stand-replacing disturbances affect an area of some 0.8–0.9 million ha annually. The most informative indicators of stand-replacing disturbances are burned areas and dead stands, which the Russian forest inventory detects rather reliably. The high correlation between these indicators and the severity of disturbance regimes means that they can be used for some indirect estimates of the nonstand-replacing disturbances. The dynamics of burned and dead forests for the period 1961–1993 suggest a strong suppression of the extent of disturbances. Data for forests under state forest management (about 95% of all Russian forests) show that disturbed areas 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.

Quantitative analysis of the extent and level of disturbances during the last 20 years reveals that the major impacts by disturbances in the Russian Forest Fund are: (1) increased share of pyrogenic, anthropogenic and biogenic forest successions, as well as increased unforested areas and 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 process; and (5) generally negative changes of biodiversity at ecosystem and landscape levels.

The following example illustrates the total impact of disturbances on forest phytomass storage. Bazilevich's map of productivity of terrestrial vegetation in Russia indicates a so-called "restored vegetational cover" (Bazilevich, 1993) that is very close to an undisturbed state of vegetation cover, even through it is a historically developed transformation of the natural vegetation. Based on a digitized version of Bazilevich's map, we estimated the total terrestrial phytomass in Russia to be 86.5 Pg C. Our estimates on phytomass of the Forest Fund area (described above) and analyses of available publications yield an estimate of total carbon in Russia's total terrestrial vegetation of about 40–46 Pg C, or about 50% of Bazilevich's estimate. Nonstand-replacing disturbances cause a high level of mortality, estimated to be in the range of 45–50% of the total productivity for some large regions.

The total carbon flux $TCF_{\rho,t1}$ during a year t_1 generated by a disturbance ρ (for annual time steps) can be expressed as:

$$TCF_{\rho,t_1} = DF_{\rho,t_1} + PDF_{\rho,t<t_1}. \qquad (4)$$

where $DF_{\rho,t1}$ is the direct flux during a year t_1, and $PDF_{\rho,t<t1}$ is the post-disturbance, as a rule biogenic, flux generated by disturbance ρ that occurred during previous years $t<t_1$. The values of DF_{ρ,t_1} and $PDF_{\rho,t<t_1}$ as well as the explicit form of equation (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:

$$DF(t') = \sum_{ilkq} [C_{ilkq} \cdot S_{ilkq} \cdot (FC)_{ilkq}]_{t1} \gamma\,, \qquad (5)$$

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 (t/ha, dry matter), and γ is the coefficient for recalculation of dry organic matter to carbon units (we used 0.5 for forest combustibles and 0.45 for the rest of vegetation; Vonsky, 1957; Filippov, 1968; Telizin, 1973). The indexes are: i = territorial units for which calculations are done; l = aggregated land-use classes; k = types of forest fire; and q = types of forest combustibles.

Post-fire flux is generated by decomposition of both incombustible residuals and post-fire die-back (mortality), as well as by changes in structure and content of soil organic matter. Let $O_{ij}(t)$ be a function which describes the amount of dead organic matter coming into a decomposition pool *j* in year *t*, and $O_{ij}(t^*)$ be the value of this function in year *t**. For a simple exponential model, the process of decomposition of organic matter of pool *j* is described as:

$$G_{ij}(t^*,\tau) = O_{ij}(t^*)exp(-\alpha_{ij}\tau), \qquad (6)$$

where $G_{ij}(t^*,\tau)$ is the mass of organic matter left non-decomposed by the end of the period τ, α_{ij} is the constant of decomposition, and τ is the number of years between the year of fire and the year of the *PDF* estimation, e.g., $\tau^* = t^* - t_1$, $0 \le \tau \le \phi + 1$, $\phi = \text{int}[T_{0.95}]$(the integer part of $T_{0.95}$). Evidently, for (6), the time of decomposition of 95% of decomposition carbon pool $T_{0.95}$ depends only on α_{ij}, $T_{0.95} = \ln 20/\alpha_{ij}$. Thus, $G_{ij} = O_{ij}(t-\tau)l^{\alpha_{ij}(\tau-1)} - O_{ij}(t-\tau)l^{\alpha_{ij}(\tau)}$ is the amount of organic matter decomposed during each year for the period [t ,τ]. The post-fire biogenic flux during year t_1 caused by fires during previous years can be estimated by:

$$(PDF)_{ij}(t1) = 1.05\chi\left[\exp(\alpha_{ij}) - 1\right] \cdot \sum_{\tau=0}^{\phi+1} O_{ij}(t-\tau) \cdot \exp(-\alpha_{ij}\tau) + \delta\,\text{SOC}, \qquad (7)$$

where χ, 0 < χ < 1, is the share of carbon from decomposed organic matter that is taken up by the atmosphere, and *δSOC* is the change of soil organic carbon during year t_1.

Generally, χ depends on many factors. Unfortunately, there is not enough data for regional estimates of χ, so we used the average value 0.88 based on available publications (Chagina, 1970: 0.92 for old cedar (*Pinus sibirica*) forests; Vedrova, 1995: 0.75–0.92 and 0.77–0.88 for 25 years of coniferous and deciduous plantations, respectively; Kurz *et al*., 1992: 0.82 for Canadian forests). The retrospective period needed to estimate PDF covered 200 years. In order to quantify changes of soil organic carbon (*δSOC* from (7)), we used the organic matter input to soil $(\delta SOC)_{ijt1} = (1 - \chi)(PDF)_{ijt1}$. Obviously, this only gives the change of soil carbon caused by the decomposition of the post-fire die-back.

Without further discussion of details on the methods, models, or specifics of initial data (which were published by Shvidenko *et al*., 1995b, 1997), we enumerate the basic quantitative estimates of the impacts of disturbances on the Russian forest carbon budget based on this model concept. The carbon fluxes generated by the different disturbances are quantified below in a "pure" form, without consideration of the regeneration processes.

Forest fires. For the period 1989–1992 the average annual area impacted by different types of forest fires was estimated to be 3.5 million ha, of which 3 million ha were located in the Forest Fund and 0.5 million ha in tundra of the state land reserve in the extreme north. Direct fire emission (for the above areas) was estimated to be 58.1 Tg C/year. The post-fire biogenic flux, caused by decomposition of organics of incombustible residuals and post-fire die-back during the period 1800–1988, was estimated to 91.6 Tg C/year. Thus, we estimate the total atmospheric carbon uptake generated by fire on Forest Fund areas to be some 150 Tg C/year.

Pest outbreaks, diseases, and other biotic factors. The total areas affected by pest and disease outbreaks are estimated to be about 4 million ha annually. No comprehensive and detailed inventory of these disturbances in Russian forests exists. Very rough and approximate estimates, based on available statistics, publications, and fragmentary data from different surveys, gave about 80 Tg C/year as an average annual flux caused by insect and diseases. 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 90 Tg C/year (this varies from 78–104 Tg C/year under different assumptions).

Harvest. The results of modeling the impact of industrial forestry on the carbon budget indicate that industrial harvest removed 4.0 Pg C from Russian forests during 1946–1995, and only about 25% was stored in forest products in 1996 (primarily in long- and medium-term forest products). Of the total estimated 87 Tg C/year carbon fluxes caused by harvest (average annual data for 1991–1993, including local consumption), most carbon releases are caused by decomposition of harvest residuals and wastes (27%), manufacturing and decomposition of forest industrial products (57%), and usage of wood for fuel (16%).

Abiotic impacts. Industrial pollution, land-use changes and unfavorable climatic conditions are the most important factors for abiotic impacts. There are no complete surveys on the extent and intensity of these processes covering all of the Russian Forest Fund area. Based on data for specific regions and expert aggregations, we obtained a rough estimate of the carbon losses caused by different abiotic factors; the levels varied between 42 and 65 Tg C annually, with an average close to 50 Tg C/year.

Disturbances in the beginning of the 1990s caused a flux from the Russian forests of about 380 Tg C annually (forest fire is estimated for Forest Fund areas, other disturbances for forested area). The accuracy of this result cannot be evaluated by available statistical methods.

3. Estimates of the Carbon Budget

Estimates Based on Biomass and Forest Inventory Data. We used long-term inventory data in a simple “bookkeeping” approach, where results are assessed as the difference between carbon storage in the carbon pools at the beginning and the end of a specific period. *Table 6* presents the dynamics of the carbon content in the vegetation of forest ecosystems between 1961 and 1993. The calculations are based on the estimated values for the ratio R (Mg C/m^3) for European and Asian Russia discussed earlier.

Table 6. Dynamics of carbon storage in vegetation of Russian forest ecosystems between 1961 and 1993.

Indicators	1961	1966	1973	1978	1983	1988	1993
Dynamics based on data from official forest statistics							
Forested Area (FA), $x10^6$ ha	695.5	705.6	729.6	749.5	766.5	771.1	763.5
FA in European Russia	148.9	161.3	158.8	163.5	164.4	166.0	166.2
FA in Asian Russia	546.6	544.3	570.8	586.0	602.2	606.1	597.3
Growing stock (GS), $x10^9$ m^3	77.5	77.0	78.7	80.7	81.9	81.7	80.7
GS in European Russia	16.3	17.0	17.4	18.7	19.3	20.3	21.1
GS in Asian Russia	61.2	60.0	61.3	62.0	62.6	61.4	59.6
C in phytomass, Pg	30.933	30.711	31.388	32.162	32.631	32.522	32.088
C in European Russia	6.147	6.411	6.562	7.052	7.278	7.655	7.961
C in Asian Russia	24.786	24.300	24.826	25.110	25.353	24.867	24.127
Dynamics based on "reconstructed" growing stock							
Growing stock, $x10^9$ m^3	75.0	75.7	77.5	80.4	84.5	85.6	84.8
GS in European Russia	16.4	16.5	17.3	18.3	19.9	21.4	22.2
GS in Asian Russia	58.6	59.2	60.2	62.1	64.6	64.2	62.6
C in phytomass, Pg	29.920	32.201	30.908	32.054	33.670	34.074	33.728
C in European Russia	6.184	6.222	6.524	6.901	7.504	8.070	8.372
C in Asian Russia	23.736	23.979	24.384	25.153	26.166	26.004	25.356
Deviation (%%) between "reconstructed" and official C storage	-3.3	-2.2	-1.5	-0.0	+3.2	+4.8	+5.1

We provide the calculations in two variants: (1) for official data of the State Forest Account (SNKh, 1962; Goskomles SSSR, 1968, 1976, 1982, 1986, 1990, 1991; FSFMR, 1995), and (2) for "reconstructed" dynamics. The latter result from estimates of the systematic errors regarding growing stock in the Russian forest inventory system (Shvidenko *et al*., 1996a). The ratio *R* depends on the state and structure of forests, and consequently our assumption is an approximation, but due to the rather stable dynamics of Russian forest characteristics, uncertainties caused by this assumption cannot significantly distort the conclusions.

If we use official data (the first variant), we conclude that during 1961–1993 the total amount of carbon in the vegetation of forest ecosystems in Russia increased from 30.93 to 32.09 Pg C, or by 1.16 Pg (+3.8%), and reached a peak value of 32.63 Pg C in 1983. This number reveals that during the last 32 years the Russian forests constituted on average a modest net sink of 36 Tg C/year accumulated in the forest vegetation. During 1961–1983 the accumulation of carbon in forest biomass was higher, about 77 Tg C/year. After 1983 the Russian forests became a source, with an average annual carbon release to the atmosphere of about 54 Tg C/year caused by changed forest dynamics in Asian Russia. While we estimate the forests in European Russia to be a net sink for the entire period 1961–1993, with an average sequestration of 59 Tg C/year, the average estimates for Asian Russia in 1961–1993, 1961–1983 and 1983–1993 are –21, +26, and –123 Tg C/year, respectively.

The picture is more optimistic if we use data according to the "reconstructed" growing stock (variant 2). In this case, the average estimates of the carbon sink for the periods 1961–1993, 1961–1983, and 1983–1993 for all of Russia are 119, 170, and 6 Tg C/year, respectively (–69 Tg C/year for the period 1988–1993). For European Russia the corresponding figures are 68, 60 and 87, and for Asian Russia 51, 110, and –81 Tg C/year.

The assessments are approximate because the State Forest Account data contain uncertainties, and because of some delay in reporting. However, these uncertainties cannot change the trends of the results and the dynamics. Thus, in the mid-1980s the processes destroying forest ecosystem vegetation in Asian Russia started to prevail over the accumulation, and that defines the result for Russia as a whole. As stated earlier, the high level and intensity of disturbances could explain the negative dynamics of Siberian forests (Shvidenko and Nilsson, 1994). During 1993–1997, the extent of disturbances in Russian forests, and therefore the total amount of carbon emissions, decreased by about 50% compared to the previous 5 years; harvest was one-third of the previous amount, total burned areas on the protected Forest Fund lands were only about half the previous size, etc.). This should significantly change the negative direction of the carbon fluxes assessed for the Russian forests.

The annual average of increased carbon content in woody coarse debris, according to the estimates above, is about 19 Tg C/year. The accuracy of this estimate is unknown.

Dynamics of Soil Organic Carbon. There are more uncertainties in assessing the dynamics of soil organic carbon. Numerous models attempt to describe the exchange of carbon between different soil organic carbon pools and the atmosphere, but at the regional level the models are only able to present very approximate aggregated estimations with unknown accuracy and for an undefined period. The main reasons for the large uncertainties are the heterogeneity of the soil cover (i.e., an unreliable basis for upscaling), and changed soil respiration and rates of organic decomposition in the boreal forests (specifically in permafrost area). These changes do not merely depend on seasonal variations of weather, but are defined primarily by the severity of disturbances (such as forest fires, industrial transformation of the area, etc.) and by the time elapsed since the most recent disturbance. The usual assumption is that there is an approximate equilibrium in soils of undisturbed forest ecosystems, at least for virgin and natural forests. Such a disturbance as fire significantly changes the amount of litter, as well as the chemical, physical, hydrological and nutrient properties of soils (for a review see, e.g., Furyaev, 1996; Balabanis *et al*., 1997). Post-disturbance changes in soil carbon dynamics on permafrost areas could be dramatic (Matveyev, 1992). Practically no information exists for permafrost areas with respect to the stabilization of the soil organic content under given disturbance regimes.

The approach used in our calculations was based on an assessment of the impact of: (1) dynamics and transformation of Russian forests, and (2) regimes of disturbances during 1961–1993. For each aggregated ecological region, the following were taken into account (for the period analyzed): (1) change of forested area (due to forest plantations or natural regeneration); (2) burned areas by type of fires; (3) areas of industrial harvest; and (4) level of industrial transformation of territories. Regional estimates of the impacts listed above were made based on available publications and expert estimates. Basic processes included in the estimations were: (1) accumulation of organic matter due to reforestation and afforestation; (2) losses of organic matter due to fire, harvest and industrial transformation; and (3) post-fire changes in forest ecosystems on permafrost areas (increased soil respiration and productivity of forests).

The results varied for different regions, from evident losses to significant accumulation. The general conclusion is that during the period 1961–1993 the amount of organic carbon in the 1 m topsoil layer increased by about 0.86 Pg (about 0.65 % of the total and about 23% of the estimated accumulation of C in vegetation of forest ecosystems).

Carbon of Russian wetlands is of special interest given that wetlands (basically peat and peat soils) are regarded as large sequesters of carbon. We used digitized soil, landscape and soil carbon maps as well as our soil database to estimate carbon in wetlands, which are primarily situated in the tundra and boreal zones (Rojkov *et al.*, 1997). The total carbon storage in the 2 m top layer of the Russian wetlands is estimated to be 118.4 Pg, and the area of wetlands to be 418.4 million ha. Of the total wetland areas, about 43% are covered by forests and shrubs, and more than 65% of the wetlands are located in the permafrost zone. By geographical zones, most of the wetlands are located in tundra (190.6 million ha), forest tundra (30.4 million ha) and taiga (170.8 million ha); only about 6% of wetlands in Russia are located outside the mentioned zones. Significant areas of wetlands have a thin layer of an organogenic horizon. Wetland areas with a depth of up to 5 cm cover 21.6% and areas with a depth of 5–30 cm cover 52.7% of the total land.

The net ecosystem production (NEP) of wetlands is estimated to be 86 Tg C per year, of which 51 Tg are accumulated in the organogenic horizon (mostly in peat). The accumulation varies between 1.2 and 34.7 g/m^2 per year, depending on the type of bogs and zones. Based on a simple model, which includes consumption of peat for fuel and agricultural use, impact of melioration on peat decomposition, wildfire in wetlands and methane generation, we estimate that Russian wetlands (excluding the forest vegetation growing on them) constituted a slight source of carbon in the beginning of the 1990s. During 1991–1996, consumption of peat decreased in Russia to half of the earlier consumption. This means that during the last 3–5 years Russian peatlands became a net sink of carbon about 30-50 Tg C per year.

Table 7 contains an aggregation of our calculations. In addition, we assume that the rest of nonforest lands — primarily ecosystems with low productivity, such as rocks, sands, steep slopes, etc. — are in equilibrium, and did not change their impact on the carbon budget during last decade. Tentative estimates for 1993–1997 are given based on comparative analysis of the rate and extent of disturbances during the latter period.

Table 7. Impact of the Russian forest fund areas on the global carbon budget. Estimates on annual average carbon fluxes for 1961–1993, and tentative estimates for 1993–1993.

Indicator	Value, Pg C, in		Difference, Tg C		Annual Average
	1961	1993	Total	Annual	for 1993–1997
Forested areas					
Phytomass of forest ecosystems	29.920	33.728	3808	+119	+210
Coarse woody debris	5604–5744	6284	540-680	+17-21	-10
Soil organic carbon (1m)	128.640	129.590	+950	+30	+40
Peat- and wetlands				-0	+40
Non forest and unforested areas				+0	+0
Total for Russian forest fund				+168	+280

4. Discussion

Russia has never reported data on gross and net growth in its forests. Therefore, we can only compare our estimates of net growth with Russian estimates of total average increment (the ratio between growing stock weighted by area and age of stands). These estimates are confined to forests under state forest management (822 million m^3 in 1993). For the total forests, we roughly estimate the average increment to be 908 million m^3, based on the ratio of growing stock of all forests (80.676 billion m^3) to that of forests under state forest management (73.028 billion m^3). Taking into account the average age of the total forests (95 years in 1993) and the distribution by age classes, our calculated net growth corresponds well to the average increment.

Two forest phytomass estimates for the total Russian forests have previously been reported (Alexseyev and Birdsey, 1994; Alexseyev *et al.*, 1995; respectively Isaev *et al.*, 1995). Both of these estimates are based on aggregated data of the 1988 State Forest Account and, to a large extent, use a similar approach. We have provided new estimates for a number of reasons, primarily:

- The initial territorial units used in the previous estimates cover very large areas that are not homogeneous from the viewpoint of forest productivity. Our calculations by ecoregions revealed a significant bias for some Siberian and Far Eastern regions;
- Previous studies used simple conversion factors in the form of averages for dominant species and age groups over vegetational zones and subzones to estimate the principal phytomass fractions. Such an approach is very rough and does not allow us to extract the maximum information available in the State Forest Account data, and
- There were big differences in the results reported by the studies. The estimates of total phytomass for forest ecosystems of Russia differed by more than 20%.

Based on the State Forest Account from 1988, which encompassed a forested area of 771.1 million ha and a growing stock of 81,644.5 million m^3, Isaev *et al.*, (1995) reported that the total phytomass of the Russian forest ecosystems was 35.07 Pg C. Alexseyev and Birdsey's (1994) estimate was 28.0 Pg C. This means that the Isaev *et al.*, estimate is 9.3% higher and the Alexseyev and Birdsey estimate is 12.7% lower than our estimates. The growing stock decreased between 1988 and 1993 by about 1 billion m^3, and perhaps more accurate comparisons can be made based on derivative indicators.

The average carbon density (*D*) calculated on Isaev *et al.*, (1995) data was 4.55 kg C/m^2 (+8.3% compared to our results) and the ratio of carbon to growing stock (*R*) was 0.430 Mg C/m^3 (+8.0%). The corresponding figures from the Alexseyev and Birdsey (1994, 1995) analyses are 3.63 kg C/m^2 (–13.6%) and 0.343 Mg C/m^3 (–13.3%), respectively. We conclude that our estimates are very close to the average of the two previous studies.

Bonnor (1987) reported an above-ground tree phytomass density of 5.90 kg (of dry matter)/m^2 for the Canadian forests. Our average estimate for Siberia is 5.98 kg/m^2

and for all of Russia 6.26 kg/m^2 (or +6.1%). Botkin and Simpson (1990) estimate the density of above-ground woody phytomass for the North American boreal forests to be 4.18±1.01 kg/m^2, which is significantly lower than our estimates of 5.46 kg/m^2 for Siberia and 5.73 kg/m^2 for the total Russian forests.

Our estimates on the aggregated carbon fluxes from phytomass contradict all other recent estimates. For instance, Isaev *et al*., (1995) reported a net sink of 184.4 Tg C/year sequestered by Russian forest ecosystems in the early 1990s, while Lelyakin *et al*., (1997) estimate a net sink of 160 Tg C/year for the same time period. Kolchugina and Vinson (1993a, 1993b, 1995) and Krankina *et al*., (1996) estimate a significantly higher sink of up to 300 Tg C/year and more for this period. For the same time period, we estimate the carbon flux to be between +15 (sink) and –54 (source) Tg C/year. A detailed analysis of the different studies explains the differences. We limit our discussion to a few representative studies from the last 2–3 years.

First of all, some of the mathematical models used (Kokorin and Nazarov, 1994; Kokorin *et al*., 1996; Lelyakin *et al*., 1997) are intrinsically unable to provide any reliable estimates for any specific short-term period; for example, to present estimates "for 1993." These models: (1) are based on long-term average aggregated data; (2) they take into account neither previous disturbance history nor, consequently, the *PDF* component of equation (3) showing current fluctuations of disturbances); and (3) they use overly simplified approaches and limited initial data. In essence, these models can only present some estimates with unknown accuracy on tendencies over some unspecified period of time.

The method used by Isaev *et al*., (1993, 1995) is based on snapshot forest inventory data, such as data from the 1988 State Forest Account. They calculated the sequestration of carbon in wood through the difference between average (per ha) growing stock by age groups (young, middle-aged, immature, mature and overmature stands were considered) multiplied by the areas covered by stands of these groups. Therefore, the model replaces the stochastic process of forest dynamics with a momentary analysis of the current state of forests. Results achieved by such an approach could be reliable under two assumptions: (1) if average growing stocks over age have not changed during the past 20 years, and (2) if mature and overmature forests do not accumulate carbon. However, both of these assumptions are false. *Table 8* below presents data on forests of main forest forming species under state forest management (which comprise about 95% of all Russian forests). The growing stock of coniferous stands increased during 1956–1993 for all age groups except mature and overmature stands by 19–27%. For deciduous species, the growing stock of young species has not changed, but for the rest of the age groups the increase is in the range of 40–50%. Second, we have shown earlier that the net increment of mature and overmature stands comprises about 15% of the total net growth of the Russian forests, which means that these groups do sequester carbon.

Table 8. Dynamics of the average growing stock of Russian forests (m^3/ha) during 1956–1993.

Age groups	Average growing stock (m^3/ha) by years							
	1956	1961	1966	1973	1978	1983	1988	1993
Coniferous species								
Young	26.4	27.3	32.9	28.7	27.9	29.1	30.9	31.4
Middle-aged	97.0	103.2	108.6	111.4	112.1	113.6	113.3	119.4
Immature	120.3	144.1	142.7	141.0	144.8	148.6	151.5	153.3
Mature and overmature	134.8	141.5	140.2	139.4	139.3	138.0	136.4	131.8
Deciduous species								
Young	22.1	19.9	19.3	20.1	21.5	22.9	22.9	22.5
Middle-aged	66.3	70.7	74.0	84.4	90.2	93.3	95.1	96.7
Immature	92.9	100.9	104.4	112.7	119.0	123.9	131.0	140.6
Mature and overmature	109.4	120.2	128.1	143.0	147.8	149.0	152.6	152.5

Sources: 1956 to 1978 data are from Fedosimov (1986); 1983 to 1993 data are calculated from the State Forest Account of 1983, 1988 and 1993.

Our estimates of organic carbon content for all Russian lands could be compared with the latest results reported by Orlov and Birjukova (1995). The assessments of the reserves of organic carbon in the soils of lowland (plain) territories are very similar, in spite of different calculation methods (222.0 Pg and 236.2 Pg, respectively, in our estimates and those of Orlov and Birjukova (1995). However, the data on the reserves of organic carbon in the soils of mountainous regions differ substantially (120.1 Pg and 60.0 Pg, respectively). This difference can be explained by the difference in the completeness and structure of the original databases. In our database, all types of soils that occur in mountain soils are considered, whereas Orlov and Birjukova used only data for several specific types of mountain soils. Based on data for forested areas (771.1 million ha, as of 1988), Alexeyev *et al*., (1995) estimate the organic soil carbon to be 74.0 Pg C. Our results for the 1 m topsoil layer are about 75% higher. Other reported estimates were calculated for forest biomes or forest zones in Russia, and cannot be compared with our results.

For comparison, we refer to studies by Vompersky (1994), Vompersky *et al*., (1994), and Botch *et al*., (1995). The Vompersky studies estimated the area of boggy organogenic soils and bogs in Russia to be 369 million ha and the storage of carbon to 113.5 Pg (±15%); the average depth of peat (for peatlands with a depth of peat of > 0.3 m) was estimated to be 1.7 m. The results reported by Botch *et al*., (1995) for the former Soviet Union estimate the total peat land area to be 165 million ha, with a carbon pool of 215 Pg C. We can conclude that our results are very close to the estimates reported by Vompersky, and the probable amount of carbon in the Russian peat lands is about 115 Pg. The estimates by Botch *et al*., (1995) are twice as large.

Linking our results back to the Kyoto negotiations and the resulting “forest credit plan,” we conclude that in order to implement the protocol through feasible policies, the research community needs:

- To improve understanding and knowledge of how different forest processes interact with atmospheric carbon,
- To improve carbon accounting methods and set international standards on required designs and qualities of the accounting methods, and
- To improve and greatly extend the data about forest inventories and processes interacting with the inventories. Therefore, to make the Kyoto protocol operational, governments should probably invest a substantial amount of money in new data collection.

These conclusions are in line with the concerns of environmental groups and policy analysts, who doubt whether science and methodologies are advanced enough to make the forest credit plan work (Environmental Science & Technology, 1998). The Intergovernmental Panel on Climate Change has published a manual for calculating carbon dioxide emissions caused by changes in the forest resources. However, this measure may not suffice to stimulate any meaningful activity.

REFERENCES

Environmental Science & Technology, 1998, Kyoto Protocol Targets could be met with "Forest Credits." *Environmental Science & Technology*, 32(5):125–126.

Alexseyev, V.A., and Birdsey, R.A. (eds.), 1994, *Carbon in Ecosystems of Forests and Wetlands of Russia*. Sukachev Institute of Forest Research, Krasnoyarsk, 170+54 pp. [in Russian].

Alexeyev, V., Birdsey, R., Stakanov, V., and Korotkov, I., 1995, Carbon in vegetation of Russian forests: methods to estimate storage and geographical distribution. *Water, Air and Soil Pollution* 82 (1-2): 271–282.

Balabanis, P., Eftichidis, G., and Fantechi, R. (eds.), 1997, *Forest Fire Risk and Management***,** Proceedings of the European School of Climatology and Natural Hazards course, Porto Carras, Halkidiki, Greece, 27 May-4 June 1992, European Commission, Brussels.

Bazilevich, N.I., 1993, *Biological Productivity of Ecosystem of Northern Eurasia*, Nauka, Moscow, Russia, 294 p. [in Russian].

Bolin, B., 1998, The Kyoto Negotiations on Climate Change: A Science Perspective. *Science* 279, 16 January 1998, pp. 330–331.

Bonnor, G.M., 1987, Forest biomass inventory. In D.O. Hall and R.P. Overend (eds.), *Biomass. Regenerable Energy*, John Wiley & Sons, pp. 47–73.

Botch, M.S., Kobak, K.I., Vinson, T.S., and Kolchugina, T.P., 1995, Carbon pools and accumulation in peatlands of the Former Soviet Union. *Global Biogeochemical Cycles*, 9(1): 37–46.

Botkin, D.B., and Simpson, L.G., 1990, Biomass of North American Boreal Forests. *Biogeochemistry* 9: 161–174.

Chagina, E.G., 1970, Carbon balance under litter's decomposition in Cedar forests of West Sajan Mountains. In A.B. Shukov (ed.), *Problems of Forestry*, Vol. 1, Institute of Forest and Timber, Krasnoyarsk, Russia: 246–252 [in Russian].

Dixon, R., Brown, S., Houghton, R., Solomon, A., Trexler, M., and Wisnievski, J., 1993, Global forest ecosystems: their carbon pools and fluxes. *Science* 263: 185–190.

Dobrovol'skii, G.V., Urusevskaja, I.S., and Rozov, N.N., 1984, *The Map of Soil-Geographical Regionalization of Russia*. Government Administration for Geodesy and Cartography (GUGK), Moscow, Russia [in Russian].

Fedosimov, A.N., 1986, Forest Inventory by Sampling Methods, Forest Industry, Moscow, 252 p. [in Russian].

Filippov, A.V., 1968, Some pyrological properties of forest combustibles. In *Burning and Extinguishing*, VNIPO, Moscow, Russia: 351–358 [in Russian].

Furyaev, V.V., 1996, *Role of Fires in Forest Generation Process*, Nauka, Novosibirsk, Russia [in Russian].

FSFMR, 1995, Forest Fund of Russia (state by 1 January 1993). Federal Service of Forest Management of Russia, Moscow, 280 p. [in Russian].

Goskomles SSSR. (prior to 1988-Gosleshoz) *Forest Fund of the USSR*, 1968 (state by 1 January 1966, 744 p.); 1976 (state by 1 January 1973, Vol. 1, 600 p., Vol.2, 561 p., Vol. 3, 800 p.); 1982 (state by 1 January 1978, Vol. 1, 601 p., Vol. 2, 973 p.); 1986 (state by 1 January 1983, Vol. 1, 891 p., Vol. 2, 973 p.); 1990, 1991 (state by 1 January 1988), Vol. 1, 1021 p., Vol. 2, 989 p.). The USSR State Committee of Forest Management, Moscow [in Russian].

Isaev, A.S., Korovin, G.N., Utkin, A.I., Pryashnikov, A.A., and Zamolodchikov, D.G., 1993, Estimation of carbon pool and its deposition in phytomass of forest ecosystems in Russia. *Forest Science* (Lesovedenie), 5:3–10 [in Russian].

Isaev, A., Korovin, G., Zamolodchikov, D., Utkin, A., and Pryashnikov, A., 1995, Carbon stock and deposition in phytomass of the Russian forests. *Water, Air and Soil Pollution*, 82: 247–256.

Kolchugina, T. P., and Vinson, T.S., 1993a, Comparison of two methods to assess the carbon budget of forest biomes in the former Soviet Union. *Water, Air and Soil Pollution*, 70: 207–221.

Kolchugina, T.P, and Vinson, T. S. 1993b, Equilibrium analysis of carbon pools and fluxes of forest biomes in the former Soviet Union. *Can. J. For. Res*. 23: 81–88.

Kolchugina, T.P., and Vinson, T.S., 1995, Role of Russian forests in the global carbon balance. *Ambio*, 24(5):258–264.

Kokorin, A.O., and Nazarov, I.M., 1994, Evaluation of the effect of climate warming and photosynthetically-active radiation on boreal forests, *Meteorology and Hydrology*, No 5, 44–54 [in Russian].

Kokorin, A.O., Lelyakin, A.L., Nazarov, I.M., and Filippchuk, A.N., 1996, Calculation of CO_2 net sinks/emissions in Russian forests and assessment of mitigation options, *Environment Management*, 20 (Suppl. 1): 101–110.

Krankina, O.N., and Dixon, R.K., 1994, Forest management options to conserve and sequester terrestrial carbon in the Russian Federation. *World Resource Review* 6, 88–101.

Krankina, O.N., Harmon, M.E., and Winjum, J.K., 1996, Carbon storage and sequestration in the Russian forest sector. *Ambio* 25(4): 284–288.

Kurz, W.A., Apps, M.J., Webb, T.M., MacNamee, P.J., 1992, *The Carbon Budget of the Canadian Forest Sector: Phase 1*. Forestry Canada, Northwest Region, Northern Forestry Center, Inf. Rep. NOR-X-326, Edmonton, Alberta, Canada.

Lakida, P., Nilsson, S., and Shvidenko, A., 1997, Forest phytomass and carbon in European Russia. *Biomass and Bioenergy*, 12(2): 91–99.

Lelyakin, A.L., Kokorin, A.O., and Nazarov, I.M., 1997, Vulnerability of Russian forests to climate change. Model estimation of CO_2 fluxes. *Climatic Change* 36: 123–133.

Matthews, G., 1993, *The carbon contents of trees*. Technical paper 4, Forestry Commission, Edinburgh, UK.

Matveyev, P.M., 1992, *Post-Fire Impact on Larch Biogeocenosis on Permafrost.* Marijsky Polytechnical Institute, Joshkar-Ola, Russia [in Russian].

Melillo, J.M., Furry, J.R., Houghton, R.A., Moor III B., and Scole, D.L., 1988, Land-use change in the Soviet Union between 1850–1980: cases of a net release of CO_2 to the atmosphere. *Tellus* 40 B: 116–128.

Olson, J.S., 1963, Energy storage and the balance of producers and decomposers in ecological systems. *Ecology*, 44: 322–331.

Orlov, D.S. and Birjukova, O.N. 1995, The reserves of carbon organic compounds in the soils of the Russian Federation. *Pochvovedenie*, 1: 21–32 [in Russian].

Rojkov, V.A., Wagner, V.B., Kogut, B.M., Konyushkov, D.E., Nilsson, S., Sheremet, V.B., and Shvidenko, A.Z., 1996, *Soil Carbon Estimates and Soil Carbon Map for Russia*. WP-96–60. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Rojkov, V., Vagner, V., Nilsson, S., and Shvidenko, A., 1997, *Carbon of Russian wetlands*. Extended Abstracts of the Fifth International Carbon Dioxide Conference, Cairns, Queensland, Australia, 8–12 September 1997, pp. 112–113.

Sedjo, R.A., 1992, Temperate forest ecosystems in the global carbon cycle. *Ambio*, 21: 274–277.

Shepashenko, D., Shvidenko, A., and Nilsson, S., 1998, Phytomass and carbon of Siberian forests, *Biomass and Bioenergy*, 14(1): 21–31.

Shvidenko, A., and Nilsson, S., 1994, What do we know about the Siberian forest? *Ambio*, 23(7): 396–404.

Shvidenko, A., Venevsky, S., Raile, G., and Nilsson, S. 1995a, A system for evaluation of growth and mortality in Russian forests. *Water, Air and Soil Pollution* 82 (1–2): 333–350.

Shvidenko, A., Nilsson, S., and Roshkov, V., 1995b, *Possibilities for increased carbon sequestration through improved protection of Russian forests*. International Institute for Applied Systems Analysis, Laxenburg, Austria. WP-95–86, 27 p.

Shvidenko, A., Nilsson, S., Roshkov, V., and Strakhov, V.V., 1996a, Carbon budget of the Russian boreal forests: a system analysis approach to uncertainty. In M. Apps and D.T. Price (eds.), *Forest Ecosystems, Forest Management and the Global Carbon Cycle*, Springer Verlag, Berlin, Heidelberg, pp. 145–162.

Shvidenko, A., Venevsky, S., Raile, G., and Nilsson, S., 1996b, *Dynamics of Fully Stocked Stands in the Territory of the Former Soviet Union*. International Institute for Applied Systems Analysis, Laxenburg, Austria, WP-96–19, 68 p.

Shvidenko, A., Venevsky, S., and Nilsson, S., 1996c, *Increment and Mortality for Major Forest Species of Northern Eurasia with Variable Growing Stock*. International Institute for Applied Systems Analysis, Laxenburg, Austria, WP-96–98, 68 p.

Shvidenko, A., Nilsson, S., and Roshkov, V., 1997, Possibilities for increases in carbon sequestration through the implementation rational forest management in Russia. *Water, Air and Soil Pollution* 94 (1–2): 137–162.

SNKh SSSR. 1962, Forest Fund of the USSR (state by 1 January 1961). Council of National Economy of the USSR, Moscow, 265 p. [in Russian].

SOFO-1997. 1997, State of the World’s Forests — 1997, Food and Agriculture Organization of the United Nations, Rome, Italy.

Vedrova, E.F., 1995, Carbon pools and fluxes of 25-year old coniferous and deciduous stands in Middle Siberia. *Water, Air and Soil Pollution*, 82: 230–246.

Telizin, G.P., 1973, Elementary composition of forest combustibles in the Far East. In: *Utilization and Regeneration of Forest Resources in the Far East*, Reports of Far Eastern Research Forestry Institute, 15: 351–358 [in Russian].

Venevsky, S.V., and Shvidenko, A.Z., 1997, Modelling of stand growth dynamics with a destructive stage. In Proceedings of the 1996 Annual IBFRA Conference, 19–23 August 1996, St. Petersburg, Russia. Moscow, pp.30-33, [in Russian].

Vompersky, S.E., 1994, Role of bogs in carbon turnover. In: Shilov I.A. (ed.), *Biogeocenotic peculiarities of bogs and their rational use*, *Academician Sukachev’s Memory Readings*, XI, Nauka, Moscow, pps. 3–37 [in Russian].

Vompersky, S.E., Ivanov, A.I., Ziganova, O.P., Valjaeva, N.A., Glukhova, T.V., Dubinin, A.I., Glukhov, A.I., and Markelova, L.G., 1994, Bogged organogenic soils and bogs of Russia and storage of carbon in their peats. *Soil Science* (Pochvovedenie), No 12: 17–25 [in Russian].

Vonsky, S.N., 1957, *Intensity of Onground Forest Fire and its Practical Impacts*. Leningrad Forestry Institute, Leningrad, Russia [in Russian].