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Climate Change and Wildfires in Russia

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Abstract—The effect of climate change on the distribution, intensity, and transforming role of wild fires is considered. A general overview of the current wild fire regimes (WRs) and impacts on forest ecosystems and environment is provided. One distinctive feature of WRs is the increasing frequency of disastrous wild fires. The application of various remote sensing instruments has shown that the average vegetation wild fire area in Russia for 1998–2010 accounted for $8.2 \pm 0.8 \times 10^6$ ha, with about two-thirds of wildfires occurring on forest lands and half on the forested lands. The average annual fire carbon balance during the above period was 121 ± 28 Tg C yr^{-1}, including 92 ± 18 Tg C yr^{-1} emitted from the forested land. The forecasts based on the General Circulation Models suggest the dramatic acceleration of fire regimes by the end of the 21st century. Taking into account the increase in the dryness of the climate and the thawing of permafrost, this will likely lead to a dramatic loss of forested area and the impoverishment of the forest cover over a major part of the forest zone. A transition to adaptive forestry would allow a substantial decrease of the expected losses. This paper takes a brief look at the general principals of adapting forest fire protection system to climate change, which is considered an integral part of the transition to sustainable forest management in Russia.

Keywords: climate change, forest fires, current and expected fire regimes, adaptation of Russian forests to climate change

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INTRODUCTION

Vegetation fires (wildfires) have various impacts on the environment and on the climate system of the earth, i.e., emissions of greenhouse gases and aerosols, changes in evapotranspiration and surface heat regime, the course of the main ecological processes (productivity and soil respiration), postfire changes of albedo on the burned areas and due to the black carbon deposition on snow and sea ice, and many other effects. An integral assessment of the impact of wildfires depends on the duration of evaluation period. The comprehensive impact of the abovementioned agents and others throughout the year of fire and the initial period of restoration of the ecosystems leads to a pronounced greenhouse effect, whereas the long-standing postfire augmentation of albedo considerably declines the net effect [39].

Forest wildfires are an integral part of the evolution of forest ecosystems and the current state of forest cover in Russia. The two-faced role of forest wildfires is evident all over the country. In the unmanaged high latitude forests, in particular, located on the perennial permafrost area, the ground fires that occur according to the historically formed fire cycles (50–80 to 150–300 years) constitute part of the natural mechanism that prevents a decrease in forest productivity, waterlogging, and green desertification [10, 11]. However, on the largest part of the forest area, fires cause the most harmful natural disturbances that determine the successional dynamics of forests, mosaicity and the structure of forest fund, and quantitative and qualitative characteristics of forest stand; they can also lead to considerable ecological, economic, and social losses. Wildfires represent the main factor that determines the dynamics of carbon pools in the ecosystems of boreal forests [29]. WRs (regionally conditioned stable combinations of types, diversity, frequency, and intensity of forest wildfires determining the degree of devastation of forest biogeocenoses and the postfire dynamics of forest regeneration) depend on four crucial factors, i.e., seasonal weather (climate), quantity and state of combustible vegetation materials (CVMs), availability of fire sources, and human activities. Consequently, climate change associated with current social and economic processes constitutes an important factor for forest wildfires and developing a strategy to abate them. The present paper endeavors to analyze the impact of current and expected climate change on forests and wildfire regimes (WRs) in the country and discuss the main measures aimed at adapting forests to climate changes expected in the 21st century.

MATERIALS AND METHODS

While performing the present study, we used both original and other available information sources. To estimate the total area of vegetation fires (wildfires) that occurred in 1998–2010, we carried out by pixel temporal control and reanalysis of the data obtained by the Sukachev Institute of Forest [17]. The initial data array, represented the results of processing signals of the 1–5 NOAA AVHRR channels of 1 km^2 resolution based on an algorithm whose details are given in [42, 44]. The usual overestimation of the wildfire area by low-resolution images was adjusted based on regressions developed by a Siberian scientists using ground evaluations and Landsat images of 30-m resolution (1). Then, we compared the areas affected by wildfires to data on the longest observations obtained by MODIS satellite devices aboard the Terra and Aqua satellites and available in the Global Fire Emissions Database GFED3 [46] and SPOT-Vegetation [2].

The distribution of wildfire areas by vegetation types and the evaluation of wildfire emissions were based on the data of the Integrated Land Information System of Russia (ILIS) developed by the International Institute for Applied Systems Analysis [40]. It includes a hybrid land cover in the form of a multilayer geographic information system and multiple attribute databases. The representation and parameterization of land cover was carried out using 12 satellite instruments, as well as the available in situ ground measurements and data from inventories and surveys (forest state account, land state account, etc). The hierarchical classification of vegetation included several tens of classes for agricultural lands and ~80 thousand classes for forests. ILIS offers a comprehensive description of landscapes and ecosystems (including live biomass, net primary production, heterotrophic respiration, etc.) and is coupled with the climatic data of the last four decades. The base spatial resolution of ILIS is 1 km^2. ILIS constitutes, apparently, the most informative georeferenced quantitative description of land cover and vegetation in Russia.

A wildfire carbon balance was estimated as part of the full verified terrestrial ecosystems carbon balance [41]. While evaluating emissions, five types of fire were analyzed (crown, superficial ground, steady and stable ground, peat, and underground fires). The monthly carbon emissions for every type of fire were assessed using long-term average regional data. CVMs were classified by 12 types. The average long-term fire intensity (the share of consumed CVMs) was adjusted based on the regional weather conditions of individual fire seasons [17, 41].

CURRENT WILDFIRE REGIMES IN RUSSIA

In Russia, climatic change over the last decades is quite obvious. The increasing temperature trend in Russia for 1976–2012 was almost three times higher than the global one: 0.43 and 0.17°C/10 years, respectively. In high latitudes, the trend reached 0.61°C within 10 years. These trends remain stable: two (2007 and 2008) out of three warmest years over the entire documented history of evaluating climate indices in Russia fall within the last decade [5]. The average annual amount of precipitation is increasing, however insignificantly (+7.2 mm/10 years during 1976–2008 compared to 1961–1990). The change in the amount of precipitation varies considerably over different areas. It is close to zero on a considerable part of the country, negative in the eastern part of Russia throughout the whole year, and also negative in European Russia in summer. The indices of climate dryness have been increasing for almost entire boreal zone following the trend of the past 50 years. Weather has become much more instable. The severe and prolonged droughts (up to 100–120 days) on the vast areas become more frequent and are often accompanied by abnormally high temperatures.

This climate trend gave rise to an increasing frequency of disastrous fires that sweep over tens and hundreds thousand hectares within large geographic regions, leading to the degradation of forest ecosystems, the depletion of biodiversity, the disturbance and destruction of the raw materials base of forest industry, and the development of specific weather conditions on the vast areas that adversely affect the economy and infrastructure, aggravate the living conditions and health of the population within the regions of their distribution, and cause the irreversible transformation of the forest environment for the period that exceeds the life cycle of major forest-forming species [1, 17, 19, 47, etc.]. In the area of disastrous fires, the composite humidity index sometimes reaches about 12000–14000; the average area of individual fires increases by 5–10 times, the smoke spreading over tens of millions of hectares. The distribution of fires by types is changing. Summarizing the available information on wildfire regimes of the second half of the 20th century, G.N. Korovin [33] classified 77% of fires as ground, 22% as crown, and 1% as underground fires. Disastrous fires of the last decade have led to a 1.5- to 2-time increase in the share of crown and underground fires. The types of fire regimes are changing, with most fires lasting for a long time during summer and also falling in early autumn. The fires spread over swamps, which are normally nonflammable; the composition of fire emissions is changing with an increase in CO, CH_4, and NO_x due to the deep soil burning. Postfire dieback in the area of disastrous fires exceeds 50% and may reach 90% of forest stand under stable ground fires. Long-term, generally unfavorable transformations of hydrothermal regime occur within the burnt areas, with the forest bioproductivity potential decreasing by approximately one third; further restoration is usually followed by the replacement of the dominant tree species. Forest fragmentation, its transformation into debris-strewn burnt areas, and the increase in the

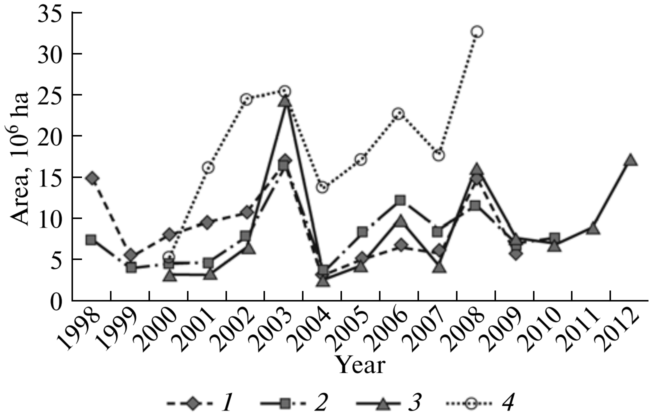

Fig. 1. Dynamics of total area of wildfires according to different sources: (*1*) GFDE3 (44), (*2*) Refined data provided by the Institute of Forest, Russian Academy of Sciences (1), (*3*) Space Research Institute, Russian Academy of Sciences (average value of (2, 8), (*4*) (4).

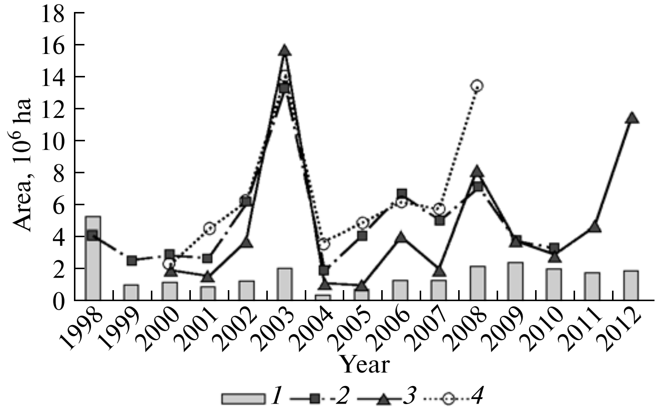

Fig. 2. Dynamics of fires of the forest lands according to different sources: (*1*) Rosleshoz (Federal Forestry Agency), areas of the protected part of forest fund; (*2*) Institute of Forest, Russian Academy of Sciences (1), forested lands; (*3*) Space Research Institute, Russian Academy of Sciences (average value of (2, 8), forested lands; (*4*) (4), forested lands.

quantity of CVMs enhances the danger of further disastrous fires [3, 14, 15, 18, 19, 47].

Another new trait of wildfire regimes is the influence of disastrous fires on seasonal weather of the areas comparable to the area of a pressure system (about 30 million hectares and more). This causes the formation of stable tropospheric ridges fed by hot smoke and aerosols of multiple intense fires. Frontal precipitation approaching the Far East regions from the southeast and Eastern Siberia from the northwest bypass the areas of massively spreading wildfires or collapse as a result of interaction with convective flows and do not reach the wildfire area [1, 12, 13, 47]. These fires persist over several months and terminate only upon the coming of cold autumn weather. These meteorological and fire conditions were observed in eastern Siberia in 1979, 1985, 1996, 2006, and 2012; in the center of European Russia in 2010; in the Sakha Republic in 1985–1986, 1996, 2001, 2002, and 2012; in Primorsky and Khabarovsky Krai in 1954, 1968, 1976, 1979, 1981, 1986, 1998, 2001, 2003, 2005, and in other years [1, 17, 19, 29, 31, etc.]. Disastrous fire conditions have been observed on multiple occasions earlier on the enormous territories of sparsely populated areas. However, they occurred rarely, in particular, before the development of vast taiga regions, normally once a century, though much more frequently during warm and dry climatic periods [19, 28].

In the last two decades, disastrous fires have occurred in various regions of Russia with increasing frequency [1, 17]. A considerable part of lands devastated by such fires, especially the northern part of the taiga zone, suffer from green desertification, which converts forested lands into areas unsuitable for forest vegetation (marshes, shrubland, stone fields, etc). According to experts, disastrous wildfires of the last two decades have increased the area of forest-unsuitable lands in the Far Eastern Federal District by 8×10^6 ha (47). On the whole, wildfires similar to those having occurred in various regions of the country in 1998, 2003, 2010, and 2012 are planetary-scale natural catastrophes.

There are no official statistics on the entire area of wildfires in Russia. The Forestry Agency offers information on the "forest area affected by fires on the protected part of forest fund," assessing it at 2×10^6 ha on average, which is several times lower than the data of satellite evaluations of the forest area. This information, with some modifications, is repeated by the Federal State Statistics Service (Goskomstat). Satellite evaluations of wildfire areas differ and depend on the technical specifications of different remote sensing devices, the reliability of the available information on land cover, the relevance of assessment algorithms, the use of various definitions of forests and other classes of land cover, the noncoincidence of boundaries of the assessed regions, numerous modifications of former evaluations by their authors, etc. One typical feature and the major defect of most satellite evaluations is the almost complete lack of verifying them using ground data.

The mean values of the main satellite evaluations of wildfire areas in Russia that cover periods of about 10 years are quite close, though some values may exceed others by two times. The assessment made based on the spatiotemporal reanalysis of data from the Sukachev Institute of Forest showed the mean area of wildfires in the country for 1998–2010 as 8.2×10^6 ha yr^{-1}, varying from 4.0 (in 2004) to 17.3×10^6 ha yr^{-1} (in 2003) [17]. Fires on the forest lands accounted for 5.9×10^6 ha yr^{-1} and 4.9×10^6 ha yr^{-1} on the forested lands. The accuracy of annual wildfire area assessment was ±9% (confidence interval 0.9). GFED3 assesses the wildfire area for this period at 9.2×10^6 ha yr^{-1} [46]. The average value of several assessments published by Space Research Institute, Russian Academy of Sciences, was 8.5×10^6 ha yr^{-1} in 2000–2010 [2]. To accurately compare the data, we did not apply the institute's assessments of areas for 2011 (11.5×10^6 ha) and 2012 (18.0×10^6 ha). There are also quite different assessments generally made within shorter periods of time or during individual years. Thus, the mean wildfire area in (4) accounted for 18.1×10^6 ha yr^{-1} in 2000–2008. According to literature data, the average value of ten assessments of wildfire area in 2003 was $20.1 \pm 6.1 \times 10^6$ ha yr^{-1} (mean square deviation ±1), ranging from 13.1 to 33.3×10^6 ha [2, 4, 17, 24, 40, 44, 46]. The most of the outlying assessments demonstrate obvious errors of methods applied.

On the whole, the mean area of wildfire distribution in Russia was assessed quite accurately and reached $(8–9) \times 10^6$ ha yr^{-1}, with about two-thirds accounting for the forest lands and half for forested lands. This value is probably somewhat underestimated because of the tundra and northern taiga ecosystems, as well as due to the burning of the southern agricultural lands, where underestimation is possible due to low-temperature burning, frequent clouds, and considerable smoke. Russia has the highest level of forest burning in the boreal zone, with the wildfire area being 3–4 times higher than in Canada, the second largest country in the world in respect to the area of boreal forests [43].

Fire severity is a crucial indicator defining the quantity of the consumed CVMs, the amount of wildfire emissions, the degree of biogeocenose destruction, and the nature of postfire restoration. Numerous studies have proven attempts to assess fire severity by satellite methods by applying fire susceptibility indices such as color change (optical and intermediate infrared band), soil structure (intermediate infrared), soil moisture, and chlorophyll (near infrared) ineffective. The use of additional in situ measurements and spectral Landsat data TM/ETM+ allows one to considerably improve the results (23, 24). The method of satellite assessment of fire radiative power (for example [30]) seems quite promising. However, complex ground studies are required to make the use of this method in Russia reliable.

The quantity and composition of wildfire emissions depend on types of wildfires and fire season; the forest composition and other biometric indicators; the quantity, composition, and state of CVMs; meteorological conditions; ratio of combustion phases (smoldering and flaming); and some other factors. We assessed the carbon fire balance (the total amount of carbon in burnt materials) due to the wildfires that occurred in Russia in 1998–2010 at 121 ± 28 Tg C yr^{-1}, with the annual variation reaching 50 (in 2000) to 231 (in 2003) Tg C yr^{-1}. Combustion products included C-CO_2 reaching 84.6%, C-CO 8.2%, C-CH_4 1.1%, C-NMHC (nonmethane hydrocarbons) 1.2%, organic carbon 1.2%, and elemental carbon 0.1%. Solid particles accounted for 3.5%, with those with a fraction of less than 2.5 μm ($PM_{2.5}$) reaching 1.2%. Wildfire carbon emissions on the forest lands reached 92 ± 18 Yg C yr^{-1} in 1998–2010 (76% of total amount). Our data almost coincided with that of GFED3 by specific emissions per area unit: the difference was less than 1%.

The amount of carbon flow associated with the decomposition of wood dead due to wildfires is somewhat higher than the amount of direct emissions and less defined, since it is impossible to accurately distinguish the postfire dieback from other types of tree mortality (pathological or natural). The number of such estimates is quite limited. Using the regional models of decomposition of coarse woody debris (snags, logs, and dry branches of living trees), we assessed the carbon emissions related to the postfire dieback at 90–100 Tg C yr^{-1} [41]. This estimate is quite rough. The total carbon emissions related to the forest wildfires are assessed at 180–200 Tg C yr^{-1}. Some models yield a considerably higher level of carbon emissions (for example, [22]), though the accuracy of these estimates is unknown and they do not fit into the full carbon balance of forest ecosystems. The emissions of nitrogen were assessed at 0.9 Tg N yr^{-1}. They are mainly represented by NO_x, N_2O, and NH_3 [41].

EXPECTED CHANGES OF WILDFIRE REGIMES

The models used by the Intergovernmental Panel on Climate Change (IPCC) predict a rather consistent and considerable acceleration of the current climate trends during the 21st century for almost all the regions of the country, especially the boreal area, though the forecasts differ considerably depending on the applied scenarios and models. According to three scenarios developed by IPCC, i.e., A2 (extreme warming), A1B (average value of different scenarios), and B1 (minimal warming), the possible increase in the mean annual temperature in various regions of Russia will reach +4 to +12°C by the end of the century [32, 37, 38]. Such warming has not been observed in many millennia. According to the modern science of global warming, an increase in global temperature by more than 2°C will create numerous risks for the earth's forests. However, the rising level of greenhouse gas emissions due to the burning of fuel and the possible scenarios of development of world economy and energy industry lead researchers to assume that global warming will reach 3.5–4°C by the end of the century. In Russia, this will mean an increase in the mean annual temperature from 6 to 12°C for various regions, the maximum value hitting the high latitudes of the Asian part of the country.

The expected mean annual increase in the amount of precipitation is assessed at $11.3 \pm 3.1\%$ (B1) to $17.7 \pm 3.7\%$ (A2). All scenarios predict an increase in precipitation during winter. A slight increase in precipitation in summer is expected in the northern and eastern regions, whereas it will decrease in the southwest of Russia and in the central and southern continental regions of the Asian part of the country. None of the scenarios foresees a summer increase in precipitation by more than 8%, which falls within the limits of the forecast accuracy. Therefore, the increase in climate dryness shall be expected on the largest part of the forest area. The increasing weather instability will aggravate the water stress of trees.

The impact of climate change on forests depends on both the degree of warming and the buffer capacity of forest ecosystems. Throughout evolution, Russian forests have for the most part adapted to a stable cold climate, which creates additional risks related to warming. Researchers assume that the expected climate change will considerably affect the structural and functional characteristics of forest cover in the country [16, 20, 45, 47, etc.], which may lead to the dramatic escalation of WRs in forests, though there is a pronounced gap between long-term and the short-term estimates.

Climate trends and an increase in the CO_2 concentration and nitrogen deposition will in theory contribute to the enhancement of productivity in Russian forests. More favorable growing conditions will be observed for deciduous species. However, the impact of growing instability and the imbalance of climate, as well as the increase in the frequency of draughts and heat waves, particularly in the southern part of the forest area, will significantly slow down the enhancement of forest-stand productivity. Scientists expect an increase in the concentration of ozone, which accelerates water stress in trees, as well as an intensification of biotic disturbances, chiefly, massive outbreaks of insects. All this will lead to an increase in the amount of CVMs and the intensification of the fire danger by weather conditions.

One should expect considerably higher risks by the end of the century if the warming surpasses certain limits. The change in the amount of precipitation in summer will not offset the temperature increase, which will accelerate water stress for trees on the larger part of Russia. In this case, the most probable scenario for boreal forests would consist in the nonlinear response of forest ecosystems, which may lead to the creation of new ecosystems and the disappearance of species with limited adaptation capacity. According to the models and expert assessments, the regional warming by 6–7°C will mean the critical limits in functioning of boreal forest ecosystems will be reached. If these limits are surpassed, this will result in a massive dieback of trees. If the threshold values of resilience are overpassed, this process will be rather quick and a considerable transformation of boreal forests may take place in 50 years. The experts consider the expected massive dieback of boreal forests to be one of the nine global potential "tipping elements," namely, a sudden and sharp response of ecosystems beyond the threshold of resilience [35]. The mechanism that governs the increased mortality of trees is based on the direct impact of accelerating water stress and the high peak temperatures, as well as on the indirect influence of forest diseases, insects, and escalation of WRs that increase the vulnerability of boreal forest ecosystems. It is highly probable that the expected climate change will lead to an escalation of biotic disturbances in Russia by the end of the century, which will have a synergetic impact on the frequency, area, and severity of fires and involve obvious consequences for forests.

In Russia, a large part of forests grows in the permafrost areas. Models suggest a reduction in the permafrost total area by about one-third and the continuous permafrost area by 25–50% by 2080 in the case of moderate climate warming. This territory is generally located in an area with a moderate amount of precipitation (about 200–300 mm yr^{-1}). The expected increase in precipitation by 10–20% will not make any difference. Therefore, one should expect an irreversible change in the hydrological regime of vast territories underlain by permafrost, a considerable decline of water table, and a decrease in the available water in soil. The adverse effect of thermokarst, solifluction, gullying, and other processes is obvious, but, apparently, it will not be as dramatic as the crucial change in growing conditions. The landscape aridization of high latitudes and the intensification of disturbances will cause the degradation and death of coniferous (especially dark coniferous) forests, as well as wide distribution of green desertification.

Large-scale drying out of forests, generally accompanied by massive insect outbreaks, have already been registered in the dark coniferous forests of the Far East, on the south of Siberian forest area, and the northeast of European Russia [9]. Upcoming decades will probably be marked by new "waves" of drying out of spruce–fir forests in the Far East and European North, an intensive dieback in Siberian cedar forests, and a decline in the viability and increase in the fall of the forest–steppe ecotone forests. There is evidence of a systematic increase in forest dieback on the entire circumpolar boreal area [20].

Particular risks are also expected to hit the forests of forest-steppe ecotone, since this region possesses the following characteristics: (1) considerably high forecast uncertainty, (2) exceptionally high forest vulnerability, (3) high probability of ecologically dangerous processes (forest ecosystem degradation and soil carbon oxidation), and (4) unsatisfactory structure of land cover and low quality of agricultural lands of the large part of the territory.

Climate forecasts and an increase in the quantity of CVMs predict a considerable enhancement of fire danger in Russian forests that will keep rising toward the end of the century. Current model estimations of future wildfire regimes on the largest part of Russia suggest the doubling of the amount of fires by the end of the century, an increase in the number of disastrous fires getting beyond control, a considerable rise in wildfire severity, and an increase in the amount of wildfire gas emissions and the change of their composition due to the intensification of soil burning (for example [24, 25, 36]. Many regions will suffer from an increasing number of lightning fires.

The major fire risks are located in the Asian part of the country and in the south of European Russia. The estimation of future WRs in European Russia by the end of the century based on the regional model using the index of fire danger developed by Nesterov and the B2 moderate scenario of IPCC demonstrates a considerable spatial variation of the fire-danger index; the substantial increase of fire danger on the southern boundary of the forest area, especially the steppe; and the decrease of fire danger in the northern area, which corresponds to the expected change in the temperature–humidity regime [38]. Another study for the entire boreal area [36] carried out using the correlation of Selianinov's hydrothermal coefficient with various fire-danger indices showed that the areas suffering from maximal fire danger would double by the end of the century; however, their spatial distribution will be quite heterogeneous.

An integrated effect of climate change and hydrological regime, acceleration of WRs, and the outbreaks of harmful insects will likely lead to considerable and mainly unfavorable changes in the forest cover in Russia. However, model forecasts are quite different. Let us look at two contrasting examples. The SibCliM biogeography model, which uses one of the most popular (average level of change) atmospheric general circulation models (AGCM), the HadCM3, and A2 scenario developed by the IPCC, suggests a decrease in the share of tundra, forest tundra, and taiga climatic areas from 81.5 to 30% and an increase in the area of forest steppe, steppe, and semidesert by 67% in Siberia. The moderate B1 scenario predicts a respective decline in the total area of the northern part of the region from 81.5 to 50%. According to the estimate, the boundaries of bioclimatic zones will shift towards the north by approximately 600 km. A considerable increase in fire danger is expected to hit the largest part of the forest area. The model is based on a limited number of climate indicators [45]. Taking into account the fact that the speed of migration of the boreal tree species does not exceed 300–500 m per year under most favorable conditions, this estimate means the death of the forests and their replacement by steppe and semideserts on the enormous territories located in the southern part of the Siberian forest area.

At the same time, LANDIS-II, the detailed Landscape Disturbance and Succession model (resolution 100 m) combined with the PnET ecophysiological model, allows us to examine the integrated effect on forests (climate change, various forest exploitation regimes, insects, diseases, etc.) and does not yield such a dramatic image. The model was used for forecasts in the transitional area between the middle and southern taiga of central Siberia [26, 27]. The same HadCm3 climatic model and A2 scenario were used. The most interesting result of this study showed that the major parameters of the future forest cover (in 100 years and more) appeared to be more dependent on forest management regimes and harmful insect outbreaks (mainly Dendrolimus sibiricus) caused by new climate conditions than on climate change itself. No drastic WR escalation was revealed. At the same time, the model predicts a substantial change in the composition of forest species (the increase in the share of deciduous species), enhancement of fragmentation of Siberian forests, and a decline in their capacity to accumulate carbon.

Nearly every model predicts a considerable increase in the wildfire carbon emissions (by 3–4 times compared to the modern values) and the possible transition of Russian forest ecosystems from the sequestration of carbon to its emission into the atmosphere along with the climatic inhibition of forest productivity and vitality [21, 22].

In Russia, there is a high probability of a considerable positive feedback between the warming and the escalation of wildfire regimes: the increase in CO_2 concentration in the atmosphere will extend the prolonged dry periods that will cause the enhancement of the fire area and fire severity and lead to a considerable increase in greenhouse gas emissions. In turn, the increase in carbon emissions destabilizes the climate system, which will potentially enhance the fire danger.

WILDFIRES AND ADAPTATION OF FORESTS AND FOREST COVER TO CLIMATE CHANGE

Forests are especially vulnerable to climatic changes, since the long life cycle of trees does not allow them to quickly adapt to environmental changes. The forests are obliged to not only adapt to the changing of the mean climatic indices, but also to an increasing variability of climate conditions and the constantly growing risks related to extreme weather events, i.e., prolonged droughts, hurricane winds, or floods. The adaptive potential of forests includes the historically developed adaptive properties of trees and forest ecosystems, as well as social and economic factors that determine the feasibility of measures aimed at the planned adaptation. The adaptation potential and vulnerability of Russian forests to climate change have been quite insufficiently studied so far.

The problem of forests adapting to climate change is an urgent issue for Russian forestry. Even today, the forest protection services of developed countries balance between satisfactory protection during moderate fire seasons and huge losses in years of high fire danger. Leading forest countries have become aware of the importance of adaptive forestry and now consider it an essential prerequisite for transitioning to sustainable forest management. Forest adaptation and mitigation by efforts of the entire forest sector are closely interconnected, though there are considerable differences between these two types of activity.

The necessary improvement of the forest fire protection system is not only an important component of the strategy of adaptation and an instrument for mitigation, but also an urgent state matter of today. A satisfactory solution to this problem will have a considerable impact on the state and protection of Russian forests. This complex problem includes (1) a system analysis of present and future regional WR and requirements for an efficient forest-fire protection system under the conditions of climate change; (2) the development of a new concept of forest fire protection; (3) the development and implementation of a strategy for preventing large-scale disturbances in forests, namely the adaptation of forest landscapes to future climate conditions, including the appropriate structure of forest cover, the development of the necessary fire-fighting facilities on site, the composition and structure of forests stands, control over CVM, etc; (4) the implementation of an efficient system of forest monitoring as part of the integral observation system; (5) the creation of a mobile system of fire suppression capable of meeting the challenges of a changing world, provided the allocation of the required human, financial, and technical resources; (6) drawing up new and improving existing legislation and institutional structures of forest management; (7) and sufficient international cooperation (see also [1, 14, 15, 18, 47]). It is clear today that the efficient implementation of these tasks may be achieved only in the future. A number of administrative and institutional decisions of the past years have caused barely reparable damage to the former system of forest fire protection.

The essential prerequisite for creating an efficient system of forest-fire protection consists of finding a solution to the problem of preventing and extinguishing disastrous fires. This requires carrying out urgent institutional, organizational, and technical measures, i.e., the restoration of the state forest protection system that was practically abolished by the last Forest Code (2007); the concentration of all informational, organizational, technical, and other functions within the centralized federal agency, namely the Aerial Forest Protection Service; the development of an efficient vertical structure of the Aerial Forest Protection Service, i.e., number, allocation, and capacity of regional centers and creation of special personnel training centers struggling against disastrous fires; the creation of effective and mobile regional fire-fighting centers in federal districts, primarily in the Far East, Yakutia, and Eastern Siberia; the creation of an integral observation system, which would detect fire danger and offer a forecast that would include characteristics of vegetation, weather, and anthropogenic impact; ensuring a complete and quick correspondence of both forecasting and current fire information to the regional and local levels; the creation of special remote sensing groups for the online monitoring of small fires (<0.1 ha), with high frequency and spatial resolution of no more than 200 m under the high level of fire danger; the improvement and adaptation of appropriate techniques of prescribed burnings in order to decrease the amount of CVMs; the implementation of improved operational methods of forecasting the weather and fire spread, as well as organizational and technical schemes of fire suppression, etc.; the adaptation of appropriate system of satisfactory and timely financing of measures for forest-fire protection [1, 14, 15, 47]. It is clear that this program may be efficiently implemented only with the continuous and successful raising of people's awareness.

CONCLUSIONS

The assessment of consequences for the direct and indirect effect of climate change on the Russian forests and the WRs depend both on the reliability of current forecasts and the regimes of forest management, especially on improving the forest-protection system. Forecasts based on the Atmospheric General Circulation Models suggest that the negative influence of climate change on forest ecosystems in Russia will significantly outweigh the positive impact on a national scale. Apparently, from the second half of the present century onwards, a considerable part of forests in Russia will remain in critical condition, unless a scientifically proven large-scale program aimed at adapting Russian forests to climate change is developed and implemented.

The creation of an efficient system of forest fire protection represents a crucial component of adaptive forestry and, therefore, constitutes an essential prerequisite for transition towards a sustainable forest management in Russia. Clearly, the implementation of this system is closely intertwined with other sectoral and cross-sectoral administrative, social, economic, and ecological problems related to the transition of the Russian forest sector to sustainable development, as well as with other issues of national and global levels. The problem of Russian forests on permafrost is one of a global importance. If the expected warming becomes a reality, the carbon emissions in this area will be almost three times as much as the current emissions from tropical deforestation by the end of the century. A considerable part of these emissions will be represented by methane, which will significantly affect the earth's climate system. At the same time, it is quite difficult to find a radical solution for controlling the process of permafrost thawing. Adapting special regimes of forest management on permafrost areas is one possible solution. Larch forests that represent a major forest formation on the areas underlain by permafrost possess a more efficient permafrost protection function than other classes of land cover in high latitudes, but this requires a minimizing disturbance of forest cover and efficient forest fire protection (for example, [7]).

So far, considerable areas in high latitudes have been actively developed for industrial purposes. This process has a pronounced adverse affect on ecosystems and the environment outside industrial facilities, the physical destruction of landscapes, and a change in the hydrological regime of territories due to the influence of infrastructure, pollution of atmosphere, water, and soil. All this considerably enhances the negative effect of climate change on forests. Therefore, a new concept of human attitude towards northern ecosystems and, in particular, forests, shall be developed.

While preparing the present paper, we used forecasts recognized by IPCC. There are other estimates that do not fully support the anthropogenic theory of contemporary warming (for example, [6]). Although the alternative point of view is not supported by substantial scientific evidence, unlike modern climate models, there is a nonzero probability of different climate scenarios than those forecasted by the IPCC. Technically, it does not deny the general ideas considered above, but creates additional requirements to the strategy and scientific grounds of adaptive forestry as a whole and forest fire protection in particular. We need a systematic approach that would minimize total losses if climate scenarios different those forecasted come to fruition.

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