# Working Paper

## Possibilities for Increased Carbon Sequestration through Improved Protection of Russian Forests

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## Abstract

Improved protection of the Russian forests through more efficient forest fire protection and control of outbreaks of insects and disease may result in additional carbon sequestration – about 0.15 Pg (150 million tons) C annually during the next 100 years. The basic uncertainties in the scenario discussed in this article are linked to the paucity of inventory data for some areas of the study, the incomplete knowledge about the reaction of forests on different disturbance regimes, and the separation of the influences of different factors on the dynamics of the forests.

## 1. Introduction

Protecting the Russian forests is crucial for increasing their productivity, for improving their sanitary state, and, consequently, for raising the levels of carbon sequestration (Isaev, 1991a, 1991b; Nilsson *et al.*, 1992; Shvidenko, 1994). In this article we consider a basic carbon scenario presented by Shvidenko *et al.* (1995b), expanded to include forest fires, infestation by insects and disease, and some negative abiotic impacts.

Russia's inventory data on forests are more or less sufficient. However, Russia's monitoring data on current changes of the condition of forests and the processes of degradation, mortality, and dieback of forests are limited and spatially incomplete. This is especially true for large territories of Siberia and the Far East.

To analyze the carbon taken up by the atmosphere due to these processes, Russia was divided into the ecoregions presented in Shvidenko *et al.* (1995a). Some basic aggregated data on the forest resources used in the calculations are given in *Table 1* by geographic zone.

The average species composition for Russia is 36% larch, 18% pine, 14% spruce, 11% birch, 10% cedar, 4% fir, 4% aspen, and 3% hard deciduous. The average growing stock for all Russian forests is 105.9 $m^3$, versus 111.4 $m^3$ for the main forest species presented in *Table 1.*

The current state forest statistics only account for the utmost forest disturbances, i.e., the death of forests. According to the *Review of the Sanitary State of Forests in Russia* (Federal Service of Forest Management, 1992, 1993, and 1994), during the period from 1990 to 1992 between 350,000 and 500,000 ha of forests perished annually. The main reasons reported were forest fires (51 to 73%), unfavorable weather (18 to 44%), insects and disease (4 to 12%), and anthropogenic impact (less than 1%, except 1992 when it was 12.6%). Data for 1992 are presented in *Table 2.* The data presented in *Table 2* are regarded by the authors of the *Reviews* as being significantly underestimated.

**Table 1.** Data on Russian forests by geographic zone. Areas given in million hectares, growing stock in $m^3$ per ha.

| | Indicator | | | | | |
|---|---|---|---|---|---|---|
| Vegetational zone | TLA | FF | FL | FA | ASC | AGS |
| SA&T | 293.0 | 111.2 | 7.1 | – | – | – |
| FT&SpT&MdF | 291.2 | 229.4 | 185.7 | 135.7 | 7L1S1P1B | 65 |
| NT | 125.6 | 123.3 | 78.7 | 66.3 | 4P3L3S | 110 |
| MT | 385.9 | 381.0 | 334.2 | 320.0 | 4L2P2S1C1B | 120 |
| ST | 232.1 | 219.0 | 176.8 | 157.3 | 3P3S2L1F1C | 145 |
| MxF&DF&FS | 242.7 | 109.2 | 93.7 | 85.6 | 3P2S2B1O1H1SL | 155 |
| S&SD&D | 104.3 | 9.5 | 7.9 | 6.2 | 5O1P1E2B1A | 70 |
| Total | 1674.8 | 1182.6 | 884.1 | 771.1 | 8.2Con 0.3H1.5SL | 111 |

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 (Kurnaev, 1973).

Indicators: TLA, FF, FL, FA – total land area (without inland waters), Forest Fund, forest land, forested area, respectively; ASC – average species composition (e.g., 7L designates 70% of growing stock in stands with dominating larch); AGS – average growing stock. (The two last indicators were calculated for main forest species under state forest management. Categories of lands are presented according to the Russian Forest State Account classification; for definitions, see Shvidenko *et al.*, 1995b.)

Species: P – pine; S – spruce; C – cedar (*Pinus sibirica* and *P. korajensis*); F – fir; L – larch; B – birch; A – aspen; O – oak; E – elm; Con – coniferous; H – hard leaves; SL – soft leaves.

Sources: Goskomles SSSR, 1990 and 1991.

**Table 2.** Dead forests in Russia in 1992.

| | Area of dead forest (1,000 ha) | | |
|---|---|---|---|
| Cause | Total | Coniferous | Deciduous |
| Insects | 45.4 | 39.0 | 6.4 |
| Wild animals | 9.5 | 9.3 | 0.2 |
| Disease | 1.6 | 0.7 | 0.9 |
| Air pollution | 62.0 | 61.7 | 0.3 |
| Other anthropogenic impacts | 2.2 | 1.8 | 0.4 |
| Unfavorable weather conditions | 90.1 | 31.1 | 59.0 |
| Forest fires | 328.8 | 314.4 | 14.4 |
| Other causes | 4.0 | 3.0 | 0.8 |
| Total | 543.6 | 461.2 | 82.4 |

Source: Goskomstat of the Russian Federation, 1993.

## 2. Model Approach

Forest fires, outbreaks of insects and disease, and different anthropogenic influences (air pollution and industrialization of forest territories such as with oil and gas exploration) typically disturb forest ecosystems. These disturbances cause an essential redistribution of carbon between different vegetational carbon pools and between terrestrial biota and the atmosphere. Impacts of these phenomena on the carbon cycle can be considered to follow the same structure. The total carbon flux (*TCF*) comprises the direct flux (*DF*), generally an increase in the carbon flow to the atmosphere, and a long-term, indirect (post-disturbance) biogenic flux (*IPDF*), which has a complicated character:

$$TCF = DF + IPDF \ . \qquad (1)$$

All indicators in equation (1), as well as those in other equations given below, are expressed in Tg = Mt = 10 * 12 g C/y.

Both direct flux and indirect (post-disturbance) biogenic flux depend on the nature of the processes, the strength and scale of the disturbances, and the conditions under which the disturbances occur.

In order to quantitatively estimate the total carbon flux, a realistic structure of the carbon pools has to be followed. In our analysis we basically followed a breakdown of the carbon pools developed by Kurz *et al.* (1992). Some changes were introduced to accommodate the available Russian data. The following carbon pools were used:

- Three aboveground phytomass pools: commercial wood (stemwood and large branches with an upper diameter greater than 8 cm under bark excluding the stump), branches (the rest of the crown wood, diameter less than 8 cm), and green parts (foliage, understory, green forest floor).
- Three belowground phytomass pools: roots with a diameter greater than 8 cm, roots with a diameter less than 8 cm but greater than 1 cm, and roots with a diameter less than 1 cm.
- Five soil carbon pools: litter, coarse detritus material (on-ground and underground coarse debris, diameter greater than 8 cm), fine detritus material (diameter less than 8 cm), and two types of soil humus (labile and stabile parts).

For some of the calculations, aggregations of the above pools have been used due to the limited availability of information for the different rates of decomposition and carbon turnover times.

To estimate the total carbon flux caused by forest fires, *DF* and *IPDF* in equation (1) can be presented in the forms given in equations (2) and (3) for each vegetational zone, category of land use, type of forest fire, and type of forest combustible:

$$DF = C_{ilkq} \cdot S_{ilkq} \cdot (FC)_{ilkq} \quad , \tag{2}$$

where $C_{ilkq}$ are the coefficients for the burned forest combustibles depending on aggregated vegetational zone $i$ [$i$ = 7: aggregated from Kurnaev (1973), as in *Table 1*]; aggregated category for land use $l$ ($l$ = 4: forested areas with dominant species, unforested areas, non-forest lands, peat land); type of forest fire $k$ ($k$ = 4: crown fire, on-ground fire, underground fire, peat fire); and type of forest combustibles $q$ ($q$ = 10: stemwood and large branches; branches of less than 8 cm and more than 1 cm; bark of living trees; dry branches of living trees; twigs less than 1 cm and needles; leaves; green forest floor; woody debris; litter; peat layers). $S_{ilkq}$ are the estimates of forest fire areas, and $(FC)_{ilkq}$ is the storage of forest combustibles (t/ha, dry matter).

$$Fire\ (IPDF) = F[t, X(t)] \quad , \tag{3}$$

where $F$ is a function dependent on time ($t$). The variable $X(t)$ is defined according to

$$X(t) = \{[(D\dot{I}W + DPFD) + SOC - (RF + BE)] - ChC\}_{ilkq} \quad , \tag{4}$$

where $D\dot{I}W$ is decomposition of incombustible wood; *DPFD* is decomposition of post-fire dieback; *SOC* are soil organic changes; *RF* is regrowth of forests; *BE* is the "boreal effect" (increased productivity after a forest fire); and *ChC* is charcoal stored in the soil.

All parts of equation (4) are considered to be functions of time dependent on the indices $i$, $l$, $k$, $q$ (see definitions above).

Numerical estimates of the quantitative and qualitative indicators of the regeneration period are needed to estimate the post-fire dynamics of the soil organic changes. The duration of the reforestation period in burned areas varies greatly, depending for the most part on ecotypes, and climatic conditions as well as the severity of the fire, the size of burned area, the intensity and frequency of recurrent fires, and the number and distribution of seed trees. The usual range is 15–20 years (Melekhov, 1948; Furjaev and Kireev, 1979; Miljutin, 1979; Sheshukov, 1970; Bondarev, 1988). Zvetkov (1988) has estimated the period of active regeneration of post-fire areas in larch forests of the European north to be 5 to 12 years. Sheingauz (1989b) reviewed data on crown fires in the Far East region and judged the period for active reforestation to be 15 to 20 years. For the southwest of the Yakut Republic, different types of post-fire regeneration have been identified: a fast mode (3 to 5 years), a slow mode (up to 20 years), and a long-term mode (30 years or more) (Sherbakov and Chugunova, 1961).

In order to characterize the regrowth influence on the soil organic changes, in our calculations we used average zonal data for the rate and share of regeneration for two classes of regrowth –fast regeneration (7 years) and slow regeneration (20 years). To estimate the productivity of regenerated forests, regional yield tables were used (Moshkaljov, 1984; Voinov, 1986; and Korjakin, 1990).

There are plenty of research results available on the post-fire productivity of forests of the northern part of the boreal zone in Russia, especially for permafrost areas. Significant increases in productivity (the "boreal effect") have been reported (Viereck, 1973; Furjaev, 1977). Sedykh (Felistov *et al.*, 1990) reported that the productivity of forest stands on post-fire and anthropogenically disturbed sites of the forest-tundra zone with permafrost on clay soils (including the complete destruction of moss–lichen cover) increases threefold. Another conclusion by Felistov *et al.* (1990) is that the bogging process eventually will stop altogether. Similar conclusions are drawn by Posdnjakov (1983) and Buzikin (1983). Sheshukov (1989) noted an average soil temperature increase of 4° to 6°C and an increased duration of the vegetation period of 10 to 15 days for post-fire areas in the zones of the northern and middle taiga on permafrost or long-term seasonally frozen soils.

In the calculations below we estimated the pure post-fire fluxes. Regrowth of forests and the "boreal effect" ($RF + BE$) were excluded from equation (4); these impacts have been accounted for in reforestation programs presented previously by Shvidenko *et al.* (1995b). The amount of charcoal carbon ($ChC$) is estimated to be about 3 to 5% of the post-fire remains (the $ChC$ is estimated to be 2.7% for the Brazilian rainforests; Fearnside *et al.*, 1993). To our knowledge only expert estimates are available for the boreal forest of Eurasia; these estimates indicate the same results as those for the rainforests.

In order to define $F[t,(D\dot{I}W + DPFD)]$ the following simple model and assumptions were used. Point $A$ in *Figure 1* illustrates the storage of an organic matter compartment ($j$) in the climatic zone ($i$) of the organic matters $D\dot{I}W + DPFD$, which have reached the decomposition pool in year $t^*$ and will decompose during the period $TD_{ij}$. The rate of decomposition is described by the function $G_{ij}(t^*)$, with the time needed for 95% of all the organic matter to decompose being written as $T0.95$. $\tau$ is the period between years $t^*$ and $t'$, during which the carbon emission is considered in the calculations. An exponential expression for $G(t)$ is assumed,

$$G(t) = \exp(-\alpha t) \ , \qquad (5)$$

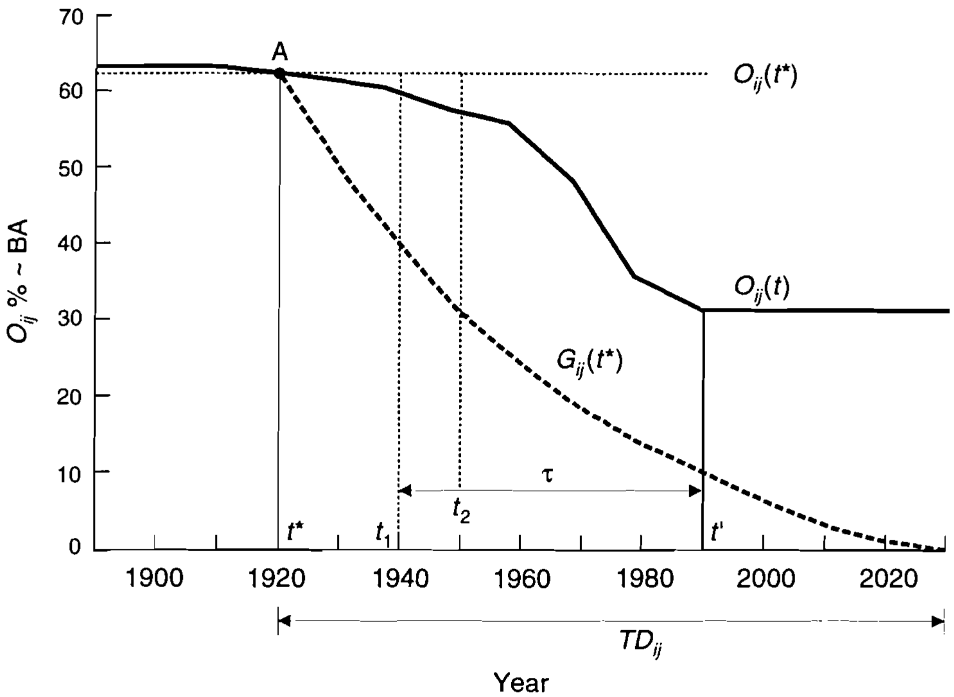


**Figure 1.** Estimation of the biogenic post-fire flux. $O_{ii}$ % ~ burned areas (BA) in million ha.

from which the times needed for 50% (*T0.5*) and 95% (*T0.95*) of the organic matters to decompose are easily determined:

$$T0.5 = \ln 2 / \alpha \ , \quad \text{and} \quad T0.95 = \ln 20 / \alpha \ . \qquad (6a, b)$$

Equation (5) works well for homogeneous carbon pools; however, aggregated results for several pools, or for heterogeneous pools may differ from those of equation (5). Auclair (1985) identified a nearly linear decrease of dead organic matter during a 140-year period in the northern *Picea mariana – Cladonia stellaris* ecosystems, which may be explained by a composite structure of decaying organic matter (wood, litter, etc.).

If $O_{ij}$ is a function for organic matter input in zone *i* by organic matter compartment *j*, then

$$G_{ij} = O_{ij}(t-\tau)e^{-\alpha_{ij}(\tau-1)} - O_{ij}(t-\tau)e^{-\alpha_{ij}\tau}$$

is the amount of organic matter decomposed for the period $t - \tau$, where $0 < \tau < int\ \{[T0.95] + 1\}$, and $int\ [T0.95]$ is an integer of $T0.95$. The total amount of decomposed organic matter in year $t'$ from the inputs in each year of period $\{0, int\ [T0.95] + 1\}$ is

$$G_{ij}(t) = \left[\exp\,(\alpha_{ij}) - 1\right] \cdot \sum_{\tau=0}^{\phi+1} O_{ij}(t-\tau) \cdot \exp\,(-\alpha_{ij}\tau) \ , \qquad (7)$$

where $\phi = int\ \{[T0.95] + 1\}$ .

Function (7) underestimates the final result by 3 to 6% due to the cutting of the $G_{ij}$ curves by the *T0.95* limits. The accuracy of the results directly depends on curve $O_{ij}$, for which the Russian conditions can be reliably reconstructed only for the last several years.

To create a historical reconstruction of $O_{ij}$ we worked with the following basic hypotheses:

- Total input of organic matter for decomposition in year $t$ is proportional to the burned areas and the areas of dead stands at a certain period [the part of $O_{ij}(t)$ during the period 1961 to 1988 in *Figure 1* corresponds to the burned areas inventoried during this period].
- The average ratios of different kinds of fires, as well as the geographical distribution of these fires, are the same for the entire period considered.
- During the period 1800 to 1950 the areas of forests that burned annually were approximately of the same magnitude (the area of extrapolation in *Figure 1*). Beginning around 1950 such areas continuously decreased due to forest fire suppression.

Although there are no data confirming the third hypothesis, there are estimates (Ministry of Forestry, 1968) that during the period from 1909 to 1913 forested areas destroyed by forest fires were around 0.5 million ha annually. This estimate is twice as large as the average annual areas of crown fires during the period from 1989 to 1992. An analysis of the age structure of stands and the age-class distribution of forests in large regions confirms the hypotheses mentioned above. In order to reconstruct $O_{ij}(t)$ for the period 1947 to 1965, the following data from the Ministry of Forestry (1968) on relative average annual burned areas (the period 1947 to 1951 was set to 100) were employed: the period 1952 to 1956 (90); 1957 to 1961 (66); and 1962 to 1965 (46).

The experimental data for the decomposition rates of litter are more or less sufficient. However, the data available on the decomposition of woody carbon components are very poor. For the latter components we used available expert estimates, taking into account ecoregional climatic conditions and average tree species compositions.

The approach discussed above was also used for the calculation of carbon emissions caused by disturbances by insects and disease. Due to a lack of historical data on $O_{ij}(t)$ with respect to disturbances by insects and disease, we used a constant over time based on the current conditions.

Soil organic changes have a very complicated nature based on several conflicting processes. After a fire, the soil respiration and the replacement of carbon by water and wind are enhanced at post-fire sites. Litter accumulates from post-fire regrowth and there are changes in forest establishment at post-fire sites (such as change of species) and changes of water regime in the areas, etc. In our calculations we applied a simple approach using aggregated estimates of the total change of the organic matter in the soil (including litter) for the period of forest regeneration or stabilization of other types of vegetation. The products of decomposition were divided into two parts: 95% was considered to be trace gases, 5% was considered to be carbon transformed into soil humus.

## 3. Forest Fires

Many types of boreal forests are unable to develop or regenerate without the periodic impact of fire (Habeck and Mutch, 1973; and Furjaev, 1977). Forest fires are one of the most dramatic causes of disturbances of the Russian boreal forests, but they simultaneously play an essential role as a natural factor of the forest dynamics.

The burning of forest organic matter is a substantial source of carbon emissions to the atmosphere. The influence of fire on the greenhouse effect is somewhat more difficult to calculate because of the cooling effect (up to 2 $W/m^2$) due to solar radiation reflection by smoke particles, both directly and through cloud condensation nuclei generation (Dickinson, 1993). This problem is currently not well researched.

Regional and global estimates of the fire and post-fire emissions of boreal forests vary greatly, as do the approaches and models used and the assumptions made about post-fire processes (Auclair, 1991; Crutzen and Goldammer, 1993; Dixon and Krankina, 1993; Levine, 1991; Kolchugina and Vinson, 1993a, 1993b). What is ultimately emitted by burning depends on many factors (Valendik and Gavel, 1975; Cofer *et al.*, 1990, 1991; Hegg *et al.*, 1990; Grishin, 1992, Cahoon *et al.*, 1994). General estimates given by Lobert and Warnatz (1993) of the carbon compounds in the gases emitted by vegetation fires are 80 to 85% $CO_2$ (from 50% in low-intensity smoldering fires to 99% in strong burns); around 7% CO (2 to 15%); and 2 to 3% hydrocarbons (0.5% CH4, about 1% NMHC, and 0.5% in the form of pure and aromatic hydrocarbons). The data presented above are in line with a review by Andrea (1991) on this subject. Roughly 2% of the emitted carbon is in the form of particulate organic carbon including about 0.5% elemental carbon.

Average carbon content in forest combustibles has been estimated at 51% for oven-dry wood, 48% for green parts (from 49% to 53% for needles), and 40% for the upper soil humus layer (Vonsky, 1957; Filippov, 1968; Telizin, 1973). Taking into account the large geographical variability of the specific density of wood and the heterogeneity of forest combustibles, we used an average content of 50% for oven-dry forest phytomass and detritus (Matthews, 1993).

The areas burned annually ($S_{ilkq}$) have only been inventoried for forests with fire protection, which in Russia in 1992 constituted about 64% of the total Forest Fund area (Goskomstat, 1993). About 50 million ha were protected by on-ground methods and 703 million ha by aerial methods. In 1989, forest fires were detected and extinguished using aircraft on 585 million ha; on the rest of the fire-protected area (167 million ha) aircraft only detected the fires (Isaev, 1991a). For the most part, areas not protected against fires are located in forest tundra, sparse and northern taiga of western Siberia (43 million ha in 1989), eastern Siberia (119 million ha), and the Far East (249 million ha). During the period from 1989 to 1992, the annual number of detected forest fires was 13,000 to 22,000.* The annual average total burned area on fire-protected areas was about 1.4 million ha (including 1.1 million ha on forest land, of which 1.0 million ha was forested area). The forest fires on fire-protected areas for 1989 to 1992 are presented in *Table 3*. The data do not include prescribed control burns on Forest Fund areas and on agricultural lands.

The areas burned annually in unprotected territories can only be estimated indirectly. By employing different VNIIZIesresours and Lesproject data, we were able to estimate the average area of forest fires in the total Russian territory to be 3 to 4 million ha annually during the period from 1985 to 1992. Stocks (1991) estimated the burned areas in 1987 to be 10 million ha. Cahoon *et al.* (1991) determined the burned areas of the territories north of the Amur River to be 3.6 million ha; in a later publication (Cahoon *et al.*, 1994) the total burned areas in the Russian Far East were estimated to be 14.4 million ha. This extent of burned areas may be possible in extremely warm and dry years. However, our estimates using Soviet satellite data for 1987 for central Siberia and the western part of the Far East are only about 6 million ha. Also, there have been years with a rather low danger of fire in Russia – for example, 1991 to 1993. Cahoon *et al.* (1995), using AVHRR data, estimate the burned areas in total Russian territory in 1992 to be about 1.5 million ha.

To estimate the component ($S_{ilkq}$) for the forest fire areas for the period 1966 to 1988, we used regional data regarding the distribution of forested areas by dominant species, the dynamics of

*The official statistics data on forest fires before 1988 are not accurate and cannot be used for any conclusions.

**Table 3.** Forest fires on fire-protected areas in Russia from 1989 to 1992. Areas given in thousand hectares, volumes in million m$^3$.

| Region | FF | FL | FA | NFL | OGF | CF | P |
|---|---|---|---|---|---|---|---|
| 1989 | | | | | | | |
| Russia | 2040 | 1628 | 1496 | 412 | 1249 | 247 | 8 |
| WS | 1407 | 1128 | 1103 | 279 | 1042 | 61 | 3 |
| FE | 515 | 397 | 319 | 118 | 138 | 181 | nd |
| 1990 | | | | | | | |
| Russia | 1673 | 1369 | 1317 | 304 | 1043 | 274 | 1 |
| ES | 762 | 715 | 691 | 47 | 483 | 207 | nd |
| FE | 834 | 608 | 586 | 226 | 521 | 65 | nd |
| 1991 | | | | | | | |
| Russia | 970 | 569 | 500 | 401 | 391 | 106 | 3 |
| WS | nd | 73 | 70 | nd | 64 | 3 | 3 |
| ES | nd | 68 | 67 | nd | 46 | 21 | nd |
| FE | nd | 397 | 334 | nd | 261 | 73 | nd |
| 1992 | | | | | | | |
| Russia | 917 | 522 | 509 | 395 | 465 | 41 | 3 |
| WS | nd | 35 | 34 | nd | 34 | nd | nd |
| ES | nd | 115 | 115 | nd | 97 | 18 | nd |
| FE | nd | 319 | 411 | nd | 293 | 18 | nd |

Abbreviations: FF, FL, FA = Forest Fund, forest land, forested area, respectively; NFL = non-forest lands; OGF = on-ground fires; CF = crown fires; P = underground peat fires; nd = no data; WS, ES, FE = Western Siberia, Eastern Siberia, Far East, respectively.

Sources: Official data for 1989, 1990 from the FSU State Committee on Forest (Goskomles SSSR, 1991b). Data for 1991, 1992 are from Federal Service of Forest Management, 1992, 1993.

the structure of the unforested areas, etc. The dynamics of burned forest, dead stands, and grassy glades of the Russian Forest Fund areas managed by state forest authorities including long-term leased areas are estimated as follows: 1961 – 70.6 million ha; 1966 – 68.4 million ha; 1973 – 53.6 million ha; 1978 – 43.9 million ha; 1983 – 36.8 million ha; and 1988 – 34.9 million ha (Goskomles SSSR, 1968, 1976, 1986, 1990, 1991). Characteristics of the post-fire dynamics and natural regeneration of burned areas have been collected from Melekhov (1948), Chertovsky *et al.* (1987), Utkin (1965), Zvetkov (1988), Bondarev (1988), and Furjaev and Kireev (1979).

Thus, an average annual estimate of the total forest areas damaged by forest fires in Russia is 3.5 million ha, of which 3 million ha are on Forest Fund areas and 0.5 million ha are on northern deer pastures and state land reserves in the extreme north. The average burned forested areas were estimated to be 1.5 million ha, non-forest lands (mires, tundra landscapes, etc.) at 1.0 million ha, and unforested areas (post-fire areas, cuttings, sparse forests, and grassy glades) at 0.5 million ha.

The ratio of on-ground fires, crown fires, and underground fires used for forested areas was 84:16:0.3%, suggesting that crown fires are probably more rare in the sparse northern forests (which are not protected from fire) than in the closed forests of the south [the average for the protected territories in 1989–1992 was 83:17:0.3%; in the extremely dry year of 1972 – 56:44:?%; and in 1978 – 76:24:0.1% (Chervonny, 1979)]. Shetinsky (1994) has presented the ratio 81.4:18.6:0.02 based on the official statistics of many years. Our assessment of burned areas in different land-use categories (*Table 4*) is very rough, but a sensitivity analysis showed that when peat land was not considered the distribution of the other land-use categories did not substantially influence the overall results.

Unforested mires (mostly peat land) were accounted to be 137.7 million ha in Forest Fund territories under state forest management in Russia, and an area of peat land at least that size is covered by forests (Sabo, 1966; Vompersky *et al.*, 1975; Glebov, 1976; and Goldin, 1976). The

**Table 4.** Distribution of annual forest fire areas (million ha) and average extent of on-ground fires combustibles (~ dry matter, t/ha).

| Vegetational zone | BA | Forest fire areas, mln. ha/year CF | On-ground fires FA | UA | NFL | OGFC (t/ha) |
|---|---|---|---|---|---|---|
| SA&T | – | – | – | – | 0.50 | 8 |
| FT&SpT&MdF | 7.9 | 0.055 | 0.29 | 0.11 | 0.22 | 27 |
| NT | 8.5 | 0.060 | 0.32 | 0.12 | 0.24 | 27 |
| MT | 10.9 | 0.074 | 0.39 | 0.15 | 0.31 | 32 |
| ST | 5.4 | 0.037 | 0.18 | 0.08 | 0.15 | 35 |
| MxF&DF&FS | 2.2 | 0.014 | 0.07 | 0.03 | 0.07 | 18 |
| S&SD&D | – | – | 0.01 | 0.01 | 0.01 | 15 |
| Total | 34.9 | 0.240 | 1.26 | 0.50 | 1.50 | – |

Abreviations: BA = burned areas, dead stands and glades, according to the FSA of 1988 (Goskomles); CF = crown fire; FA, UA, NFL = on-ground fires on forested areas, on unforested areas, and on non-forest lands, respectively; OGFC = on-ground forest combustibles. See *Table 1* for vegetational zone abbreviations.

latest estimations on the extent of wetlands in Russia (Vompersky, 1994) show that 139 million ha are occupied by mires defined as areas with a depth of peat greater than 0.3 m, of which 95 million ha are located on the tundra and on frozen soils in the taiga. Additionally, 230 million ha are swamp lands (with a depth of peat up to 0.3 m) of which 179 million ha are located on the tundra and on frozen soils in the taiga. Overwet lands, located only in the taiga take up about 163 million ha. Fires on peat lands are not specifically inventoried. However, there are different possibilities for estimating the risk of peat fire. One possibility is through the Nesterov fire index (for a definition see Chervonny, 1979, pp. 22–23). There is a peat fire risk with an index value of 1,000 to 4,000 during the spring and with an index value greater than 1,000 in the autumn (Starodumov, 1966). More risk for peat fire exists if the precipitation during a forest fire period is below 50 to 60% of the long-term average. Kurbatsky (1962), Furjaev (1970), Arzibashev (1974), and Gundar (1978a) have identified a peat fire risk if the water table level in the peat is lower than 0.3 to 0.5 m. Sofronov and Volokitina (1990) have identified a risk with a water table level lower than 0.6 to 0.9 m in southern and western Siberia. Peat can burn with a water content of 200 to 230% in the Far East (Gundar and Kostirina, 1976), and with a water content up to 400 to 500% in Siberia (Kurbatsky, 1962). A critical water content where on-ground fires can turn into deep peat fires is 200 to 250% (Gundar, 1978a). Under some conditions, drained peat lands (5.3 million ha in Russia in 1989) are able to burn even with a snow cover (Rjabukha, 1973). Isaev (1966) has illustrated that larch forests on peat lands are subject to higher fire risk than is larch on dry sites.

The conditions for peat fire risks noted above occur one to three times during a 10-year period in the majority of the main boreal regions of Russia (Chibisov, 1974; Chervonny, 1979). About 60 to 90% of the annual fire areas are usually concentrated in five or six regions, in which the fires have a catastrophic effect. In Siberia on average about 1% of the fires are large fires (with an area of more than 200 ha); in dry years this may rise to 10%. However, large fires occupy 50 to 80% of the burned areas and cause up to 90% of the total damage (Valendik, 1985). In 1989, 3,400 forest fires occupying 0.81 million ha were detected in the Tyumen region; 900 (0.47 million ha) in the Tomsk region; 100 (0.32 million ha) in the Sakhalin region; and 1,000 (0.17 million ha) in the Khabarovsk region. Thus, more than 80% of the burned areas in the country were concentrated in the territory of four administrative regions. A high concentration of fires influences "the strength" of the flames and the amount of burned biomass. Based on our regional estimates from different regions of the Russian boreal zone, we assume that 10% of the areas that burn annually are peat and peat soil lands, i.e., 350,000 ha.

The extent of burned organic mass [forest combustibles (*FC*) in equation (4)] depends heavily on the type and intensity of the forest fires, the frequency of fires, the type and productivity of the forest, the dominant species, the grade of humidity of soils, etc.

As a rule, the length of fire cycles is 25 to 70 years However, the variation in the fire frequency is very large: upper limits are 270 to 300 years, lower limits are 7 to 15 years, and even a lower limit of 3 to 4 years can be observed (Moiseenko, 1958; Zubov and Belkovich, 1960; Furjaev and Kireev, 1979; Afanasjev, 1989; Valendik, 1990). The amount of the forest combustibles is inversely proportional to the periodicity of the forest fires.

During crown fires, trunk wood and branches of trees (over 7 to 10 mm in diameter) usually do not burn, but needles and dry branches usually burn completely. There are numerous data on storages of branches and needles (e.g., Posdnjakov *et al.*, 1969; Smoljaninov, 1969, Elagin, 1985; Usoltsev, 1988a; Gabeev, 1990). Usoltsev (1988b) estimated the dry biomass of canopy combustibles in stocked pine plantations in the northern Kazakhstan to be in the range of 9 to 15 tons per ha depending on site indexes and age of the stand. For middle-aged and immature pine stands in the southern Krasnoyarskiy Krai, Semetchkina (1977) estimated a content of dry branches of 0.7 to 4.8 tons per ha and a content of branches of a diameter of less than 1 cm to range between 3.7 and 9.2 tons per ha. The amount of burned biomass and the strength of the fire increase significantly in areas with an easily combusted shrub layer (such as *Dwarf pine*, *Sasa kurilensis*, etc.) or in heavily slashed areas. The pre-fire history also plays a role. Sheshukov's measurements (1978) of the content of forest combustibles in mature (150 to 180 years) spruce stands in the northern taiga, which were generated after large fires and were not further influenced by any fire, identified about 40 tons of combustible content in the moss and upper layers of litter. In larch stands with marsh tea and spagnum layers, the amount was 132 tons/ha.

Large amounts of the forest combustibles are left on clear-cutting areas. A study of spruce-fir uneven-aged forests harvested by heavy machinery in the southern taiga zone of Krasnoyarskiy Krai identified 40 to 49 tons/ha of stem remains and 8 to 14 tons/ha of slash, i.e., a total of about 40 to 50 tons/ha of dry matter (Zvetkov and Ivanova, 1985).

A model developed by Grishin (1992) for analysis of the coniferous forests identifies a maximal amount of 117 tons/ha of forest combustibles. This can be considered as a possible theoretical maximum of matter burned during a crown fire. Kurbatsky (1970b) has estimated the maximum amount of aboveground phytomass that can be burned in a crown fire to be 20 to 30% of the existing phytomass.

Using published data (partially listed in *Table 5*) we calculated the average amount of forest combustibles by forest zone. In *Table 5* we present for comparison the aggregated data for phytomass and mortality mass by vegetational zones, calculated on the basis of digitized maps produced by Bazilevich (1993a).

The amount of aboveground forest combustibles is estimated to be greatest in the Far Eastern mature dark coniferous (spruce-fire) forest, where the living phytomass reaches 350 to 400 tons/ha. For mixed cedar forests the amount is estimated to be 300 to 330 tons/ha; for larch with green mosses, 350 to 370 tons/ha (Dukarev, 1989).

The share of unburned aboveground forest combustibles in a forest fire varies significantly, too. One study estimates an amount of 12 to 39% for mosses, 13% for lichens, and 10 to 20% for falldown of coniferous species (Valendik and Isakov, 1978). In on-ground fires (small, with a medium intensity) the amount of litter burned is estimated to be some 30% in the Ural Mountains

**Table 5**. Onground forest combustibles (OGFC), expressed in dry matter tons per ha.

| | Dry matter (t/ha) | | |
|---|---|---|---|
| Vegetational zone | Phytomass | Mortality mass | Characteristics of OGFC |
| Subarctic | 14.5 | 39.7 | 1.5–2 (1) |
| Tundra | 52.0 | 78.3 | Lichens 3 (1), mires (without peat) 12 (2) |
| Forest tundra & sparse taiga | 64.7 | 64.5 | Meadow 10 (3), shrubbery, DP 8–10, DA 23(2), L 16 (1), L40–75, lichens + march tea 25 (3), litter + floor in B 42, in S 48–56 (17), slash on L cuts, in valley 31–45, on slopes, 12–25 (1), DP, litter 15–21 (24), DP, aboveground phytomasss 20–100 (28) |
| Northern taiga | 101.0 | 87.7 | Litter in S stands with green mosses 26 (17), in L 12–30, S 60–100 (20), litter in S 50–65, fresh cuts 25–38, B 30–60 (26) |
| Middle taiga | 137.9 | 68.7 | P, L, young stands 15–18 (4), P10–20 (8), P 25–30, S 30–35 (9), lichens in P (11), litter 5–25 (13), P, litter 23 (range 16–135) (21), litter (range 76–89) (29) |
| Southern taiga | 172.1 | 78.5 | P 30–60, B 7–15 (5,6) P, basic types, 25, S with green mosses 65 (7), P 33–41 (8), P 25–30, S 30–35 (9), slash on cuts 25–30, P 22–36 (14), L 10–50 (18), litter: S 25–127, B 21–24, P 19–36 (23), undergrowth P 0.1–8.2, green forest floor 1.9–9.0, litter 0.7–5.4 (30) |
| Mixed forests | 272.0 | 90.5 | Pine 28–34 (8), B 19, S 45, O 28, C 34, L 30–90 (12), C 5–6, S 13–14, A, WB 4–5, meadow 2–3 (15), P 9–26, L 7–56 (16), 5–20 (19) |
| Decidious forests | 232.2 | 67.9 | P 8–14 (8), 5–20 (19), litter in sub–alpine zone of meadow 10–19, small shrubbery 17–49, shrubbery 4–76, forest 8–24 (25) |
| Forest-steppe | 96.2 | 42.1 | 5–20 (19), 6–18 (22), liter P 32–87 (27) |

Abbreviations: DA = dwarf alder; DP = dwarf pine; L = larch; B = birch; S = spruce; P = pine; O = oak; C = cedar; WB = white birch, A = aspen.

Sources: source number is given in parentheses. (1) Sheshukov *et al.*, 1992; (2) Snitkin, 1969, 1971; (3) Sofronov, 1988; (4) Sementin, 1978; (5) Atkin and Atkina, 1985; (6) Atkin and Smirnova, 1983; (7) Kurbatsky, 1970a; (8) Dichenkov, 1993 (European part of Russia); (9) Kurbatsky, 1970b (aggregated data for taiga zone); (10) Zvetkov and Ivanova, 1985; (11) Valendik *et al.*, 1977; (12) Sheshukov, 1970; (13) Telizin, 1970; (14) Ivanova, 1985; (15) Kostirina, 1975; (16) Solovjov, 1973; (17) Chertovsky *et al.*, 1987; (18) Isaev, 1966 (Amur oblast including mixed forests); (19) Remezov and Pograbnjak, 1965 (forest floor, aggregation for temperate zone); (20) Bogatirev and Fless, 1983 (European North-Komi); (21) Morozova and Lazareva, 1983 (European North, Karelia, including Middle Taiga); (22) Popa, 1983; (23) Popova, 1983; (24) Pugachev, 1983; (25) Zarik, 1983; (26) Chertovsky *et al.*, 1983; (27) Shakirov, 1983; (28) Krilov *et al.*, 1983; (29) Zasukhin, 1989 (European North-Arkhangelsk); (30) Shakhnovich, 1985.

(Firsova, 1960) and up to 50% in Krasnoyarskiy Krai (Popova, 1978). Average estimates by Saposhnikov (1994) for the basic forest formations of the Far East are 20 to 25%.

Post-fire mortality for trees varies greatly and depends heavily on the type and the intensity of the fires and the distribution of dominant species. The following are average estimates: for on-ground superficial fire, 6 to 12%; on-ground steady fire, 15 to 20%; litter fire, 30 to 50%; turf fire, 60%; peat fire 70%; and crown fire, 75%. The variations are, however, very large, e.g., 5 to 90% for litter fire and 35 to 85% for turf fire. Sibirina (1989) identified a mortality rate of about 60% (190 $m^3$/ha) in cedar stands of the Far East during the first four years post-fire, and the dying-off process still continues. An example of the impact on post-fire mortality in pine and larch stands in the European north by ground fires of different intensity is illustrated in *Figure 2*. At a post-fire site where burns or traces of the fire reach a stem height of 6 m all the pine trees will die. A similar situation in larch stands will only cause a mortality of 50 to 60%. The rate of

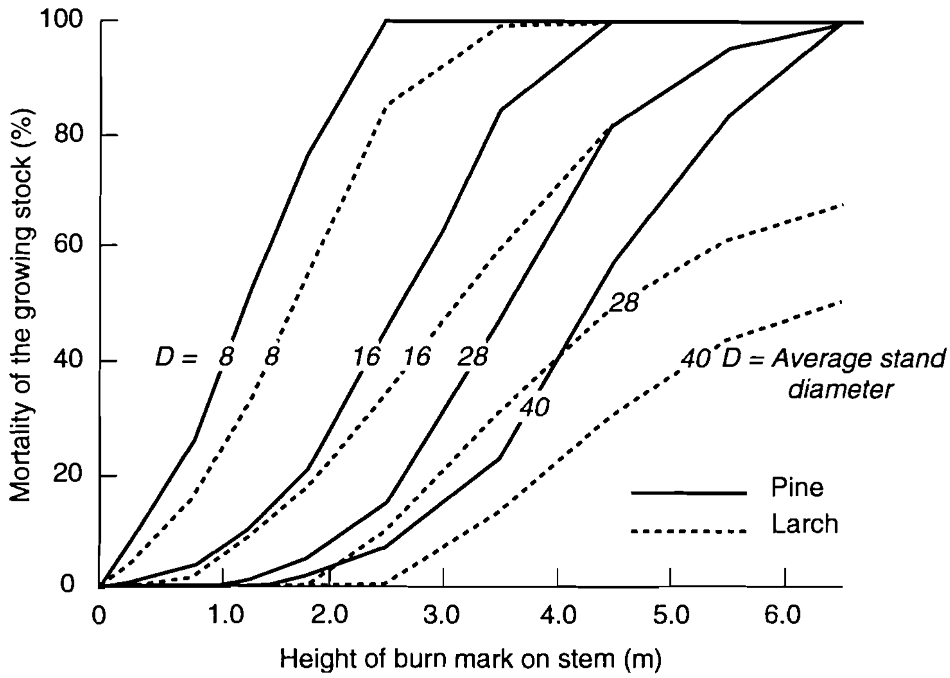


**Figure 2.** Post-fire mortality of the growing stock at different stem heights with fire burns and for different average stand diameters for pine and larch. [Based on Voinov (1986).]

mortality increases from pine to larch to cedar to spruce (Solovjov, 1973; Mishkov and Starodumov, 1976; Solovjov and Sheshukov, 1976; Sheshukov *et al.*, 1978; Mikhel, 1984; and Sibirina, 1989). The average period for the dieback caused by fire is estimated to be five years (Girs, 1982; Balbishev, 1958; Solovjov and Krokhalev, 1973).

Some specific features of the post-fire dieback have been observed for forests growing on permafrost. For larch stands in the northern part of the Yakut Republic, the extent of post-fire dieback seems to be dependent on the tree diameter of the stands. With a low fire intensity the post-fire dieback is estimated to be 10 to 30% of the growing stock, with a strong fire intensity, 40 to 95% (Matveev, 1992). As a rule, post-fire mortality is further increased by outbreaks of secondary pests, especially xylophagous insects.

Many publications report the full destruction of stands even after steady on-ground fires (e.g., Zvetkov, 1988; AUIRCFR, 1990). According to estimates of the Russian National Center of Forest Pathological Monitoring (Federal Service of Forest Management, 1992, 1993, 1994), 0.23 million ha of forest will die within a five-year period due to the post-fire impact of forest fires in 1990. The data for 1991 and 1992 are 0.20 and 0.18 million ha, respectively. In the case of unfavorable weather conditions (such as drought) the mortality rate may be substantially higher. In our calculations the average post-fire mortality for different zones and types of forests was estimated to be in the range of 25 to 40%. Additionally, we estimated the post-fire mortality of lichens and mosses to be 50% of the uncombusted amount (Auclair, 1985). The same assumption was made for the forest understory and bushes.

In order to calculate the direct fluxes from the peat fires, the following assumptions were made. The upper 20-cm layer of burned peat areas and 40% of the soil organic matter will contribute to the carbon emissions to the atmosphere. The density of undrained peat is estimated to vary from 0.05 to 0.10 tons/m$^3$ (Vompersky *et al.*, 1975); the weight of dry peat (peat soil) in the 20-cm layer is estimated to be about 160 tons/ha. The total area of underground fires is estimated to be

12,000 ha (the average for 1989 to 1992 for fire-protected area was about 4,000 ha), with an average depth of burning of 0.8 m (Gundar, 1978b).

The basic post-fire dynamic processes in soil increase with regard to the intensity of oxidation of soil organic matter but decrease with regard to density and air permeability. Dynamics of soil organic matter [*SOC* in equation (4)] strongly depend on the type of fires and the total amount and the share of burned forest combustibles. As a rule, prescribed burning and superficial on-ground fires do not cause any essential losses of mineral soil organic matter in the boreal forests (Wells, 1971); in many cases there is a slight increase of soil organic matter during the years after the fires (see, for example, McKee, 1982; Johnson, 1992). In contrast, steady on-ground litter and turf fires can cause considerable post-fire losses of humus content. A 40% loss during a 25-year period in the 60-cm top layer has been reported by Sands (1983) for *Pinus radiata* in Australia, but such results are exceptions rather than the rule (Dyrness *et al.*, 1989).

Numerous Russian studies support the above results, although high losses of soil organic matter are not reported. Two major conclusions concerning the post-fire effects in the taiga forests in the Far East, Siberia, and the European north are as follows:

- There are no essential changes in the amount of organic matter in the mineral horizons after most on-ground fires. The post-fire rehabilitation of litter and soil organic matter is estimated to take two to seven years (Saposhnikov and Kostenkova, 1984; Orphanitskaja and Orphanitskiy, 1959; Firsova, 1960; Popova, 1978; Saposhnikov *et al.*, 1993);
- Fertilization and heat melioration effects of forest fire are common for the taiga and especially for all kinds of permafrost areas.

The available data on post-fire soil erosion are contradictory. Identification of such processes has been done for different mountain areas but the level of erosion as a rule has been limited and has taken place only for a short period (Furjaev and Kireev, 1979; Sheshukov *et al.*, 1992). A different result is observed in areas affected by frequent repeated fires, especially in mountain regions where this phenomenon often leads to the full destruction of the soil cover (Sheingauz, 1989a).

Based on the above reports, in our calculations we estimated the direct post-fire losses of soil humus to be 5% of the average content in the one-meter top layer.

The rate of decomposition of organic matter ($D\dot{I}W + DPFD$) for different phytomass pools depends on many factors (for example, climatic zone, species composition, humidity, etc.) and the variation is great (Academy of Sciences, 1983; Vedrova *et al.*, 1989; Smoljaninov, 1969; Kobak, 1988; Bazilevich, 1993b). Commercial wood from larch in the forest-tundra on permafrost is estimated to have a decomposition time of 200 to 300 years (Ivshin, 1993). Glasov (1989) estimated the average decomposition time for spruce stemwood in the southern taiga to be 25 to 30 years. Storoshenko (1990) showed a complete decomposition cycle for uneven-aged spruce stands of up to 70 years. Similar stands under anthropogenic pressure showed a decomposition period of 25 to 30 years. For aspen and white birches in the southern Far East, the corresponding time is 30 years. Even within a climatic zone the variation may be very large. Bogatiriev and Fless (1983) showed that for the northern taiga in the Komi Republic the period for litter decomposition was 100 to 300 years for wetlands and 2 to 10 years in productive stands. Taking into account the uncertainties of initial data and the limited knowledge of the rate of the decomposition of the woody pools, we used average zonal data for the organic matter decomposition shown in *Table 6*. In *Table 6*, $\alpha$ is a coefficient from equation (5), and *T0.5* and *T0.95* represent the average time (in years) required for decomposition of 50 and 95% of the organic matters, respectively. The values within parentheses identify the range in years.

**Table 6.** Rate for the organic matter decomposition by phytomass pools.

| | 1. Litter (fast) pool | | | | | |
|---|---|---|---|---|---|---|
| Zone | α | *T0.5* | *T0.95* | | | |
| SA&T | 0.038 | 18.4 | 78.8 (50–110) | | | |
| FT&SpT&MdF | 0.072 | 9.3 | 41.6 (25–60) | | | |
| NT | 0.16 | 4.3 | 18.7 (15–35) | | | |
| MT | 0.32 | 2.2 | 9.4 (5–20) | | | |
| ST | 0.75 | 0.92 | 4.0 (2–8) | | | |
| MxF&DF&FS | 1.2 | 0.58 | 2.5 (1–5) | | | |
| S&SD&D | 4.0 | 0.18 | 0.75(0.2–1.5) | | | |
| | 2. Medium-fast pool | | | 3. Slow pool | | |
| | α | *T0.5* | *T0.95* | α | *T0.5* | *T0.95* |
| SA&T | 0.03 | 23.1 | 99.9 | – | – | – |
| FT&SpT&MdF | 0.043 | 16.1 | 69.7 | 0.017 | 40.8 | 176 |
| NT | 0.075 | 9.2 | 39.9 | 0.027 | 25.7 | 111 |
| MT | 0.097 | 7.1 | 30.9 | 0.03 | 23.1 | 100 |
| ST | 0.16 | 4.3 | 18.7 | 0.047 | 14.7 | 64 |
| MxF&DF&FS | 0.27 | 2.6 | 11.1 | 0.07 | 9.9 | 43 |
| S&SD&D | 0.37 | 1.9 | 8.1 | 0.13 | 5.3 | 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 results of our calculations for the direct and indirect fire fluxes are presented in *Tables 7* and *8*. In order to calculate the post-fire biogenic flux the normalized expression ($O_{norm}$) for retrospective reconstruction of $O_{ij}$ has been employed:

$$O_{norm} = -0.00008075\, t^2 + 0.30124\, t - 278.58 \ ,$$

and

$$O_{ij}(t) = b_{ij}\ O_{norm} \ ,$$

where $b_{ij}$ is a scaling coefficient calculated based on the output of organic matter by zone and pool.

Based on these calculations the total average annual emissions of carbon caused by forest fires in Russia from 1989 to 1992 are estimated to be TCF = 58.1 + 87.2 x 1.05 = 150 million tons of carbon per year. The factor 1.05 is a correction factor for the decomposition period employed.

The trace gas emissions caused by forest fires can be estimated using the approach developed by Cahoon *et al.* (1994). The average mean emission ratios were used: 90.2:6.6:0.6:0.6% for $CO_2$, CO, $CH_4$ and NMHC, respectively, for the flaming stage, and 84.3:12.3:1.3:0.1% for the smoldering stage (Cofer *et al.*, 1990, 1991; Andrea, 1991). Particulate carbon has been estimated to be 2% of the total carbon consumed during each stage of the fire. The ratios used for the share of carbon consumed during the flaming and smoldering stages were 50:50% (Cahoon *et al.*, 1994 and 1995) for crown and on-ground fires, 20:80% for peat fires, and 0:100% for underground fires. Under such assumptions the annual atmospheric loading of the direct fire emissions is 184 Tg $CO_2$, 14 Tg CO, about 1 Tg of $CH_4$, and 0.3 Tg NMHC; particulate carbon is 1.2 Tg. Assuming that almost all carbon uptake to the atmosphere will eventually be converted into $CO_2$, we can conclude that forest fires totally produce about 500 Tg $CO_2$.

**Table 7.** The yearly average forest fire carbon emissions caused by fires during the period 1989 to 1992. Expressed in million tons of carbon per year.

| Subject/type of fire | Area (mln. ha) | Emissions (mln. tons C/year) |
|---|---|---|
| Forested areas | 1.35 | 19.3 |
| Crown fires | 0.25 | 5.6 |
| On-ground fires | 1.10 | 13.7 |
| Unforested areas | 0.45 | 4.5 |
| Non-forest lands | 1.35 | 8.4 |
| Peat fires | 0.35 | 22.4 |
| Below-ground fires | 0.012 | 3.5 |
| Total | 3.512 | 58.1 |

**Table 8.** Average post-fire biogenic emission resulting from fires of previous years (1810–1989).

| Vegetational zone | Average input organic matter for decomposition in 1990 by pool | | | Average total post-fire emissions in 1990 by pool | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | Total |
| SA&T | 2.2 | 0.1 | – | 3.2 | 0.2 | – | 3.4 |
| FT&SpT&MdF | 3.1 | 0.4 | 2.4 | 4.2 | 0.6 | 4.1 | 8.9 |
| NT | 4.4 | 1.3 | 7.4 | 5.9 | 1.8 | 11.6 | 19.3 |
| MT | 6.3 | 2.2 | 10.0 | 9.8 | 2.9 | 15.7 | 28.4 |
| ST | 4.4 | 1.0 | 6.2 | 10.0 | 1.4 | 8.8 | 20.2 |
| MxF&DF&FS | 0.8 | 0.4 | 2.3 | 3.0 | 0.6 | 3.0 | 6.6 |
| S&SD&D | 0.4 | – | – | 0.4 | – | – | 0.4 |
| Total | 21.6 | 5.4 | 28.3 | 36.5 | 7.5 | 43.2 | 87.2 |

See *Table 1* for vegetational zone abbreviations. Decomposition pools: 1 = litter (fast) pool; 2 = medium-fast pool; 3 = slow pool.

## 4. Biotic Factors

Several factors restrict the possibilities of producing accurate estimates of carbon flows caused by biogenic disturbances:

- The lack of a developed monitoring system and the consequent incompleteness and low accuracy of data;
- The lack of measurements of some important indicators (e.g., mortality in areas attacked by insects, numerical data on post-disturbance dynamics, etc.);
- The highly dynamic character of the biogenic processes (e.g., the area reported attacked by insects by the beginning of 1992 was nearly 2.9 million ha, and by the end of 1992 it was some 1.2 million ha);
- The lack of measured historical records to reconstruct time series;
- The complexity of the estimation of each biogenic factor's impact due to the interaction and dependence on external (non-biogenic) factors.

According to official statistics, the total area of outbreaks of insects and forest diseases in the Russian Forest Fund area under state forest management during the period from 1973 to 1988 ranged between 1.5 and 3.8 million ha annually, with an average of 2.73 million ha (Isaev, 1991a). Data for 1990 to 1992 are presented in *Table 9* (Federal Service of Forest Management, 1992, 1993, 1994).

In 1989, 90% of the total area of insect outbreaks was occupied by leaf- and needle-gnawing insects, leaf miners, xylophagous insects, and fungus diseases. The degree of damage caused by

**Table 9.** Area of outbreaks of insects and diseases (thousand ha).

| Year | IT | ILG | ING | IOI | FD | TOT |
|---|---|---|---|---|---|---|
| 1990 | 1628 | 1086 | 302 | 240 | 520 | 2148 |
| 1991 | 2869 | 1833 | 868 | 168 | 162 | 3031 |
| 1992 | 1234 | 716 | 334 | 183 | 206 | 1440 |

Abbreviations: IT = total area of outbreaks of insects by end of year; ILG, ING, IOI = leaf-gnawing, needle-gnawing, and other insects, respectively; FD = area of forest diseases; TOT = total area attacked by insects and diseases.

the outbreaks varies considerably. The area of forests reported to be totally destroyed by insects varies from 3,000 to 25,000 ha annually during the period from 1985 to 1990 (for comparison, the total area reported for forests killed by biogenic factors varied during this period from 15,000 to 43,000 ha).

Official data seem to underestimate the real conditions. Isaev (1980) and Kiseljov (1994) estimate that the current total damage caused by insects and disease is of the same magnitude as that caused by forest fires. In 1954, Flerov reported (Petrenko and Kondakov, 1980) that before the Second World War the areas of insect outbreaks were 11 to 85 times larger than the forested areas damaged by forest fires. Unfortunately, reliable up-to-date statistics on biogenic disturbances for all the Russian forested areas do not exist. Relatively accurate data from special surveys are available for the most dangerous insects in managed forests, and the data on the damage are impressive. In just the southern taiga of Tomsk Oblast and Krasnoyarskiy Krai, seven outbreaks of Siberian bombyx (*Dendrolimus sibiricus*) occurred during the period from 1878 to 1970, and the areas of dark coniferous forests that perished totaled more than 8 million ha (Petrenko and Kondakov, 1980). Roshkov (cited by Katajev, 1980) estimates the area of forest killed in Siberia by *Dendrolimus sibiricus* during the first half of the twentieth century to be 13 million ha. In such stands, so-called *shelkoprjadniki*, much dry wood is accumulated; as a rule outbreaks of xylophagous insects are followed by forest fires, making direct estimates of the damage caused by the insects difficult. Outbreaks of xylophagous insects are common phenomena occurring in wind-broken stands and caused by windfalls.

Kondakov *et al.* (1990) reported that during the period from 1980 to 1990 about 40 million m$^3$ of stemwood was lost in the Siberian forests, with the following distribution of causes: forest fire, 17 million m$^3$; *Dendrolimus sibiricus*, 15 million m$^3$; *Monochamus urussovi* (black coniferous sawyer), some 2 million m$^3$.

Significant areas of cedar and larch forest stands completely dried up in the Far East due to the intensive propagation of the *Dendrolimus sibiricus*. The area amounted to about 60,000 ha of larch forests and more than 100,000 ha of cedar forests within the recent years in the territories of Khabarovskiy Krai and Amurskaya Oblast (data are incomplete). Outbreaks of other damaging insects are periodically occurring over large areas (2 to 3 million ha) with decreased increment and partial mortality as a result (Sheingauz, 1989a).

Dryness of spruce and fir forest stands, repeated periodically in Khabarovsk and Primorsk regions and caused by complicated combinations of biotic and abiotic factors, has been detected in hundreds of thousands of hectares (Ageenko, 1969; Sheingauz, 1989a). Large waves of such dryness were reported in the second half of the 1960s. Based on a special survey of the Far Eastern spruce-fir forests, the areas of drying stands were estimated to be 5.5 million ha in Primorskiy and Khabarovskiy Krais (44% of the total area of the spruce-fir forests), with a storage of dead wood of 366.2 million m$^3$ (24% of the total living and dead growing stock). This corresponds to 66 m$^3$ of dead wood per hectare (39 m$^3$ of standing dead trees and 27 m$^3$ of wind-fallen trees; Ageenko, 1969). The latest large dieback of spruce and fir forests was observed during the period from 1989 to 1993. The extent of the damage is only partially known, but the surveys indicate damaged areas of about 100,000 ha of which 60,000 ha are dead stands in the middle of the Sikhote Alin Mountains (Ribakov, 1993).

A cyclical dryness of oak stands has been repeated about seven or eight times during the last 80 years in the European part of Russia. The reason for the dryness was a general weakening of stands due to an unfavorable combination of weather, different biogenic factors, and pollution. The most harmful dryness of oak stands occurred in the 1970s and 1980s after cold winters. The losses (estimated as a percentage of the trees) were in the northeastern parts of the growing areas for oak: 15% for young stands; middle-aged, 25%; premature, 50%; mature, 74 to 100%. In the central growing areas for oak the percentages were 5, 10, 15, and 25%, respectively (Novoseltsev and Bugaev, 1985).

The forested areas officially reported to be infested with disease amounted to 237,700 ha at the end of 1993. The reported data are mainly related to European Russia. Local surveys indicate that the total area infested to different degrees by different diseases may reach several million ha. In our calculations concerning disease and impacts on the carbon budget, we only consider trunk and root decay.

In mature and overmature coniferous stands of the European north, 1 to 20% of the trees are damaged by *Phellinus pini* and about 8 to 30% by *Fomitopsus annosa* (Chibisov, 1974). Stands of birch and aspen older than 60 to 70 years are damaged up to 50% by rot (Chertovsky *et al.*, 1974). Butt rot is observed in 50 to 80% of the mature trees in larch stands in the southern part of the Yakut Republic (Sherbakov, 1975), in 44% in Buryatia (Zai *et al.*, 1977), in about 70% in the center of the Yakut Republic (Kudelja, 1988), and in 40 to 60% (depending on the forest type) for cedar species of 100 years of age and up to 70 to 90% for stands of up to 200 years of age in the East Sajan Mountains (Tikhomirov *et al.*, 1961). Data for younger stands show a similar rate of infestation. Stem rot caused by *Phellinus pini* affects 60% of the cedar stands in the Irkutsk region (Golutvin and Katajev, 1978), and about 80 to 90% in low mountain cedar stands in the Far East (Ljubarsky and Vasiljeva, 1975). The average rate of stem rot of the growing stock in the Far Eastern forest stands is 58% (Sheingauz, 1989a) and more than 20% in the Urals (Kartavenko, 1955). Butt rot (mainly *Fomitopsis annos* and *Phaeolus schweinitzi*) is observed in 35 to 40% of the stands in the Urals (Kartavenko, 1955), up to 40% in the Irkutsk region (Golutvin and Kataev, 1978), and to 40 to 80% in the Far East (Ljubarsky and Vasiljeva, 1975, Korjakin, 1973).

Impacts of other types of biogenic disturbances are lower but nevertheless significant. Dead dry forests due to game damage were officially reported to be 10,000 ha in 1982, 11,900 ha in 1988, 12,600 ha in 1984, 13,300 ha in 1990, 9,200 ha in 1991, and 9,200 ha in 1992 (this information is only available for intensively managed young forests). In some regions of the European part of Russia (Central, Povolshsky) and in western Siberia, the game damage resulted in dead forests on 10 to 20% of the areas of forests. Partial damage is not specifically registered. A survey of an area of 107,000 ha in the northern part of the Moscow region reported that 9.1% of all stands had been partially damaged by elk (Federal Service of Forest Management, 1992).

The references cited above and other sources only afford us the possibility of assessing the magnitude of the impact of biogenic factors on the carbon budget of the forest ecosystems in Russia. Unfortunately, no accurate data are available for a more precise reconstruction of time series of the biogenic damage. We estimated the damage in the following way:

- The total annual areas affected by insect and disease outbreaks are 4 million ha. The biogenic dieback in these areas is estimated to be 15% (Koltunov *et al.*, 1990; Storoshenko, 1990).

Based on an average growing stock for all Russian forests (1988) of 105.9 $m^3$, the biogenic dieback will have a direct input of organic matter for decomposition of about the same magnitude as from a post-fire death of 500,000 to 600,000 ha of forests, corresponding to emissions of not less than 30 million tons of carbon annually.

- The damage caused by biotic factors that are not classified as insect and disease outbreaks is much more difficult to estimate. The available statistics only make it possible to come up with very rough calculations. The calculations indicate that the emissions caused by other biotic factors are of the magnitude of 30 million tons of carbon annually.
- Different stages of decay make up about 10% of stemwood in mature and overmature stands. The total amount of growing stock in this category in all Russian forests (main forest-forming species) is 47.7 billion $m^3$. If we assume that average "turnover" of current decayed wood is 40 years, the annual decomposition of the wood is 119 million $m^3$, corresponding to emissions of some 30 million tons of carbon.

Such "back of the envelope" calculations give an estimate of the carbon emissions caused by biogenic factors of about 90 million tons of carbon annually. If we take into account some other impacts (e.g., damage caused by recreation, unregulated forest grazing, etc.), our total estimate is in the range of 90 to 110 million tons of carbon. This corresponds to about 60 to 70% of the total carbon flux caused by forest fires in Russian forests. In this estimate the increment losses due to the damage of leaves and needles are not included.

## 5. Negative Abiotic Impacts

The vitality and productivity of the forests in Russia are substantially influenced by some abiotic factors, mostly industrial pollutants. According to current assessments (Isaev, 1991a) nearly 1 million ha of forests have been damaged to some extent due to these factors. A special survey of the forests damaged by pollutants has been provided by the State Committee of Statistics of the former Soviet Union (*Table 10*). This survey, covering about 60% of the Russian forests, estimated the area of dead stands caused by air pollution to be 321,000 ha, and that of strongly disturbed forests to be 465,000 ha. The data presented in *Table 10* are probably underestimates. In 1989, in the area around Norilsk alone (Krasnoyarskiy Krai), there were 2 million ha of dead forest tundra landscapes, of which 565,000 ha were forested areas (Kovalev, 1990). Surveys of these areas in 1992 added about 60,000 ha of dead forests (Federal Service of Forest Management, 1993).

The decline due to the impact of pollutants can only be estimated in a very rough way. The average decrease of the increment in the European part of the FSU induced by atmospheric pollutants was estimated to be 0.3 $m^3$/ha annually (Nilsson *et al.*, 1992). For the Asian part of Russia the increment decline is lower.

Two other important abiotic factors are the so-called industrial mastering of territories (exploitation and development of the infrastructure) and unfavorable weather. Areas of territories destroyed by industrial mastering are significant in the northern areas. We are only able to present some examples of this. The total extent of land disturbed by technogenesis in the Tyumen region of western Siberia during the last 30 years has reached some 24%. The Forest Fund areas discharged for current and future oil and gas exploitation exceeded 100,000 ha annually during the period from 1985 to 1990. In reality, the areas of technogenically affected territories due to underflooding, erosion, and contamination are 10 times greater. During the period from 1973 to 1982, 17.1 million $m^3$ of wood had to be cut in areas transferred from forested areas to industrial land. Of this amount only 4.1 million $m^3$ were removed, the rest was

**Table 10.** Damage caused by air pollution in Russian forests by October 1990 (in thousand hectares).

| Region | Total damage | Partially damaged | Dead forests |
|---|---|---|---|
| Total Russia | 785.5 | 464.7 | 320.8 |
| Murmanskaya Oblast | 93.1 | 83.1 | 10.0 |
| Sverdlovskaya Oblast | 14.2 | 13.3 | 0.9 |
| Chelyabinskaya Oblast | 16.5 | 16.4 | 0.1 |
| Krasnoyarskiy Krai | 565.2 | 263.1 | 302.1 |
| Irkutskaya Oblast | 77.8 | 70.9 | 6.9 |

Source: AUIRCFR, 1990.

left in the forests (Vegerin, 1990). There are about 600,000 ha of land with negatively changed hydrological regime (so-called *podtoplenie*, an increase of the water table with strong impacts on the vegetation). About 40 to 50% of this area is situated on forest lands and about 25 to 30% of this forest land has totally lost its productivity (Isaev, 1991a).

During the last decades unfavorable weather conditions have been reported as being the second most important reason for forest death during the last 20 years. These conditions caused 17 to 44% of all reported areas of dead forests (185,000 ha in 1991; 87,000 ha in 1992). However, only data for the European part of Russia can be considered as being relatively accurate on this matter. For example, in 1992, 75,500 ha of dead stands were reported for the territory of Irkutskaya Oblast. A partial forest pathological survey carried out in the region in May 1993 estimated the dead areas to be 580,000 ha (Federal Service of Forest Management, 1993). Different sources confirm the incompleteness of the statistics on the weather impacts. Windfalls and windbreaks occur in many places in Russia. For example, in 1961 a hurricane destroyed 75,000 ha of spruce-fir forests on Sakhalin Island resulting in a loss of 5.4 million $m^3$ (Klintsov, 1969). In the central region of Russia windfalls of different degrees occurred in 1975, 1978, 1983, 1986, and 1987. In 1987 storms caused windfalls corresponding to 10 to 35% of the growing stock in spruce stands of the Central Forest Natural Reserve (Pugachevsky, 1990). In 1989, in the southern part of Siberia more than 7 million $m^3$ of wood was destroyed by storms (Kondakov *et al.*, 1990). However, statistics for all of Russia on this subject are missing.

Thus, due to the factors discussed above there is no complete and reliable information on which to base a complete assessment of the carbon losses of ecosystems. Based on regional expert assessments of carbon losses due to the impact of different abiotic factors (pollutants, industrial damage of ecosystems, catastrophic natural phenomena, etc.), we have received a rough estimate of the total direct losses in different scenarios ranging between 40 and 65 million tons of carbon annually.

## 6. Discussion

Our results on the impact of forest fires in Russia on the carbon budget (emissions of 150 million tons of carbon annually) are lower than estimates obtained earlier and reported in different publications [Stocks, 1991: some 34 million tons C/year of direct fire emission for the FSU (however, Stocks' estimate does not include peat and underground fires); Dixon and Krankina, 1993: 170–330 million tons C/year as the average for the period from 1971 to 1991 in Russia; Kolchugina and Vinson, 1993b: 199 million tons C/year for the FSU]. During the last 20 to 30 years the fires in Russian forests corresponded to about 98% of the forest fires in the FSU. The average estimate on aboveground organic matter burned during fires in boreal forests is reported to be 1.125 kg C/$m^2$ (Stocks, 1991). This corresponds with the results achieved for Russia (1.022

kg C/m$^2$ excluding peat and underground fires). If the peat and underground fires are included, we get a value of 1.66 kg C/m$^2$.

Our carbon loss estimates of 130 to 165 million tons annually due to different biotic and abiotic factors in addition to the fire losses are uncertain and we have not been able to validate our results against similar studies elsewhere in the boreal forest belt. However, an important conclusion seems to be that the carbon emissions caused by biotic and abiotic factors (other than forest fires) are not less, and are probably higher, than the total emissions caused by forest fires.

The uncertainties in the estimates of the impacts of the possible increase of the carbon sink in Russia due to improvements in the sanitary state and the protection of the Russian forests are much greater. There are at least two major groups of uncertainties. The first deals with predictions of the socioeconomic development in Russia. The second deals with the lack of knowledge of the direct and indirect regional impacts of global climate changes on the boreal forests. Under such conditions any definite quantitative estimates of possible increased carbon sequestration in the future are difficult. But if the protection measures achieved in Canada and the Nordic countries are used as guidelines, it would be within the reach in the long run to reduce the emissions by fires by some two-thirds and the biotic emissions by one-third. These measures would increase the carbon sequestration by the Russian forests by some 150 to 170 million tons C per year.

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The following abbreviations are used in the references: AIFFCh – Arkhangelsk Institute of Forestry and Forest Chemistry; DalNIILKH – Far Eastern Forestry Institute (*Khabarovsk*); IFW – Institute of Forest and Wood (*Krasnoyarsk*); SDAS of the USSR–Siberian Division of the Academy of Sciences of the USSR; Nauka – Publishing House of the Academy of Sciences of the USSR.

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