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GEOGRAPHY

Impact of Wildfire in Russia between 1998–2010 on Ecosystems and the Global Carbon Budget[1]

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Abstract—Verified estimates of wildfire area and related carbon emissions in territories of Russia are reported for the period of 1998–2010. It is shown that the average burnt area is estimated to be at 8.23 million hectares per year (uncertainty ±9.0%, confidence interval 0.9), and carbon emissions—121 Tg C yr^{-1} (±23%), with a significant interannual variability of these indicators. A quantitative characteristic of fire emissions by species is reported. Forests are a source of three quarters of all carbon emissions caused by wildfires. A significant acceleration of fire regimes is expected during the 21st century as a result of climate change in the country.

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Wildfire is the most dangerous exogenous disturbance in Russian natural ecosystems. Climate change of recent decades significantly increases the threat of the occurrence and distribution of wildfire, especially forest fire. An increasing temperature trend in Russia during the three past decades was significantly higher than the global one: 0.51 and 0.17°C/10 years, respectively, during 1976–2008. Although there has been some slowdown in global warming of recent years, rising annual temperatures continue in Russia [4]. The average amount of precipitation has increased slightly over the country (0.71 mm/month/10 years in 1976–2010, compare to the 1961–1990 average). However, for the southern European part and continental Asia, the observed trend in precipitation is close to zero, and the climate's dryness (for example, measured by Palmers Drought Severity Index) has increased significantly, continuing the trend of previous decades [10]. The variability of the weather increased substantially, as indicated by alternation of periods of torrential rainfall and long warm and dry periods, sometimes with heat waves (as in the summer 2010 in the center of European Russia). This specificity poses a threat of emergence and spread of large wildfire of high intensity, particularly in forests. These so-called catastrophic fires [8] lead to degradation of ecosystems and the profound depletion of biodiversity, while creating special atmospheric and seasonal weather over large areas causing considerable damage to the economy and infrastructure, as well as adversely affect the living conditions and health of the population in the regions of fire spread. This situation is exacerbated by a significant reduction in the level of control of natural resources in the country, the degradation of civic awareness and professional destruction of nature protection systems (in particular, by the practical elimination of the state forest protection service).

Over the past two decades, catastrophic fire situations in various regions of Russia (as a rule, in its Asian part), are observed almost every year with the frequency of about 10 years [6]. Environmental consequences of catastrophic fires are significant. By estimates, single or repeated catastrophic forest fires deforested 8 million hectares in the Far East during recent years. About a third of the forest area affected by fires is turned into unproductive areas where natural reforestation is not possible within 2–3 life cycles of major forest forming species (i.e. 300–600 years) [8]. These areas convert mainly to marshes (70%), shrubs and grassland (15%), sparse forest (10%) and rock outcrops (5%).

Fire emissions significantly affect the Earth's climate system. However, published estimates of areas of wildfire in Russia and the ensuing greenhouse gas emissions vary significantly (e.g. [2, 14]). This is explained by differences in assessment methods and, most importantly, by the completeness and reliability of initial data. Official wildfire statistics are limited to

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only the “forest area affected by fire” [5, also available on http://www.gks.ru/bgd/regl/b10_14p/Main.htm], which are lower than the actual area of wildfire on average 5–7 times.

Current satellite systems such as NOAA/AVHRR, Terra/Aqua/MODIS, ENVISAT/MERIS, Terra/ASTER, etc., allow us to substantially improve our knowledge of the distribution and intensity of fires and their effects on ecosystems and carbon emissions. However, the application of these methods is not trivial, requires adequate simulation tools and knowledge of vegetation characteristics of the underlying territory. The major aim of this study is to provide the most accurate and verified estimate of areas and spatial distribution of wildfires in Russia, as well as related carbon emissions between 1998–2010. Our assessment is based on the application of remote sensing methods and quantitative estimates of the basic biophysical characteristics of vegetation.

MATERIAL AND METHODS

An Integrated Land Information System of Russia (ILIS) was used to evaluate the biometric characteristics and spatial distribution of terrestrial ecosystems. The ILIS is developed by the International Institute for Applied Systems Analysis (Austria). It is represented in the form of a multilayer geographic information system, including a hybrid land cover dataset and the corresponding attribute databases. This information base is built on a multi-sensor remote sensing concept (12 products from 8 satellites were used), in situ measurements, data from various surveys and inventories (including forest state account, state land account, environmental monitoring data, etc.) and other appropriate information. Land cover classes were established based on vegetation types. For instance, forested areas (closed forests) on peat soils were accounted for as forest, and wetlands included unforested areas only. Parameterization of land cover was provided based on the principle of sequential use of the most accurate data which were available from multiple sources. In the case of insufficient resolution of satellite data for pixel wise parameterization (e.g., identification of dominant tree species, estimate of age or amount of live biomass), we applied a multivariate optimization algorithm that maximized likelihood of spatial identification and accuracy of the attributes for area units of about $15' \times 15'$. In particular, the ILIS provides a comprehensive description of the amount and structure of combustible materials (live biomass by fractions, understory, green forest floor, snags and logs, on-ground organic layer and soil organic matter) for each 1 km pixel. The hierarchical classification of terrestrial ecosystems comprises from a few hundred (for example, natural grasses and shrubs) to tens of thousands (for forests) individual account records. A more detailed description of the ILIS structure and the optimization algorithm are presented in [11].

Burnt areas were estimated for each month of the fire season, using the channels 2, 3, 4 and 5—of the AVHRR radiometer from the NOAA satellite by using the modified algorithm described in [14]. Since AVHRR overestimates burnt area, particularly if the size of fire affected is less than 10–15 thousand hectares, the results were adjusted based on regional ground based regressions which were developed by the Institute of Forest SB RAS. Distribution of burnt area by fire type (crown, superficial ground, steady ground and peat fires) was estimated monthly using long-term average data within geographical zones and vegetation classes.

Intensity of fire and share of consumed available combustibles (12 types of fuels were used) were estimated by regression models. These models take into account the season and duration of active combustion, as well as the ratio of the burnt area of individual years to the long-term average by administrative units. The amount of consumed organic matter (in units of carbon) was determined for each pixel using a modified formula initially suggested by Seyler and Crutzen [12] as a product of burnt area, fire type probability, amount of combustible materials, share of consumed organic matter, and share of carbon content in dry matter. The composition of gaseous and solid products of burning was estimated by using emission factors, presented in the latest version of Andrea’s database [7].

RESULTS AND DISCUSSION

The total area of wildfires in Russia between 1998–2010 is assessed at 106.9×10^6 ha or 8.23×10^6 ha yr^{-1}, varying from 4.2 (1999) up to 17.3×10^6 ha yr^{-1} (2003) (Fig. 1). This estimate is 5.9 times larger than the average annual area of fires reported by official statistics for 2000–2009—1.40×10^6 ha yr^{-1} [5]. There is a weak trend of increasing burned areas, but it is not statistically significant within the observed period.

As a rule, 90–95% of the burnt area is allocated in the Asian part of Russia, mainly in its southern half. The exception was in 2010, when unprecedented drought and temperature anomalies caused a catastrophic outbreak of fires in the central regions of European Russia (Fig. 2). More than half (59.3%) of burned area is situated on forested areas, and almost two-thirds (65.1%) if sparse and damaged forests are included (these are mostly old burns and areas affected by insects' outbreaks). A significant portion of observed fires happened on agricultural land, usually due to prescribed fire (18.9% of total area). 8.7% of burnt area are detected on grass- and shrubland, another 7.3%—on wetland. There are two major types of seasonal distribution of fires—spring and late summer fires. The first one concentrates burnt areas in spring after the snow thawing and before greening up of vegetation. The second type is a consequence of an abnormally dry spring and summer. It provides a nearly uniform fire area distribution by time, some-

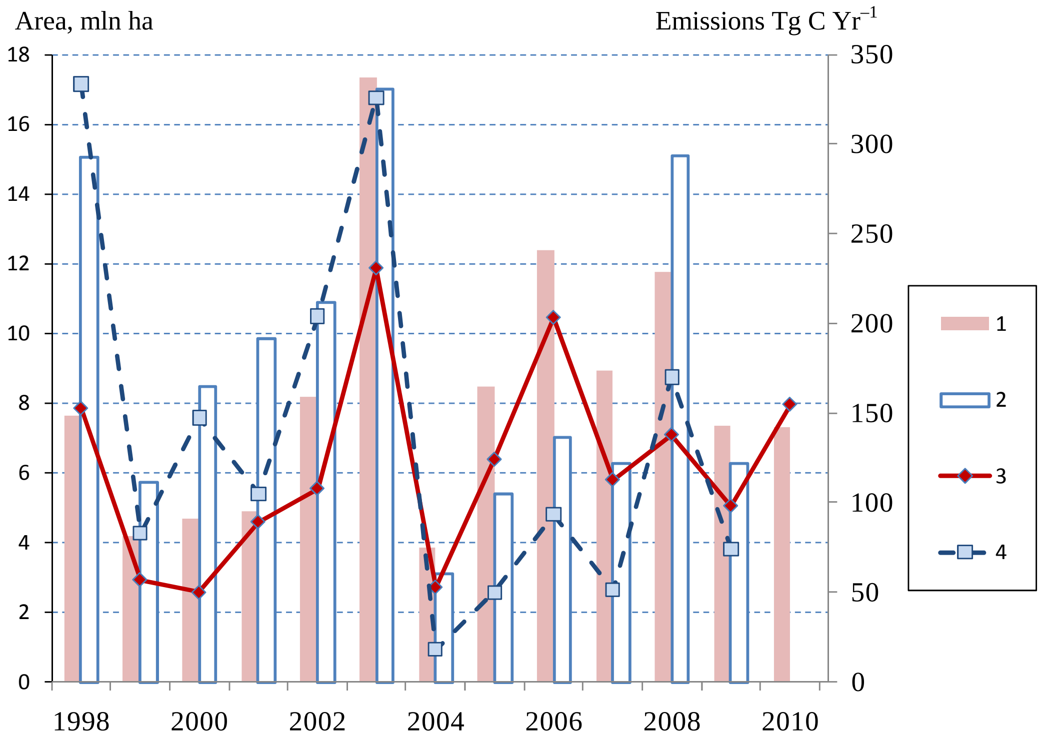

Fig. 1. Wildfire area and carbon emissions in Russia in 1998–2010. (*1*) Area by authors; (*2*) area by GFED3; (*3*) emissions by authors; (*4*) emission by GFED3.

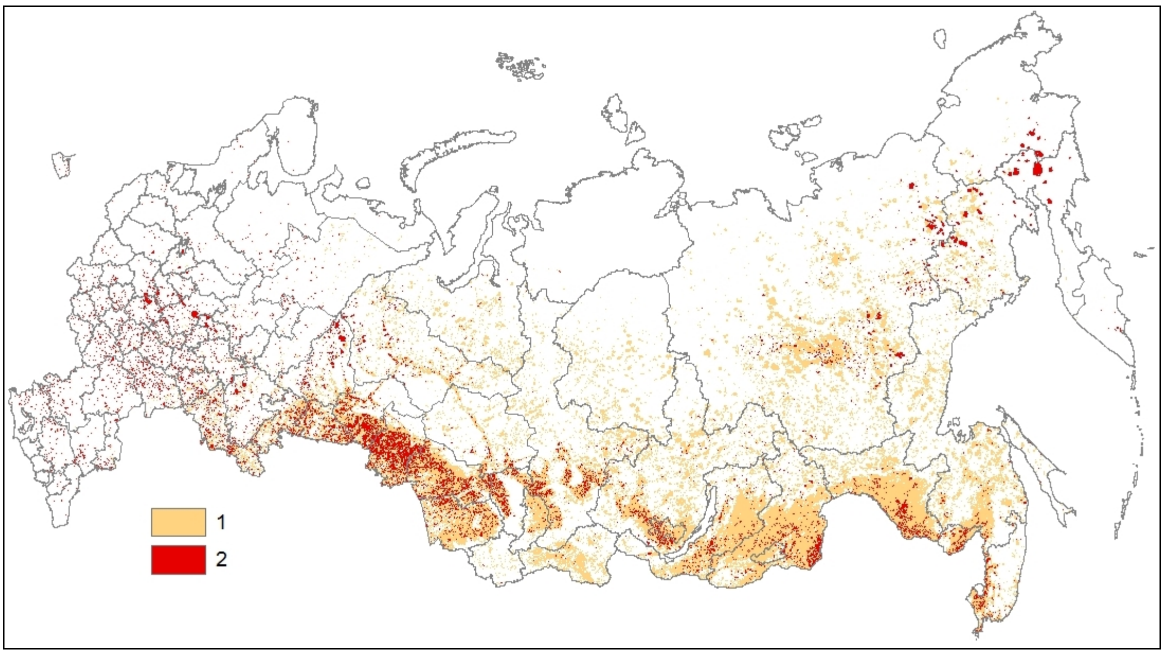

Fig. 2. Burnt area in 1998–2009 (*1*) and 2010 (*2*).

times increasing at the end of the fire season. Such years (1998, 2003, 2008, 2010) are characterized by a considerable increase in extent of crown and steady on-ground fires. For these years, we also found increasing of wetland fire with high levels of methane and carbon monoxide emissions.

The amount of organic matter burnt between 1998–2010 was assessed at 1.57×10^9 t C, or 121.0 Tg ($=10^6$ t) C yr^{-1}. Fire emissions amounted to about 2.4% of net primary production of ecosystems, corresponding to the global average (2.5% [15]). Interannual variability of this value is high—from

50 (2000) up to 231 Tg C yr^{-1} (2003) depending on fire season type and geographical location of the fire. Average carbon consumption over 1998–2010 (for all land cover types) was 1.47 kg C m^{-2} yr^{-1}, the maximum value received was for 2010 (2.12 kg C m^{-2} yr^{-1}), while the total burnt area this year was slightly below the long-term average. The majority of carbon emissions were provided by forest fires (including sparse forest)—76.0% of the total, followed by emissions from wetland fires (15.8%). On average, wetland fire shows the highest average emissions (3.06 kg C m^{-2} yr^{-1}), while emissions of steady individual peat fires may exceed this value by ten times.

The average composition of combustion products for the evaluation period was as follows: 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 elemental carbon (black carbon)—0.1%. Particulates accounted for 3.5%, of which 1.2% were $PM_{2.5}$. The highest content of CH_4 and CO in the combustion products is observed on peat soil.

The above mentioned data refer to direct fire emissions. Significant post-fire emissions are observed in forests due to post fire dieback of a significant number of trees, especially after crown and peat fires, as well as after steady on-ground fire on permafrost. Our estimates show that on average the postfire dieback is about one third of the growing stock, and the emissions due to decomposition of dead wood slightly exceed the direct emissions. Overall wildfire has emitted ~250 Tg C yr^{-1} over the last decade, which is about 50% of industrial carbon emissions of the country.

Estimation of uncertainty of the results requires consideration of the fuzzy nature of the problem. Using the techniques described in [13], we estimated the uncertainty in the assessment of burnt area at ±9%, and direct emissions of carbon at ±23% (CI 0.9). On average, our result is quite close to estimates given by the global fire emissions database (GFED3) [15] which assessed the average burnt area in Russia at 9.17×10^6 ha yr^{-1} (+11.5% to our estimate), and emissions—137 Tg C yr^{-1} (+13.2%). GFED3 uses different satellite sensors to identify burnt area and the CASA model for emissions assessment [15], in contrast to the consistent empirical approach used in this study.

Current models suggest a doubling of the number of fires by the end of this century in the boreal zone (e.g. [9]). They predict increases of numbers of catastrophic fires and fires covering large areas; a significant increase in the intensity of fires; and increasing the amount and change in the composition of the gas emissions due to enhanced soil burning. The correlation between catastrophic fires and large-scale climatic anomalies becomes more and more clear (e.g., 1998—catastrophic wildfires in the Russian Far East and the flooding in China, 2010—fires in the European part of Russia and the floods in Pakistan and India). Permafrost melting and subsequent landscape aridity most probably will lead to the degradation and destruction of coniferous forests, as well as the widespread distribution of "green desertification" [8]. Irreversible replacement of forests by other vegetation types already is identified in different southern ecotones of the forest zone [1, 3].

A significant feedback between warming and escalating fire regimes is very probable in Russia and particularly in the permafrost areas. Increasing atmospheric CO_2 concentration (i.e. climate change) leads to an increase in the frequency of long dry periods that causes an increase of size and intensity of fires and a significant increase of greenhouse gas emissions. In turn, the growth of carbon emissions leads to destabilization of the climate system that causes the increasing threat of wildfires.

Forest wildfires have become a top priority issue for some countries. Forest protection services in developed countries are balancing within a narrow range between satisfactory protection of forests from fires and large losses in years of high fire danger. Fires in the European part of Russia 2010 have clearly demonstrated the threats that wildfire brings under changing climate. Russia should expect a disproportionate escalation of fire regimes compared to increasing climatic fire danger as 90% of the country's forests are represented by boreal forests of high fire danger. Thus, a radical improvement of forest fire protection is an urgent national task of today. This complex problem includes (1) systems analysis of current and future fire regimes and regional requirements towards a rational system of forest fire protection; (2) development of a new paradigm of forest fire protection; (3) development and implementation of strategies for the prevention of large-scale disturbances in forests, including adaptation of forest landscapes to the future climate; (4) implementation of an effective system of forest monitoring; (5) allocation of sufficient resources; (6) development of new/improvement of existing legislation and institutional frameworks of forest management which would be satisfactory to react on challenges of climate change; and (7) international cooperation. Currently, the effective implementation of all the above problems is a matter for the future.

REFERENCES

1. L. V. Buryak, A. I. Sukhinin, and S. A. Moskal'chenko, Lesovedenie, No. 5, 17–23 (2009) [in Russian].
2. A. V. Vivchar, K. B. Moiseenko, and N. V. Pankratova, Izvestiya, Atmospheric and Oceanic Physics **46** (3), 307–320 (2010) [in Russian].
3. M. D. Evdokimenko, IVUZ Lesnoy Zhurnal, No. 4, 12–18 (2009) [in Russian].
4. Roshydromet RF, *Report on Climate Particularities in Russian Federation in 2010* (Federal Service for Hydrometeorology and Environmental Monitoring, Moscow, 2011) [in Russian].

5. RosStat RF, "Regions of Russia," in *Socio-Economic Indicators in 2010. Statistical Handbook* (Federal State Statistics Service, Moscow, 2010) [in Russin].
6. A. V. Rubtsov, A. I. Sukhinin, and E. A. Vaganov, Journal of Siberian Federal University Biology, No. 1, 30–39 (2010) [in Russian].
7. M. O. Andreae and P. Merlet, Global Biogeochemical Cycles, No. 15, 955–966 (2001).
8. D. F. Efremov and A. Z. Shvidenko, International Forest Fire News, No. 32, 43–49 (2004).
9. M. Flannigan, B. Stocks, M. Turetsky, et al., Global Change Biology, No. 15, 549–560 (2009).
10. A. Lapenis, A. Shvidenko, D. Shepaschenko, et al., Global Change Biology, No. 11, 2090–2102 (2005).
11. D. Schepaschenko, I. McCallum, A. Shvidenko, et al., Journal of Land Use Science. Published online 22 December 2010).
12. W. Seiler and P. J. Crutzen, Climatic Change, No. 2, 207–247 (1980).
13. A. Shvidenko, D. Schepaschenko, I. McCallum, et al., Climatic Change **103**, 137–157 (2010).
14. A. J. Soja, W. R. Cofer, H. H. Shugart, et al., Journal of Geophysical Research D: Atmospheres **109**, D14S06 (2004).
15. G. R. Van Der Werf, J. T. Randerson, L. Giglio, et al., Atmospheric Chemistry and Physics **10**, 11707–11735 (2010).