The 5th International Wildland Fire Conference
Sun City, South Africa
9–13 May 2011

Carbon Emissions from Forest Fires in Boreal Eurasia between 1998-2010

Anatoly Shvidenko
International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria;
Institute of Forest, Siberian Branch, Russian Academy of Sciences, Academgorodok, 660036 Krasnoyarsk, shvidenk@iiasa.ac.at
Dmitry Schepaschenko
International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria;
Moscow State Forest University, Mytischi-5, Moscow region, Russia, schepd@iiasa.ac.at
Anatoly Sukhinin
Institute of Forest, Siberian Branch, Russian Academy of Sciences, Academgorodok, 660036 Krasnoyarsk, boss@ksc.krasn.ru
Ian McCallum
International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria, mccallum@iiasa.ac.at
Shamil Maksyutov
National Institute for Environmental Studies, Tsukuba, Japan, shamil@nies.go.jp

---

Abstract

We present results of a quantitative analysis of fire regimes and a verified assessment of fire carbon emissions in Northern Eurasia's ecosystems (limited to territories of Russia) for 1998-2010. Burnt areas were defined based on a consistent methodology (AVHRR data were modified to eliminate biases) over the period. A hybrid land cover (resolution 1 km^2) was used for identification of forest classes and spatial quantification of fuel by components. Consumption of fuel was assessed by land classes based on multiyear empirical data on distribution of fire type, time of burning, and bioclimatic zone. The average annual burnt area on forest land was estimated at 5.35×10^6 ha (65% of the area of all vegetation fires) with seasonal variation from 3.16×10^6 ha (1999) to 13.17×10^6 ha (2003). Average annual amount of consumed carbon by all vegetation fire is 121.0 Tg yr^{-1}, including an estimated 92.0 Tg yr^{-1} on forest land (76.0% of the total emissions), ranging from 35.8 Tg yr^{-1} (2004) to 201.5 Tg yr^{-1} (2003). Specific density of consumed carbon in forest fires (average 18.73 Mg C yr^{-1} ha^{-1}) depends mostly on severity of seasonal fire regimes and regional distribution of burnt areas.

Keywords: Russian boreal forest, wild fire, carbon emissions

1. Introduction

Fire is a major natural disturbance in Russian natural ecosystems, in particular, in forests, due to: (1) vast extent of natural ecosystems in Russia – forest, wetlands, grasses and shrubs; these comprise almost 90% of all vegetative areas; (2) about 95 percent of Russian forests are boreal forests, and 71% of them are dominated by coniferous stands of high fire hazard; (3) a significant part of the forested territory is practically unmanaged and unprotected, and large fires (>200 ha) play an important role in this region; (4) due to slow decomposition of plant residuals, natural ecosystems contain large amounts of accumulated organic matter; and (5) a major part of natural ecosystems are situated in regions with limited amounts of precipitation and/or frequent occurrences of long drought periods during the fire season that often initiate fires of high severity.

Relatively complete and reliable data on extent of vegetation fires in Russia exist since 1997 when remote sensing estimates became available. Official statistics have been limited by fires on protective forest land and were incomplete and unreliable (Shvidenko, Goldammer, 2001). A specific feature of fires in Northern Eurasian (NE) territories is the dominance of on-ground fire. Numerical data on previous forest fire regimes in Russia could be found in Shvidenko and Nilsson (2000a,b).

Specifics of weather in Russian territories during recent decades increased fire danger substantially. The trend of increasing annual temperature during recent decades over Russia was substantially higher than the global trend: 0.51 and 0.17 °C per decade over 1976-2008, respectively. This trend remains rather stable during recent years: 2007 was the warmest year for Russia (the temperature anomaly to the average for 1961-1990 was +2.06°C), the second – 1995 (+2.04 °C) and the third 2008 (+1.88 °C) (Roshydromet, 2011). Annual average precipitation over the country is also increasing (+7.22 mm per decade over 1976-2006 comparatively to the reference period of 1961-1990). However, the observed precipitation trends for the south of European Russia and continental Asian Russia were close to zero, and climate aridity (measured, for instance by Palmers Drought Severity Index) substantially increases, continuing the tendencies of the previous 50 years (Lapenis et al. 2005). Instability of weather is increasing during recent decades. Periods with heavy rain alternate with prolonged warm and dry periods, sometimes with anomalous heat waves, as in the Summer of 2010 in European Russia.

Such climate specifics pose a threat to large vegetation, primarily in the form of forest fires of high intensity, so called catastrophic fires. This term has been initially introduced in the USA as a fire whose liquidation would require capacity and resources of at least an entire USA state. There are several definitions of such fires in Russia (Sapozhnikov 1984; Efremov and Shvidenko 2004; Sukhinin 2008). Sukhinin (2008) defines catastrophic fire as that which envelops a substantial part of a landscape (>20 000 ha) under conditions of a long-period anticyclone and the highest, 5th class of drought, resulting in post-fire dieback greater than 50% of growing stock. Average intensity of burning at the fire edge exceeds 2 MW/m, speed of contour's increase more than 40km/24 hours, time of combustion of fuel at fire edge more than 4 minutes. There is no economic sense in extinguishing of such fires due to the need of huge labor and financial resources, thus fire protection activity is limited to protection of settlements and elements of infrastructure. Catastrophic fire could lead to a catastrophic situation when several catastrophic fires are distributed over a total area of 400,000 ha and the part of this area directly enveloped by fire exceeds 10%. Under a catastrophic situation, growth of the total perimeter of burning areas exceeds the rates of fire localization. Meteorological distance of vision becomes less than 200 m that prevents the use of aviation for forest fire protection.

Catastrophic fires result in substantial ecosystem degradation and impoverishment of biodiversity, create a specific condition in the atmosphere affecting seasonal weather over huge territories, provide large economic and infrastructure damage, substantially impact living conditions of the local population and the general health of people. For Russia, this situation is aggravated by substantial decline of forest governance in the country, degradation of civil self-consciousness and destruction of professional nature-protected systems (particularly, by practical elimination of the state forest guard).

During the last twenty years, catastrophic fire situations have occurred in different regions of Russia, generally in the Asian part, with a frequency of about 10 years.

Ecological consequences of catastrophic fires are substantial. By estimates, catastrophic forest fires during the last two decades increased the total area deprived of forest in the Far Eastern region by 8 million ha. About one-third of area enveloped by catastrophic fires is transformed into not-productive territories where natural reforestation did not occur during 2-3 life cycles of major forest-forming species (e.g. 300-600 years) (Efremov, Shvidenko 2004). Such areas are basically represented by bogs (up to 70%), small shrubs and grasses (15%), open woodlands (10%), and stone fields and outcrops (5%).

2. Data and methods

In order to estimate biometric characteristics and vegetation fuel of ecosystems, an Integrated Land Information System (ILIS) of Russia has been used. The ILIS has been developed by the International Institute for Applied Systems Analysis (Schepaschenko et al. 2011) as a multi-layer Geographic Information System that includes a hybrid land cover of Russia at a resolution of 1 x 1 km and corresponding attributive databases (Figure 1). This system was developed based on a multi-sensor remote sensing concept (12 RS products from 8 satellites were used), measurements in situ, results of different inventories and surveys (including forest state account, state land account, ecological monitoring) and other relevant information.

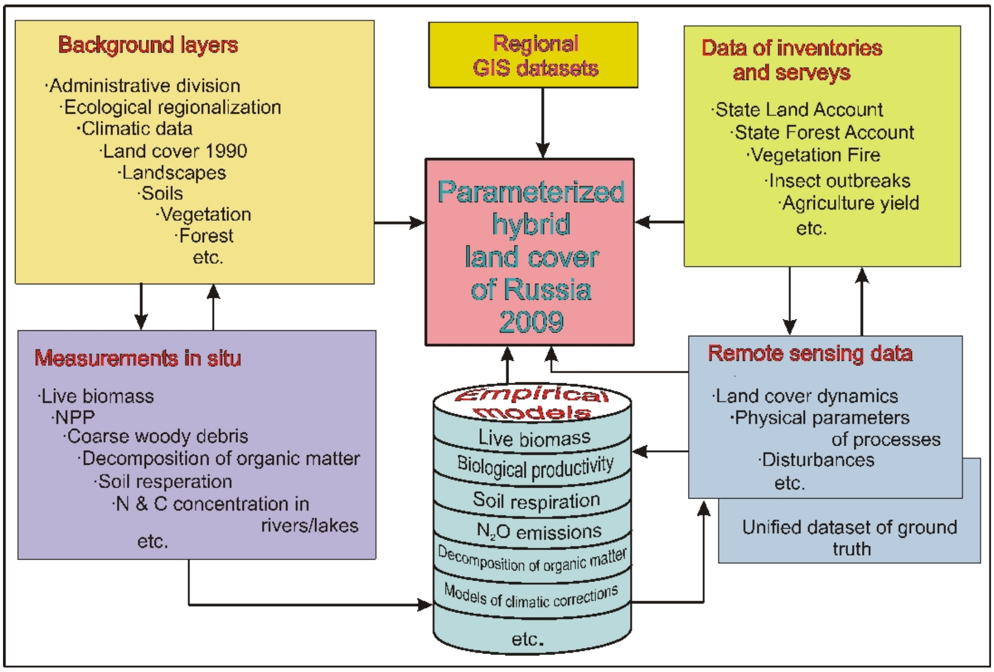

Figure 1—Integrated Land Information System for Russia

The hierarchical classification of land cover classes was based on types of ecosystems and included at the top level forests, agricultural lands, wetlands, natural shrubs and grasses, and unproductive areas. Land cover classes were classified based on vegetation types. For instance, areas of peatland covered by forests were accounted as forests; treeless bogs were identified as wetlands etc. Parametrization of land cover was based on a principle of consequent use of the most accurate and updated sources from available sets of information. In cases when the resolution of satellite products were not enough for direct by-pixel parametrization (e.g., identification of dominant species, age, or live biomass in forests), an algorithm of multidimensional optimization was used. This algorithm provided maximal probability of spatial distribution of elements and parameters of land cover for spatial units of 15 x 15'. Within the terrestrial ecosystems classification, the number of primary land classes over the country which have been parametrized varied from several hundreds (e.g., for natural grass- and shrubland) up to ~80,000 for forests. More detailed description of the structure of ILIS and the algorithm of optimization could be found in [Schepaschenko et al. 2010].

The ILIS includes a comprehensive description of type, amount and structure of potential fuel (live biomass of trees by components; undergrowth and understory; green forest floor; snags and logs; on-ground soil organic matter; and organic matter of the top 1m layer of mineral soils) by 1 km^2 pixel. Aggregated data by bioclimatic zones are presented in Table 1, examples of spatial distribution of live biomass and soil organic carbon are presented in Figures 2 and 3.

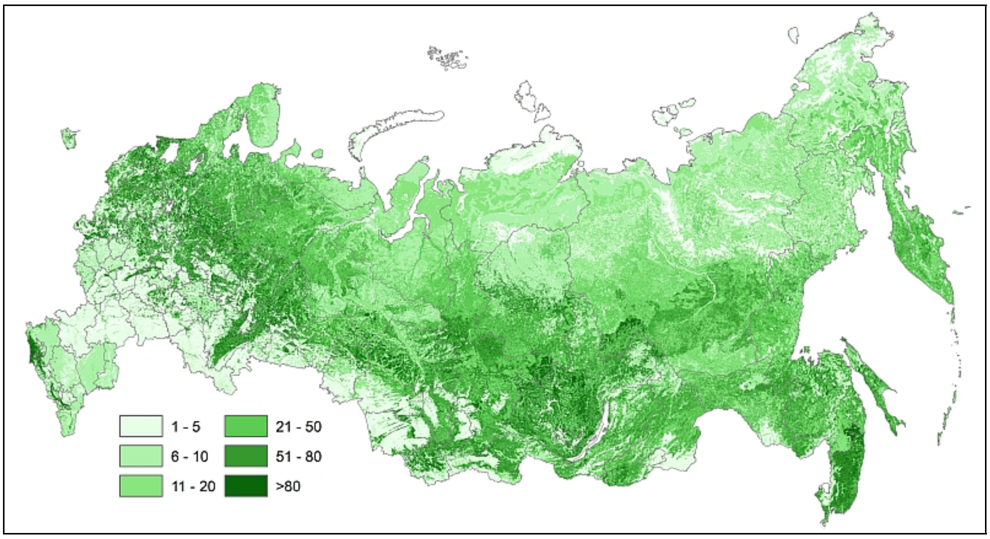

Figure 2 — Live biomass of Russian ecosystems, Mg C ha^{-1}

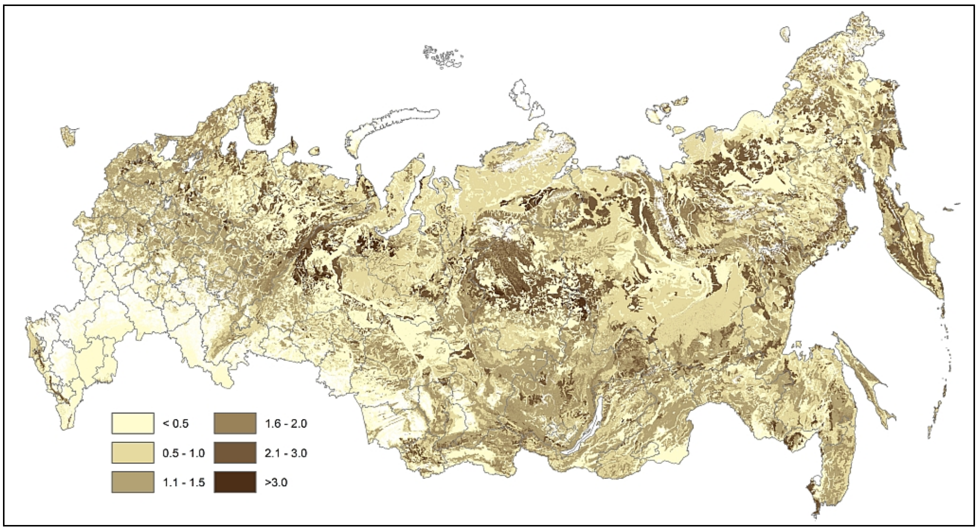

Figure 3 — On-ground soil organic layer for Russian vegetative land, kg C m^{-2}

Table 1. *Distribution of some pools of organic carbon in vegetation ecosystems of Russia by bioclimatic zone and aggregated land classes, Tg C*

Zone	Organic matter by land classes, Tg C						
	Forest	Open woodland	Burnt area	Agricultural land	Wetland	Grassland & shrubland	Total
	Live biomass						
Arctic	0.0	0.0	0.0	0.0	0.0	0.8	0.8
Tundra	681.6	94.4	3.1	4.7	439.7	1,145.8	2,369.3
PT & NT	4,241.8	218.9	5.7	1.6	268.5	309.2	5,045.7
MT	21,046.7	332.0	65.6	47.0	389.0	1,341.6	23,221.9
ST	8,718.6	103.6	3.0	150.8	196.2	52.3	9,224.7
TF	1,864.5	20.5	0.5	120.1	14.6	59.6	2,079.8
Steppe	848.9	10.6	0.7	473.4	40.9	81.3	1,455.7
SD & D	48.3	0.6	0.1	91.0	10.1	19.5	169.6
Total	37,450.4	780.6	78.6	888.5	1,359.1	3,010.2	43,567.4
	Above ground coarse woody debris						
Arctic							
Tundra	129.2	16.1	17.9		6.7	88.9	258.7
PT & NT	807.6	34.1	47.4		33.0	36.4	958.4
MT	4,221.2	57.9	633.8		56.1	452.3	5,421.3
ST	1,462.9	15.6	18.4		28.8	9.8	1,535.4
TF	275.9	2.5	2.5		1.7	8.5	291.0
Steppe	104.8	1.1	3.9		3.9	5.8	119.5
SD & D	18.6	0.2	0.5		0.8	1.6	21.7
Total	7,020.1	127.4	724.4		131.0	603.2	8,606.1
	On-ground soil layer						
Arctic						2.8	2.9
Tundra	236.0	121.1	16.6	6.4	252.7	1,829.6	2,462.3
PT & NT	1,617.1	332.4	24.0	1.5	299.5	359.6	2,634.2
MT	5,309.5	482.2	124.7	75.0	292.4	1,321.3	7,605.2
ST	1,685.4	75.8	3.7	161.6	97.4	70.0	2,093.9
TF	321.5	8.9	0.5	57.4	9.3	38.1	435.8
Steppe	119.2	3.3	0.5	113.1	23.0	48.4	307.6
SD & D	4.3	0.1	0.0	20.4	3.8	10.1	38.7
Total	9,293.1	1,024.1	170.0	435.4	978.0	3,679.9	15,580. 6

Burnt areas for 1998-2010 were estimated for each month of fire season based on 2nd, 3rd, 4th and 5th bands of AVHRR NOAA using the algorithm described in [Sukhinin et al. 2004; Soya et al. 2004]. It has been ascertained that AVHRR data substantially overestimated burnt area in Russian territories, particularly for relatively small fires (less that 10,000 – 15,000 ha), the results of measurements were corrected using the regressions developed for taiga forests by the V.N. Sukachev Institute of the Forest, Siberian Branch, Russian Academy of Sciences (Krasnoyarsk). Distribution by types of fire (crown fires; superficial on-ground; steady on-ground; and peat fire), as well as share of combusted fuel (totally 12 types of fuel were used) monthly estimates were based on many year averaged data within bioclimatic zones and land cover classes. Examples for pine forests are presented in Tables 2 and 3.

Table 2. *Average probability (x100) of crown fire in Pine forests (S11)*

Zone	Month								
	March	April	May	June	July	August	September	October	November
Tundra	0	0	0	0	0	0	0	0	0
FT, ST, NT	0	0	0	4	7	8	6	1	0
Middle Taiga	0	0	3	11	16	17	13	5	0
Southern Taiga	0	1	8	15	21	20	16	9	1
Temperate For	0	2	6	11	12	12	10	4	2
Steppe, SD, D	1	3	6	9	10	10	7	3	2

Table 3. *Average probability (x100) of on-ground superficial fire in Pine forests (S12)*

Zone	Month								
	March	April	May	June	July	August	September	October	November
Tundra	100	100	95	75	51	28	11	0	100
FT, ST, NT	100	100	83	65	47	30	16	6	100
Middle T	100	100	68	42	22	8	8	9	100
Southern T	100	92	53	25	14	9	9	11	95
Temp For	97	90	50	26	15	12	14	16	95
Steppe, SD, D	88	81	55	34	25	16	23	34	95

Notes: (1) Abbreviation in Tables 2 and 3: FT, ST, NT are forest tundra, sparse taiga and northern taiga respectively; SD and D – seni-desert and desert. (2) Probability of on-ground steady fire is calculated as S13 = 100- S11 –S12

Intensity of burning (= percent of combusted fuel) was assessed by regression models which account for period and length of burning, as well as by the ratio of burnt area during individual months to the long period average within administrative regions of Russia. Empirically based corrections have also been done for ecosystems on peat soils. Practical application of fire intensity measured by satellites (e.g., Wooster and Zhang 2004) requires substantial on-ground research due to wide distribution of on-ground fire. Consumed carbon was calculated for each pixel by a modified equation, initially suggested by Seiler and Crutzen (1980), as a product of probability of fire type, amount of fuel by components, percent of consumed fuel and content of carbon by fuel type.

Gaseous and particulate species composition of products of burning was estimated based on emission factors represented in a database by Andrea (Andrea, 2010, personal communication).

3. Results and discussion

The total area of vegetation fire over the Russian territory between 1998-2010 is estimated as 106.9 x 10^6 ha, or on average 8.23 x 10^6 ha year^{-1}, varying from 4.2 (1999) to 17.3 x 10^6 ha year^{-1} (2003) (Tables 4 and 5, Figure 4). There is no statistically significant trend of burnt area during this period. As a rule, more than 90% of burnt areas are situated in Asian Russia, mostly in its southern part. An exception is the year of 2010 when unprecedented temperature anomalies and drought initiated a catastrophic fire situation in central regions of the European part of Russia. More than half of burned areas (59.3%) are in forests, and together with open woodlands and destroyed forests (old burns, forests damaged by insects etc.) – about two thirds (65.1%). A substantial part of low intensive fires is observed on agricultural lands, basically as a result of prescribing burning of different types (18.9% of the total area). The areas of fire in natural grass and shrub ecosystems were estimated at 8.7%, and on wetlands – 7.3% of the total area affected by fire.

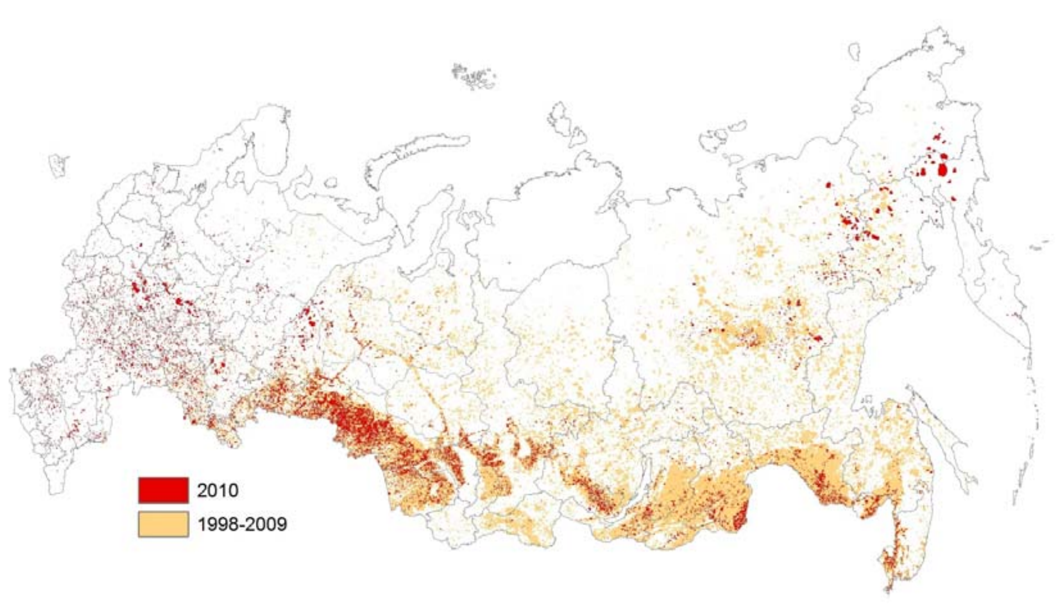

Figure 4 — Burnt areas over Russian territories between1998-2010

Table 4. *Total vegetation fire related carbon emissions 1998-2010 by species*

Vegetation	Area, 10^3 ha	Emission, 10^3 t C	including the main emission species, 10^3 t C							
			CO_2	CO	CH_4	NMHC	OC	BC	$PM_{2.5}$	TPM
Forest	63,518	1,066,469	894,657	89,956	10,873	7,784	10,854	1,067	11,416	16,700
Arable	5,226	7,881	6,816	609	88	76	39	8	64	103
Hayfield	4,166	10,115	8,732	791	117	98	51	10	82	133
Pasture	6,479	12,131	10,530	914	132	112	61	12	95	156
Fallow	937	1,769	1,545	128	18	16	9	2	13	22
Abandoned arable	3,398	7,332	6,391	536	74	66	37	7	56	93
Wetland	7,823	239,520	207,611	17,800	3,259	1,404	1,420	240	1,643	2,601
Open woodland	3,388	81,174	66,923	7,714	1,050	554	797	81	955	1,361
Disturbed forest	2,638	47,941	40,411	3,840	440	366	509	48	507	747
Grassland	9,363	98,354	86,646	6,341	1,078	543	567	98	642	1,035
Total	**106,935**	**1,572,686**	**1,330,260**	**128,628**	**17,129**	**11,017**	**14,344**	**1,573**	**15,472**	**22,949**

Table 5. *Average fire related carbon emissions 1998-2010 by species*

Vegetation	Area, 10^3 ha	Emission, 10^3 t C	including the main emission species, 10^3 t C							
			CO_2	CO	CH_4	NMHC	OC	BC	$PM_{2.5}$	TPM
Forest	4,886.0	82,036.0	68,819.8	6,919.7	836.3	598.8	834.9	82.0	878.1	1,284.6
Arable	402.0	606.3	524.3	46.8	6.8	5.8	3.0	0.6	4.9	7.9
Hayfield	320.4	778.1	671.7	60.8	9.0	7.5	3.9	0.8	6.3	10.2
Pasture	498.4	933.2	810.0	70.3	10.1	8.6	4.7	0.9	7.3	12.0
Fallow	72.1	136.1	118.8	9.8	1.3	1.2	0.7	0.1	1.0	1.7
Abandoned arable	261.4	564.0	491.6	41.2	5.7	5.1	2.8	0.6	4.3	7.2
Wetland	601.7	18,424.6	15,970.1	1,369.3	250.7	108.0	109.3	18.4	126.4	200.1
Open woodland	260.6	6,244.2	5,148.0	593.4	80.8	42.6	61.3	6.2	73.4	104.7
Disturbed forest	202.9	3,687.8	3,108.5	295.3	33.9	28.1	39.2	3.7	39.0	57.4
Grassland	720.2	7,565.7	6,665.0	487.8	82.9	41.8	43.6	7.6	49.3	79.6
Total	**8,225.7**	**120,975.8**	**102,327.7**	**9,894.5**	**1,317.6**	**847.5**	**1,103.3**	**121.0**	**1,190.1**	**1,765.3**

Two types of seasonal distribution of burnt areas are clearly revealed – spring and (late) summer (Figure 5). The first one has a peak in spring, some time after thawing of the snow cover and before greening. The second type has a more even distribution of burnt area as a consequence of drought-affected spring and summer and is typical for years with catastrophic fire. Specific features of such a fire season (e.g., seasons of 1998, 2003, 2008 and 2010 in different regions of the country) are: substantial increase of the share of crown and steady ground fires; distribution of fire in usually unburned wetlands; and elevated level of emissions of greenhouse gases, particularly methane and carbon oxide due to deep soil burning.

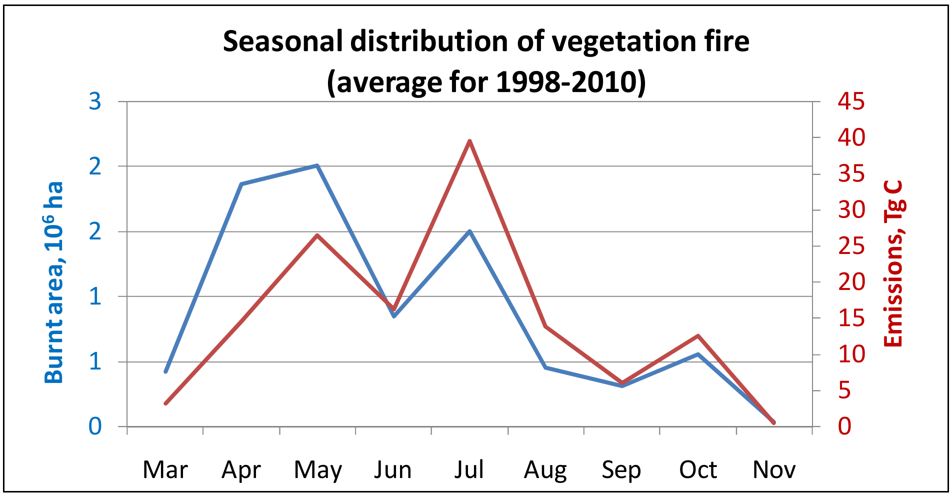

Figure 5 — Seasonal distribution of vegetative fires in Russia between 1998-2000

Amount of organic matter consumed by vegetation fires between 1998-2010 is estimated at 1.57 x 10^9 t of carbon, or on average at 121.0 x 10^6 t C year^{-1}. Direct carbon fire emissions are estimated at 2.4% of Net Primary Production that is very close to the average global estimate (2.5%, van der Werf et al. 2006). The interannual variability of carbon emissions is high – from 50 x 10^6 t C year^{-1} (2000) to 231 x 10^6 t C year^{-1} (2003). Type of fire season and geographical location of fire impact specific density of the emissions substantially. Under average specific density of carbon consumption on all classes of land cover at 1.47 kg C m^{-2} year^{-1} during 1998-2010, the maximal value was observed for 2010 (2.12 kg C m^{-2} year^{-1}), when the area enveloped by fire for the season was slightly less than the average for the period. Forest lands deliver a major part of carbon emissions – 76.0% of the total. Wetlands are a second source (15.8%). The average specific density of emissions here is the highest (3.06 kg C m^{-2} year^{-1}), but emissions of steady peat fire for individual fire events could be higher by several orders of magnitude.

The average composition of major products of burning for the estimated period was: C-CO_2 84.6%, C-CO – 8.2%, C-CH_4 – 1.1%, C-NMHC (non-methane hydrocarbons) - 1.2%, organic carbon 1.2% and black carbon – 0.1%. Particulate matter accounts for 1.5% including 1.0% of $PM_{2.5}$. The highest content of CH_4 and CO is observed in ecosystems with peat. In spite of the low content of black carbon in annual emissions, it is accumulated along millenniums in soils of high latitudes and could reach 0.6-3.0% of organic carbon in tundra soils of central Siberia (Guggenberger et al. 2008).

Uncertainty of estimates of the annual amount of consumed carbon depends upon reliability of major inputs to the calculation scheme: (1) burnt areas, including their seasonal distribution; and (2) amount and consumption of fuel. The latter substantially depends on reliability of empirical regional models that define probability of fire type and severity of fire. Using the methodology that is oriented to specifics of such *full complexity* or *fuzzy* tasks (Shvidenko et al. 2010), we assessed the most probable uncertainty of the area at 9% and total carbon emissions at 22% (CI 0.9).

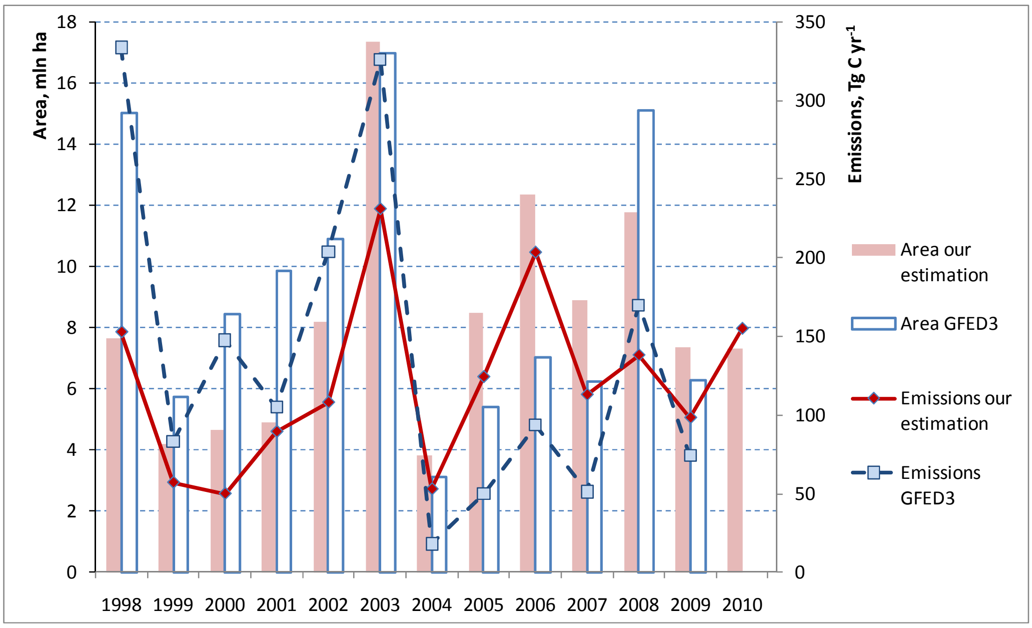

Figure 6 — Carbon emissions of vegetation fire in Russia between 1998-2010 and comparison with data of GFED3

An independent assessment of carbon emissions that were caused by vegetation fires in Russia has been recently presented in the Global Fire Emissions Database – GFDB3 (van der Werf et al., 2006, 2010). The assessment of areas was done based on different satellites, which were available during 1997-2009 (mostly TERRA/MODIS). The approach used to calculate burned areas for 1997-2000 was described in Van der Werf et al. (2006) and for 2001-2004 - in Giglio et al. (2006). The calculation of the emission has been done using the satellite-driven Carnegie Ames Stanford Approach (CASA) model (Van der Werf et al. 2010). CASA calculates the seasonal flow of carbon between the atmosphere and the terrestrial biosphere on a number of different time steps and a multitude of spatial resolutions. The main strength of the CASA model is its ability to use remote sensing data to calculate net primary production (NPP) and carbon turnover mechanistically through a CENTURY-like plant and soil carbon cycling model. The results were provided for major trace gases and particulate matter: CO_2, CO, CH_4, NMHC, H_2, NO_x, N_2O, SO_2, PM2.5, TPM, TC, OC, BC and total carbon losses. Major conclusions of this estimate are: (1) the average burnt area in Russia for 12 years 1998-2009 comprises 9.17 million ha with substantial interannual variability – from 3.1 (2004) to 17.0 million ha (2003); (2) of the considered 12 years, three years are presented by extremely severe fire conditions and the largest fire areas: 1998 – 15.0 million ha, 2003 – 17.0 million ha and 2008 – 15.1 million ha; (3) as a rule, severe fire years are represented by "late summer" types of fire seasons (1998, 2003), although exclusions are possible (e.g., fire season of 2008); and (4) the average annual carbon loss is assessed at 137.6 Tg C yr^{-1}. As one can see (Figure 6), overall our assessment is rather consistent with the results reported by GFED3 (GFED3 average annual area and total carbon loss is 11.5% and 13.2% higher, than our estimates, respectively).

There are other estimates for individual years and shorter periods based on different satellites and approaches of emissions' calculation. These data are diverse. Among others, Vivchar (2009) estimated the average burnt area in 2000-2008 at 19.7 x 10^6 ha including forests (the latter were defined as stands with relative stocking 0.6 and more) at 6.78 x 10^6 ha; Soja et al. (2004) – 7-11 x 10^6 ha in 1998-2002; Ershov et al. (2009) – only for forest – 3.875 7 x 10^6 ha in 2003-2007. Published information is not complete enough to reliably assess uncertainty of the reported estimates. Published estimates of carbon emissions are usually reported in a wide interval of uncertainty (e.g., 116-520 Tg C yr^{-1} in Soja (2004)) which mostly include the result of this study.

The carbon emissions estimates of this study relate only to direct carbon losses during the year of fire. Post fire dieback could be significant, particularly on wet sites and on permafrost, even after low intensive fires. Our preliminary estimate is that on average for the country the post-fire dieback under non-stand-replacing fires is in limit of 30-40% of initial growing stock. It results in annual carbon emissions from burnt areas of previous year of about the same magnitude as average direct fire emissions. It allows us to assess the average full output of carbon due to vegetation fire in Russia about 250 Tg C yr^{-1}.

Current model predictions of future fire regimes in the boreal zone suppose doubling of number of fire by end of this century; substantial increasing of number of catastrophic and escaped fires; dramatic increase of the intensity of fires and fire emissions; and change of composition of products of burning due to a wider distribution of deep soil burning (e.g., Flannigan et al. 2009). Very likely, thawing of permafrost and following aridization of landscapes on permafrost will lead to degradation and death of coniferous forests and to wide distribution of "green desertification". There is a high probability of positive feedback between warming and escalation of fire regimes: the increase of concentration of CO_2 in the atmosphere will lead to increase of frequency of long and dry periods which would promote the growth of area and intensity of fires, and, consequently, to substantial increase of emissions of greenhouse gases. In turn, growth of the emissions leads to destabilization of the Earth climatic system and following increasing threat of fire.

Already today, forest fire protection services of developed boreal countries balance in the narrow range between successful forest fire protection and large economic, ecological and social losses, particularly over catastrophic fire years (Stocks 2010). The situation in Russia is much more dramatic. Very likely, escalation of future fire regime will be disproportionate large comparatively to increase of fire danger. Russia needs urgent development of a new system of forest fire protection which would be satisfactory in a rapidly changing world. Such a system should be part of a more comprehensive strategy of adaptation of Russian forests to, and mitigation of, negative consequences of climate change. Development and introduction of such a strategy still remain a problem of the future.

References

Efremov DF, Shvidenko AZ (2004) Long-term environment al impact of catastrophic forest fires in Russia's Far East and their contribution to global processes. *International Forest Fire News* **32**, 43-49.

Flannigan M, Stocks B, Turetsky M, Wotton M (2009) Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology* **15**, 549-560.

Lapenis A., Shvidenko A., Shepaschenko D. (2005) Acclimation of Russian forests to recent changes in climate *Global Change Biology* **11**, 2090-2102.

Roshydromet RF (2011) Report on Specifics of Climate in Territories of the Russian Federation in 2010. Federal Service on Hydrometeorology and Environmental Monitoring, Moscow, 66 pp. [in Russian].

Seiler W, Crutzen P (1980) Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Climatic Change* **2(3)**, 207-247.

Sapozhnikov AP (1984) Problems of land resource estimation of burned areas. In: 'Dynamic Processes in Forests of Far East'. Biological and Soil Institute, AS of the USSR, Vladivostok, pp. 147-155 [in Russian].

Schepaschenko D, McCallum I, Shvidenko A, Fritz S, Kraxner F, Obersteiner M. (2010) A new hybrid land cover dataset for Russia: a methodology for integrating statistics, remote sensing and in-situ information. *Journal of Land Use Science*, (Published online 22 December 2010) [DOI: 10.1080/1747423X.2010.511681].

Shvidenko AZ, Nilsson S. (2000a). Extent, distribution, and ecological role of fire in Russian forests. In 'Fire, Climate Change, and Carbon Cycling in the Boreal Forest'. (Eds ES Kasischke, BJ Stock). Springer Verlag, pp. 132-150.

Shvidenko A, Nilsson S, (2000b) Fire and the carbon budget of Russian forests. In 'Fire, Climate Change, and Carbon Cycling in the Boreal Forest' (Eds ES Kasischke, BJ Stock) Springer Verlag, pp. 289-311.

Shvidenko A, Goldammer JG. (2001) Fire Situation in Russia. *International Fire News* **24**, 41-59.

Shvidenko A, Nilsson S, Schepaschenko D, McCallum I (2010) Can the uncertainty of full carbon accounting of forest ecosystems be made acceptable to policymakers? *Climatic Change* **103 (1-2)**, 137-157.

Soja AJ, Cofer WR, Shugart HH, Sukhinin AI, Stackhouse PW Jr, McRae DJ, Conard SG (2004) Estimating fire emissions and disparities in boreal Siberia (1998-2002) Journal of Geophysical Research 109, D14S06, doi:1029/2004JD004570.

Van Der Werf GR, Randerson JT, Giglio L, Collatz GJ, Kasibhatla PS, Arellano Jr AF (2006) Interannual variability of global biomass burning emissions from 1997 to 2004. *Atmospheric Chemistry and Physics Discussions*, **6**, 3175-3226.

Van Der Werf GR, Randerson JT, Giglio L, Collatz GJ, Mu M, Kasibhatla PS, Morton DC, Defries RS, Jin Y, Van Leeuwen TT (2010) Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009). *Atmospheric Chemistry and Physics* **10**, 11707-11735.

Vivchar A (2010) Wildfires in Russia in 2000-2008: estimates of burnt areas using the satellite MODIS MCD45 data. *International Journal of Remote Sensing* (in review)

Wooster MJ, Zhang YH (2004) Boreal forest fires burn less intensely in Russia than in North America. *Geophysical Research Letters*, **31**, L20505 1-3.