Forest fires as a component of natural ecodynamics

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This review of issues concerning forest fires (mostly natural fires) includes the analysis of the conditions and scales of forest fires and their effect on the environment, showing itself in changes in the underlying surface properties and surface processes, as well as variations in the atmospheric chemical composition. Particular emphasis is placed on the effect of forest fires on the carbon cycle and the role of forest fires as a factor of environmental dynamics.

Introduction

Forest fires regularly arising in different regions of the globe attract considerable attention as natural disasters causing serious economic damages.[1–52] The problem becomes even more pressing with the increase of biomass burning in low latitudes. The role of natural fires as a factor of ecosystem dynamics is obviously underestimated. Therefore, already at the early stage of development of the methods for remote sensing of the environment, much attention was paid to development of, first, airborne and, then, space-borne techniques for monitoring of forest fires.[5,6] Keeping in mind that the issues of forest fires have been paid a detailed consideration in the recent papers,[3,32] in this review, we discuss only the newest results.

Forest fires are not only disasters, but also important factors of local, regional, and even global ecodynamics, for example, due to emissions of greenhouse gases and aerosol into the atmosphere. According to the available estimates, they are sources of about 30% of tropospheric ozone, atmospheric carbon monoxide and dioxide. Atmospheric emissions of aerosol attributed to forest fires can significantly affect the microphysical and optical characteristics of the cloud cover (and, consequently, the climate). The satellite observations of Indonesia have demonstrated, for example, that the atmospheric smokes connected with long-term fires have resulted in suppression of precipitation, that favored a further development of fires. In this context, Ji and Stocker[25] have performed a statistical processing of the Tropical Rainfall Measuring Mission (TRMM) fire products as well as the Total Ozone Mapping Spectrometer (TOMS) aerosol index products for a period from January 1998 to December 2001 in order to analyze the annual, seasonal, and interannual variability of global land fires. The fire behavior in this period manifested a strong annual cycle of land fires in Southeast Asia with a peak in March and in Africa and North and South America with a peak in August. The data analysis also indicated interannual variations in Indonesia and Central America correlated with the 1998–1999 El Niño–Southern Oscillation cycle.

The global atmospheric aerosol variability evidently correlates with natural fire incidence and variations over these regions. However, in southwestern Australia, intense fires, recorded in TRMM data, were not accompanied by formation of smoke layers (TOMS data). Excluding the Australian region, the coefficient of correlation between the fire incidence and TOMS aerosol index is about 0.55. Statistical analysis of data through calculation of empirical orthogonal functions (EOF) has shown a contrast between the Northern and Southern Hemispheres and intercontinental transfer of aerosol produced by fires in Africa and America. This analysis also identified 25–60 diurnal intraseasonal oscillations superimposed on the annual behavior of fire incidence and aerosol content. Some similarity was found between the intraseasonal variability of fires and Madden–Julian oscillation dynamics.

1. Minor gaseous constituents

In the context of investigation of forest fires as a factor affecting the environment, a particular attention was focused at the monitoring of emissions of various chemically and optically active minor gaseous constituents (MGC) into the atmosphere.

In 1998, the boreal forests have been burnt out at vast territories of Russia and North America.[26] According to the official statistics, fires covered the territory of about 4.8 million ha in the boreal forests of North America (Canada and USA) and 2.1 million ha in Russia (the processing of satellite observations has shown that the fire territory in Russia might be much more significant, covering 9.5–11.5 million ha). In summer, the burning biomass under dry weather conditions causes voluminous emissions of chemically and optically active minor gaseous constituents, which considerably (and specifically) affect the chemical processes and radiative transfer in the atmosphere.

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The earlier results have shown that the global MGC emissions from the burning biomass achieve 3800–4300 TgC/yr with a very small contribution from fires in boreal forests (23 TgC/yr or 0.6%). However, such estimates are rather contradictory. Thus, for example, for carbon monoxide emissions due to forest fires in the latitudes higher than 30°N, the estimates of 50 TgC/yr (~ 6% of global emissions) and 121 TgC/yr were obtained. The methane emissions were estimated as 0.9 TgC/yr (~ 3% with respect to the global methane emissions from the burning biomass).

Kasischke and Bruhwiler[26] have analyzed the observation data on the boreal forests damaged by fires in five different regions of North America and Russia in 1998 to assess the total carbon release due to CO_2, CO, and CH_4 emissions. Different levels and categories of biomass, as well as different proportions of the consumed carbon were considered for each of the five regions (including bogs in the Russian Far East and steppes in Siberia). Two different ratios of contributions from burning and smoldering were included in the model.

Boreal forest fire emissions for 1998 make 290–383 Tg of total carbon, 828–1103 Tg of CO_2, 88–128 Tg of CO, and 2.9–4.7 Tg of CH_4. The higher estimate represents 8.9% of total global carbon emissions from biomass burning, 13.8% of global CO emissions, and 12.4% of global CH_4 emissions from forest fires. The contribution of fires in Russia makes 78% of the total emissions (the share of North America's fires is 19%). Different assumptions regarding the ratios between contributions from burning and smoldering resulted in small changes in the estimates (< 4%), although in two cases these changes were higher (6% and 12%). In the fall of 1998, peatland fires in the Russian Far East contributed up to 40 Tg of carbon to the atmosphere. The combined seasonal CO emissions from forest and peatland fires in Russia are consistent with anomalously high atmospheric emissions of CO observed at Point Barrow, Alaska. Of particular interest is the indirect effect of forest fires on soil respiration in high latitudes, where carbon-rich soils in permafrost zones are located. The fire-induced soil warming must enhance the respiration processes and, thus, favor the intensification of CO_2 emissions into the atmosphere for the 10-year post-fire period.

2. Statistics of forest fires

Fires were the dominating factors affecting the Canadian forests, starting from the last ice age. For giant Canadian forests, the fires governed the processes, which were of crucial importance for the existence itself of such species of the primary forest flora, as pine, spruce, and aspen, and were an important factor of the forest landscape diversity, affecting its energy exchange and biogeochemical cycles. Physiognomy of Canadian forests, closely related to the fire regime, requires the appearance of periodic powerful fires, determining stand replacement. The characteristics of the natural fire regime are the fire repetition, scales, intensity, seasonality, and type. The frequency of fires in Canadian forests affects the dynamics of forest life cycles. The fire scales determine the spatial inhomogeneity ("spottiness") of the forest stand, as well as affect the effective regeneration intervals. The widely variable (depending on the types and mass of wood, topography, and weather conditions) fire intensity characterizes the energy released during burning. The season, when a fire occurs, is a key factor of post-fire succession evolution, because it affects the fire intensity, as well as the post-fire structure of ecosystems and landscapes. The fire type is characterized by participation of different stand and litter components in the burning and depends on weather conditions. The measure of the fire intensity is the degree of wood and top humus consumption during the fire.

Stocks with co-authors[44] have discussed a Large Fire Database (LFDB), including information on fire location, scale, cause, and actions for fire suppression, which has been developed for registering all fires larger than 200 ha for Canada for the 1959–1997 period. The LFDB represents only 3.1% of total Canadian fires during this period. The remaining 96.9% of fires were suppressed before reaching 200 ha in size. Such fires cover ~ 97% of the total area burned out and are of interest for spatial and temporal analysis of forest fire impacts on ecosystems.

Annually, fires in Canada take place at about 2 million ha, although in some years more than 7 million ha are covered with fires. Ecozones in the boreal and taiga regions experienced the greatest fire impact, about 0.7% of the forested land burn out annually. Lightning fires predominate in the northern Canada, causing 80% of the fires registered by LFDB. Large fires, although small in number, contribute substantially to the area burned, particularly, in the boreal and taiga regions. The Canadian fire season runs from late April to August, with the most damage in June and July primarily due to lightning fire activity in the northern Canada. Close to 50% of Canadian territories affected by fires are not properly documented because of their remote location. Therefore, the LFDB is annually updated and replenished with retrospective data to estimate the long-term trends.

The global climate warming has attracted the attention to the possible variation of the global lightning activity as a fire-risk factor. According to the earlier data, at any time, on the average, 1800 thunderstorms occur on the globe, and every storm is accompanied by 200 lightning flashes an hour (or 3.3 flashes a minute). The mean global frequency of flashes is 100 flashes/s (the processing of the data of various satellite observations gave the estimate of 22–65 flashes/s).

Christian with co-authors[14] have discussed the observations of lightning flashes conducted with the Optical Transient Detector (OTD) installed on the MicroLab-1 satellite that was launched into a 70° inclination low Earth orbit in April 1995. Given the orbital trajectory of the satellite, most regions of the Earth are observed by the OTD more than 400 times during a 1 year period, and the average duration of each observation is 2 min. The OTD instrumentation allows detecting lightning flashes, which occur within its 1300×1300 km^2 field of view under day and night conditions.

A statistical processing of the OTD lightning data reveals that nearly 1.4 billion flashes occur annually over the Earth, that corresponds to 44 ± 5 lightning flashes per second (both intracloud and cloud-to-ground), which is well below an earlier estimate of 100 $\mathrm{fl \cdot s^{-1}}$. The OTD measurements were used to construct lightning frequency maps for different seasons. Analysis of the maps confirms that lightning flashes occur mainly over land, with an average land/ocean ratio of ~10 : 1. The 30°N–70°S latitudinal belt accounts for about 78% of lightning flashes. Most intense year-round regime of lightning flashes shows the Congo basin, where the mean annual flash frequency is 80 $\mathrm{fl \cdot km^{-2} \cdot yr^{-1}}$ (Rwanda), that corresponds to the flash density of central Florida (USA). The high year-round lightning frequency is a characteristic of the northern Atlantic and western Pacific Ocean basins, where the atmospheric instability is produced from the cold air advection over the warm ocean surface. Lightnings are less frequent in the eastern tropical Pacific and Indian Ocean basins where the atmosphere is warmer. A peak of lightning frequency in the Northern Hemisphere falls on summer, while tropics are characterized by a semiannual cycle.

3. Forest fires in Alaska

Very substantial program of studying forest fires and their role in ecosystem dynamics for the Alaska region has been conducted.

The reaction of boreal ecosystems to possible future climate warming is significantly governed by the dependence of the forest fire and green cover dynamics on the climatic conditions. The fire frequency is an important factor determining the evolution of high-latitude forests at the level of ecosystems. The analysis of meteorological observations revealed a distinct correlation between the weather conditions (for example, air temperature and precipitation) and the forest fire frequency and intensity. A consequence of the current global climate warming is an increase in the fire intensity and duration.

For purposes of retrospective studying of the spatiotemporal variability of fires in boreal forests of the Kenai Peninsula and interior Alaska, the charcoal and pollen analyses were conducted,[37] which have shown the charcoal accumulation for the last 1000 years in the two regions under consideration to be low at somewhat higher level in central Alaska. An exception to this general pattern was the period of the post-European population of the Kenai Peninsula, where a 10-fold charcoal accumulation took place, which reflects possible increase of fires of the anthropogenic origin.

The Holocene charcoal and pollen data from Dune Lake (Central Alaska) indicate a low fire occurrence during the period from 9000 to 5500 (yr BP) for birch–white spruce–alder (*Betula–Picea glauca–Alnus*) community and high fire occurrence for black spruce (*Picea mariana*) upon its dominating abundance after 5500 yr BP. The increase of fires probably resulted from the change to more fire-prone black spruce forests. For the past 5500 yr BP, two distinctly seen fire regimes took place. The period of 5500–2400 yr BP is characterized by frequent fires, with a fire return interval of 98 years. Fewer fires, with a fire interval of 198 years, characterize the period after 2400 yr BP. Important factors of the nature-dependent dynamics of forest fires are the wood-pulp accumulation, as well as structure and species composition of the stand.

Soils of boreal forests are among ecosystems having the highest carbon density and contain about 1/4–1/3 of all soil carbon (200–7500 GtC). During the last 15000 years, the low winter temperature, annual moisture deficit, and the frost soils restricted the decay rate of organic matter, which caused accumulation of organic substances on the forest underlying surface. In the central (interior) Alaska, the highest rate of carbon accumulation is attributed to black spruce characterized by a low productivity and low rate of biogenic cycles. The combination of the low temperature, moisture-saturated surface soil horizons, and low quality of the litter results in restriction of organic decay in the litter and moss, which determines the intense accumulation of carbon and biogenes in organic layers. The rate of carbon accumulation in the mature black spruce of the Canadian boreal forests is 0.1–0.3 million gC/ha per year.

Soils in northern forests and wetlands can accumulate about 0.70 Gt carbon per year. For northern landscapes, forest fires are among the main factors regulating the carbon accumulation and release at the level of ecosystems. In addition to the direct emissions of carbon in the process of burning, the post-fire changes of the soil temperature and humidity, as well as chemical processes are the potential factors accelerating the organic decay in the post-fire period, resulting in emission of great amounts of accumulated carbon into the atmosphere. Since these losses are not immediately balanced through the carbon uptake for formation of the primary productivity (PP), the increased rate of decay causes a loss of carbon by ecosystems during the first after-fire year. However, for longer periods, the mobilization of soil biogenes due to permafrost thawing, ashes depositing, and changing the thermal and water regimes of soil can provide for more favorable conditions for plant growth, increase of the net primary productivity (NPP), and the carbon ingress into soil.

Finally, the ecological significance of carbon losses in the burning processes and the post-fire organic decay depends on the time periods, during which the plant communities are restored after destruction. Years and decades after a fire are needed to balance the carbon losses and uptakes. Over thousands years the northern soils achieve the dynamic equilibrium after forest fire impacts.

Based on the data on the 140-year after-fire evolution of the black spruce, O'Neil, Kasischke, and Richter[39] evaluated timescales of action of the disturbing impacts. Depending on the forest age, the mean rate of the CO_2 flow into the atmosphere was from 0.12–22 MgC a year. During the same time period, organic soil horizons sequestered carbon and nitrogen at rates of 0.28–0.54 MgC/(ha·year) and 0.0076 MgN/(ha·year), respectively. The mass balance modeling has shown the post-fire changes in root and microbial respiration to determine soils as a net source of carbon during the 7–15 year post-fire period, releasing from 1.8 to 11.0 MgC ha^{-1} to the atmosphere (12.4–12.6% of the total soil organic matter). These estimates are of the same order of magnitude as carbon losses during combustion and suggest that current models may underestimate the effect of fire on carbon emissions by a factor of 2.

The high-latitude ecosystems occupy about 22% of land surface and involve about 40% of global soil carbon, whose content must be sensitive to climate changes. Among all Earth's biomes, boreal forest is the largest carbon reservoir, and the most part of the forest is "underlaid" by the permafrost, whose dynamics is determined by the cycles of degradation (thermokarst formation) and aggradation. These cycles are closely related to forest fires, which form the major disturbance acting on the boreal forests. The fire-induced permafrost thawing results in significant changes of the soil temperature and humidity conditions and, correspondingly, in changes of the soil carbon reservoir in ecosystems of boreal forests.

In the 1960s, the fire impact on boreal forests was more significant than earlier. For the last 20 years, the burned area of the boreal forests in North Canada has almost doubled. For the past century, the surface temperature in the boreal and arctic regions of Alaska increased by 2–4°C (in particular, by 1–2°C for the last decades). The climate warming in Alaska for the last decades is a part of the warming observed all over the northwest of North America. Now permafrost warming takes place in Alaska.

Some data indicate that natural fires can be the cause for the climate-warming trend in North America, though, of coarse, the inverse dependence of the fires on the climatic conditions exists as well. Estimates show that the global climate warming, which can be induced by the CO_2 concentration doubling, is able to cause a 40% increase of the burned area in boreal forests. In its turn, a change of the fire conditions in the boreal forests affects the formation of the global carbon cycle, changing the spatial structure and conditions of functioning of boreal ecosystems. To assess the effect of the forest fire disturbances on the carbon cycle, it is necessary to use large-scale models of the land biosphere with the allowance for the processes determining the soil temperature and humidity conditions, as well as the hydrogeological and biogeochemical dynamics of the boreal forest ecosystems.

Zhuang with co-authors[52] have proposed a model capable of simulating the above-mentioned and other processes to analyze the dependence of the carbon budget of boreal forests on changes in the atmospheric CO_2 concentration, characteristics of climate and forest fires. The ability of the model to simulate principal regularities in the primary production and ecosystem respiration was verified through comparison with observation data on the mature black spruce ecosystem in Canada; and the age-dependent pattern of the simulated vegetation carbon was verified with the inventory data on the growth of black spruce forests in Alaska.

The model was applied to reconstructing the post-fire chronosequence in interior Alaska. The comparison between the simulated and field-based temperatures estimates for the growing season (May to September) of 1997 has shown the model to accurately restore monthly temperatures at 10 cm depth ($R > 0.93$) for control and burned stands. Similarly, the simulated and field-based estimates of soil respiration for control and burned stands well correlated ($R = 0.84$ and 0.74, respectively). The calculated and observed decadal-to-century-scale changes of soil temperature and carbon well correlated as well ($R = 0.93$ and 0.71 for soil temperature at 20- and 10-cm depths; $R = 0.95$ and 0.91 for soil respiration and soil carbon, respectively). The simulation has shown the sensitivity of carbon dynamics to fire disturbance to be influenced by a number of other factors. These factors include the nitrogen fixation, growth of moss, changes in the depth of the organic layer, soil drainage, and fire severity.

The boreal forests account for about one third of carbon of all continental ecosystems. The high-latitude ecosystems are especially sensitive to climate changes, which can be caused by variations of giant carbon reservoirs contained in the northern soils characterized by the presence of permafrost. The northern boreal forests, making up about 35% of all global forests, contain about 66% of the global soil carbon. Since the boreal forests take up atmospheric carbon dioxide and are characterized by a slow decay of the litter, they function as carbon sinks. Fires, whose appearance significantly depends on the climate conditions, form the major disturbing effect on the boreal forests. Therefore, climate changes imply changes in the forest fire regime.

Under fire conditions, a considerable amount of CO_2 and other trace gases (TG), including greenhouse gases (GG) is emitted into the atmosphere. Thus, the fire regions are the sources of carbon. To estimate the influence of forest fires on emission and reservoirs of GG, CO_2, CH_4, and N_2O fluxes were measured before and after fires at the Caribou-Poker Creek Research Watershed (CPCRW) research station, interior Alaska, in the summer seasons of 1998, 1999, and 2000. In the period from 8 to 15 July 1999, the FROSTFIRE burning experiment was executed in a typical boreal forest. The forest fire resulted in almost 50% decrease of the soil CO_2 and N_2O emissions.[27] On the contrary, CH_4 flux from the soil increased by 7–142%, suggesting that the forest fire plays an important role in accelerative thawing of the frozen soil, and subsequent release of CH_4 from permafrost. Most part of CH_4 was oxidized in the soil after the fire; however, some portion was released from the soil during the maximal permafrost thawing at the end of August 1999 and September 2000.

Relationships between the pre- and post-fire fluxes of trace gases and soil temperature show good exponential correlations, indicating that soil temperature is one of the factors determining the TG fluxes from boreal forest soils. Also, the higher post-fire soil temperature may result in the enhanced diffusion of CO_2, CH_4, and N_2O between the atmosphere and the forest soils due to enhanced microbial activity and the increased TG fluxes from burned black spruce stand soils.

In order to understand the influence of moss and lichen mats on the black spruce stands, Kim and Tanaka estimated their net respiration through light and dark chamber measurements.[27] The post-fire net respiration made 42–58% of the pre-fire one. Therefore, the net respiration by moss and lichen layers was responsible for one-half of total soil CO_2 emissions. The maximum rate of carbon flux due to moss and lichen mat respiration in the black spruce forests of central Alaska was 0.018 ± 0.009 GtC/yr, which is an important source of CO_2 for the boreal forest atmosphere. The post-fire soil respiration can be attributed only to contribution of roots and microbes. Estimates of the post-fire microbial respiration are almost three times higher than those calculated for the pre-fire conditions. This result indicates the post-fire condition to stimulate microbial respiration because of higher concentration of biogenics and substrates in the soil remainder, as well as the enhanced soil temperature. The microbial respiration can be estimated as 14.7 tC/ha in the burned black spruce stands over ten years after the fire. This suggests that the burned black spruce forest in central Alaska is a crucial source of the atmospheric CO_2.

The boreal forests form the second, in importance, biome on the globe, which determines their key role in formation of the dynamics of the global environment and, in particular, climate. Earlier, based on the numerical simulation, the climatic effect of the changes in the extension of the boreal forests due to the climate warming in the high latitudes has been analyzed, ignoring the changes in the spatial structure of energy exchange in the ecosystems of boreal forests. It was shown repeatedly that climate warming increases the probability of forest fires. But the associated climatic consequences of the changes in the land surface characteristics due to fires remain unstudied. Meanwhile, fires change many characteristics of ecosystems, which can significantly affect the energy exchange between the surface and the atmosphere. For example, the surface albedo decreases, and the loss of vegetation leads to the decreased evacotranspiration. Both these changes cause an increase of the surface temperature and the explicit heat flux (turbulent heat exchange). The loss of trees results in smoothing of the surface roughness, while the temperature increase leads to augmentation of the thermal radiation from the surface.

In this connection, in summer, Chambers and Chapin[12] conducted tower-based micrometeorological measurements at six recently burned black spruce stands aged between 0 and 14 years. The processed data have shown that, at first, fires cause a reduction of minimal albedo from ~0.09 to 0.06 followed by its rapid increase to 0.135 due to the successional vegetation increase. Under clear-sky conditions, near noon hours, the combined acting of the increased surface temperature and the change in the stand structure cause a reduction of the net radiation by 9.3% (~70 $W \cdot m^{-2}$) for the first decade of succession. The average daily net radiation fell by 5.5%. Near noon, the thermal flux onto the ground of burned territories doubled compared to neighboring unburned timberland, although the daily mean radiation increase was significant only for the first several post-fire years.

Reduced net radiation, enhanced incident thermal flux, and Bowen ratio reducing during the first decade of succession could reduce the midday thermal flux to 80 $W \cdot m^{-2}$ as compared to an unburned stand. Across the boundary between burned and damage-free forests, the contrast in the implicit heat fluxes and roughnesses could induce associated mesoscale circulations and augmented convection. Since the areas of the burned out forest frequently exceed 10^4 ha, fires can cause some local climatic changes. Given the abundance of fires throughout interior Alaska, these effects may contribute to the regional climate pattern.

4. Forest fires and carbon cycle

Coarse woody debris (CWD) are an important and scientifically interesting characteristic of all forest ecosystems – from boreal to tropical. CWD affect the biogenics cyclicity, humus formation, carbon accumulation, the frequency of forest fires, and the water cycle; they also form the habitat for heterotrophic and autotrophic organisms. Usually, the presence of dead trees and CWD is ignored when determining the carbon budget, though in the recent time the importance of these carbon reservoirs was noticed.

Bond-Lamberty with co-authors[11] examined the distribution and respiration dynamics of woody debris (WD) in a black spruce-dominated fire chronosequence in northern Manitoba, Canada. The chronosequence included seven stands that have been burned between 1870 and 1998; each stand contained separate well-drained and poorly drained areas. The authors aimed: (1) to quantify the distribution of WD by diameter and decay class; (2) to measure the evolution of CO_2 emitted by WD samples and to model the effects of moisture, WD decay size and degree on respiration, and (3) to estimate the annual WD respiration and to compute decay constants for each site under consideration.

The CWD biomass ranged from 1.4 to 177.6 $Mg{\cdot}ha^{-1}$, generally declining with the stand age. The most decayed WD had significantly higher moisture, lower density, and higher respiration rates comparative to the less decayed ones. The moisture level and decay class could be important predictors of respiration at the moisture below 43%. Above this level, moisture lost its importance, and stand soil drainage took on great significance: the WD respiration grew at drier sites. Year of burn was not important in the respiration models. Modeled annual carbon emissions from WD ranged from 0.11 to 1.92 $Mg\,C \cdot ha^{-1} \cdot yr^{-1}$. Modeled annual decay rates changed across the age sequence between $k = 0.01$ and $k = 0.06$. This means that an individual single-exponential decay model is not suitable for the whole data series under consideration. Calculating k directly from wood respiration measurements may be useful when analyzing its year-to-year changes.

The main conclusion is that woody debris are a significant carbon reservoir and a source of CO_2 for different landscapes (consequently, a factor of the annual carbon emissions), and their decay rate depends on time and the soil drainage. The models of ecosystems and carbon budget ignoring the presence of woody debris, thus ignore a significant component of the carbon fluxes, especially, in such regions as boreal forests, where fires are regular.

The assessment of the effect of the climate change on the cumulative net ecosystem exchange (NEE) of carbon dioxide, connected with the ecosystem dynamics in the Northern Hemisphere, gave a carbon value of about 1 Gt and higher. According to the IPCC Third Assessment Report, the anthropogenic increase of the air temperature in boreal forests must be higher in winter than in summer. It follows herefrom that the climate change will have a contradictory impact on NEE in the boreal zone, manifesting itself, on the one hand, in the increasing vegetation season and, consequently, in intensification of cumulative photosynthesis, and, on the other hand (which is possibly more significant), in the winter mitigation and intensification of the soil respiration. The latter is especially important, because in the boreal zone about 84% of carbon stock is concentrated in the soil organic matter.

In this connection, of significant urgency are combined studies of the effect of photosynthesis and respiration on the carbon budget of ecosystems, as well as the climatically determined seasonal and interannual variability of NEE in boreal forests. Many boreal ecosystems are carbon sources in winter and sinks in summer (during the growing season). Suni et al.[45] studied the interannual variability of cumulative net ecosystem exchange of CO_2 (NEE) and its connection with cumulative or average climatic variables during five growing seasons. The analysis was based on a 5-year-long time series of CO_2 flux measured from April 1996 to April 2001 in a Scots pine forest (southern Finland) by the eddy covariance technique. The onset of the ecosystem growing season was best indicated by the air temperature, and its end – by the day length.

The analysis of the observations has shown that forest is a sink of carbon in the presence of only slight interannual variability: during the four full growing seasons its uptake changed by 80 $gC \cdot m^{-2}$, ranging from 230 to 310 $gC \cdot m^{-2}$. The estimated winter release varied yearly between 60 and 90 $gC \cdot m^{-2}$. The interannual variation in seasonal (spring, summer, fall) carbon exchange ranged from 30 $gC \cdot m^{-2}$ in fall and spring to 80 $gC \cdot m^{-2}$ in summer.

The average climatic variables only partly explained the variability of the seasonal or growing-season cumulative NEE. Both the daytime and the nighttime CO_2 fluxes contributed markedly to the carbon exchange formation, indicating that photosynthesis and respiration have an equally important influence on NEE. The obtained results are indicative of a complex, as a whole, connection between NEE and climate.

Boreal forests are assumed to be a region of carbon sink. However, forest fires, characteristic of the forests, may transform them into the carbon source due to direct its emissions at burning biomass and indirect influences of fires on their thermal and water conditions, as well as on the structure and functioning of ecosystems.

For the last few decades, the frequency of fires in boreal forests increased and it can increase even further under conditions of the global climate warming. This must result in contraction of the time for recovery of ecosystems in the periods between fires, as well as to the intensified emissions of greenhouse gases into the atmosphere. Soil surface CO_2 flux (R_s) is the second largest carbon flux in boreal forests, which determines its role in formation of the global carbon cycle.

The magnitude of R_s varies under the effect of different processes: (1) fires result in partial liquidation of the green cover and reduce the surface albedo (the latter causes an increase of the surface temperature and the rate of decay of woody debris); (2) fires break the process of accumulation of the organic matter in soil and change the balance between the detritus intake and heterotrophic respiration (as a result of intake of a large amount of detritus); (3) fires change the succession and the species composition of plants, as well as the litter quality.

For better understanding of the effect of forest fires on the carbon cycle in boreal forests, Wang with co-authors[47] measured and modeled R_s for black spruce (*Picea mariana*) by the example of post-fire chronosequence for seven forest fires in northern Manitoba, Canada, for conditions of well and poorly drained soil. Their specific objectives were (1) to quantify the relationship between R_s and soil temperature for differently aged boreal black spruce forests, (2) to examine R_s dynamics along post-fire successional stands, and (3) to estimate annual soil surface CO_2 flux.

The CO_2 flux significantly depended on the class of soil drainage and stand age. It also positively correlated to soil temperature ($R^2 = 0.78$), but the results of numerical simulation significantly differed depending on the combination of the drainage class and stand age.

During growing season, the CO_2 flux was significantly greater from the well-drained soil than from the poorly drained one. Annual soil surface CO_2 flux for the 1998, 1995, 1989, 1981, 1964, 1930, and 1870 burned stands were 226, 412, 357, 413, 350, 274, and 244 $gC \cdot m^{-2} \cdot yr^{-1}$ from the well-drained ground and, correspondingly, 146, 380, 300, 303, 256, 233, and 264 $gC \cdot m^{-2} \cdot yr^{-1}$ from the poorly drained. Soil surface CO_2 flux during the winter (from 1 November to 30 April) varied from 5 to 19% of the total annual R_s. It seems that the smaller soil surface CO_2 flux in the recently burned stands than in the older ones was mainly due to the decreased root respiration.

In the considered fire chronosequence, soil surface CO_2 flux changed roughly twice at achieving maximum values before closing the tree zones, when soil was the warmest and both the surface and undersurface biomass accumulation took place. The observed decrease of the soil surface CO_2 flux in the case of older stands can be explained by the lower soil temperature, caused by accumulation of the heat-insulating organic matter and by other factors.

Boreal forests occupy the territory of about 14 million km^2 in the 50–70°N circumpolar latitudinal belt, which makes up about 10% of the global land surface. These forests contain a disproportionately large amount of soil carbon due to climatic conditions, which are unfavorable for decay of the organic matter. The mean annual temperature in the boreal forests is close to 0°C at poor soil drainage because of lowland domination. The features of the considered latitudinal belt are the prevalent permafrost and insulation of deep soil horizons from summer warming by moss and fine roots, which burn during forest fires, but recover in the following decades. This thermal insulation favors the permafrost preservation, which complicates the soil drainage and slows down the decay of the organic matter stored in the deep soil layers under the moss layer. The intensification of respiration at the sacrifice of deep layers measured in July and August 1996 achieved about 10 kgC/(ha · day). This intensification correlated with the temperature increase in the deep layers. Thus, the organic matter of the deep soil layers is characterized by a lability at a low decay rate because of the low temperature.

In connection with the above-said, Hirsch with co-authors[23] have analyzed the monitoring data on isotopic composition of soil respiration products. The results have supported the hypothesis that the deep soil respiration at the BOREAS Northern Old Black Spruce site is sensitive to soil thaw and that the most part of the CO_2 flow represents decomposition of the old organic matter, rather than simply the root respiration. During the summer of 1999, deep soil respiration was characterized by a linear dependence on the temperature at 50 cm depth, with a slope of 0.2 $kgC \cdot ha^{-1} \cdot d^{-1} \cdot °C^{-1}$. Late in the season, the respiration mainly depended on decomposition of the old soil organic matter (formed from the atmospheric CO_2 centuries ago).

Reliable measurements of the CO_2 exchange between different land ecosystems and the atmosphere are of high priority, because of the great attention focused at CO_2 as a greenhouse gas in the context of the global warming problem. The principal attention is given to the analysis of possibilities of the global carbon balance closure and estimates of the role of anthropogenic CO_2 emissions in formation of biogeochemical cycles. Such works are carried out, in particular, within the framework of such international programs as AmeriFlux (North America), CarboEurope, and FLUXNET, and the main role in the observations is played by the tower-mounted and airborne instrumentation in direct (correlation) measurements of CO_2 flux, as well as by laboratory measurements in cells and chambers (in the last case, the gas exchange for different plant parts (leaves, stalks, branches) and plants as a whole is studied).

Smith with co-authors[42] have discussed the results of quantitative comparison of measurements of net CO_2 fluxes on spatial scales: from branch and community to vast vegetation areas (tower and aircraft measurements). Principal attention was paid to the provision of data comparability at minimal samples in the case of local measurements. The effect of time inhomogeneity was taken into account through repeated measurements in identical days with two-hour intervals at high and low values of CO_2 fluxes (at different stages of the growing season).

Measurements of the CO_2 flux density ($\mu mol \cdot m^{-2} \cdot s^{-1}$) from a high elevation, sagebrush steppe community in southeastern Wyoming (USA) under conditions of high-land ecosystem were performed with different instrument systems (leaf cuvette and 1 m^2 community chamber for gas exchange measurements; tower and aircraft eddy covariance systems) at minimizing spatial and temporal variability. The degree of homogeneity in plant species composition, density, cover, and the amount of leaf area per unit ground area, as well as little topographic variability were measured at the intensive site and along the flight transect.

Flux measurements were compared on days with relatively high and low soil moisture availability.

Same-day, mean flux values between the four measurement systems ($4.0–4.6\ \mu mol \cdot m^{-2} \cdot s^{-1}$) over identical time intervals (09:00–11:00 hours) varied by a maximum of ±9% (23% maximum range). Ground-level measurements taken within ±1 day of flight measurements, varied by a minimum of ±7% (25% maximum range) of aircraft values. This difference increased curvilinearly to a maximum of ±31% (38% maximum range) for a 2-week separation between flight and ground-based measurements. Thus, under near-ideal conditions of topographic and vegetative homogeneity, temporal heterogeneity in the measurement regime of only a few days resulted in greater disparity in measured CO_2 flux density than occurred among the four instrument types.

5. Forest fires and climate

To predict the role of the land ecosystem dynamics in global changes, it is necessary to have the information, in particular, about main surface processes affecting the formation of climate. The understanding of the urgency of this problem has stimulated the development of numerical models accounting for corresponding feedbacks, which allow, in particular, reconstructing the effect of temperature and humidity fields on the exchange of trace gases between the atmosphere and surface with allowance for the varying surface properties.

Since the existing models ignored such significant factor as forest fires, Hinzman with co-authors[22] have undertaken the FROSTFIRE field research project to examine the impacts of weather and vegetation on the fire dynamics and the resulting effects of the fire on feedbacks based on the data of a man-made forest fire on the area of 970 ha of watershed in interior Alaska (near Fairbanks). This region is characterized by the presence of boreal (mostly spruce) forests and "spotty" (broken) permafrost. A detailed post-fire survey of the burned forest area has shown that although the fire was artificially ignited, its behavior and effects were similar to those of naturally occurring fires.

The spotty permafrost zones are among the regions most sensitive to global climate warming. These zones to a significant extent overlap with the circumpolar belt of boreal forests in the Northern Hemisphere. The thermal state of the permafrost in the considered zones is unstable, because the temperature is often close to −1°C or even higher. Spatial distribution of the permafrost strongly depends on such factors as types of landscape, soil, and green cover.

The most important factor governing the permafrost degradation or development is the presence and thickness of the surface organic soil layer. If this layer is removed, then the surface albedo decreases, and the thermal conductivity of the surface soil layer increases roughly from 0.2 to 1.0 W/(m · K). Fires in boreal forests significantly affect the thickness of the top organic soil layer. They are among natural components of the ecosystem dynamics. In the last half of the 20th century, the fire area in the North-American boreal forests increased from 1 million ha/yr (1950) to almost 3 million ha/yr (2000). The effect of fires on the forest ecosystems manifests itself in the change of the thermal and water balances of permafrost and invokes both short-term and long-term processes. The typical period of recurring fires in boreal forests varies within 29–300 years depending on the climate conditions and anthropogenic impacts. As to the short-term processes associated with the effect of fires on the humidity and thermal conditions of soil, they are relatively well studied. The fire is immediately accompanied by the increase of the soil humidity due to the reduced evacotranspiration, but in two years the soil humidity at the burned area sometimes reduces. The post-fire situation is characterized by a considerable redistribution of components of the surface thermal balance, in particular, due to decrease of the surface albedo and, consequently, increase of the absorbed short-wave radiation with the following increase of the explicit and hidden heat fluxes. This results in reduction of the radiative budget, but in increase of the heat inflow to the soil.

Using the observations of fire consequences (11 fire sites including two controlled burns) in interior Alaska, Yoshikawa with co-authors[51] have analyzed their effect on: (1) heat transfer to the soil surface due to thermal conductivity and convection; (2) removal of moss as a heat-insulation layer; (3) thermal balance; (4) soil humidity; (5) thickness of the active soil layer. Heat transfer by heat conduction to the permafrost was not significant during fires, but immediately after fire ground thermal conductivity can increase 10-fold and the surface albedo can decrease by 50% depending on the extent of burning out of the surface organic soil layer.

The thickness of the remaining organic layer strongly affects the permafrost degradation and aggradation. If the organic layer thickness is not reduced during the fire, then the active layer (the layer of soil above permafrost that annually freezes and thaws) does not change after the fire in spite of the surface albedo decrease. Any significant disturbance of the surface organic layer increases the heat flow through the active layer into the permafrost. Approximately 3–5 years after severe disturbance, the active layer thickness increases to such a degree that the layer does not completely refreeze during the following winter. This results in formation of a talik (an unfrozen layer below the seasonally frozen soil and above the permafrost). For example, in 1983, a thawed layer (4.15 m thick) was observed at the burned site. Model calculations show that if an organic layer of more than 7–12 cm thickness remains after a fire, then the thermal impact on the permafrost is minimal.

6. Ecology of forests

Forest fires strongly affect the ecology of forests, including the carbon cycle formation. Fires initiate new succession of the forest canopy and, thus, regulate the carbon accumulation determined by the primary productivity. In addition, fires affect the thermal conditions of the soil, which, in their turn, influence the soil respiration processes. Finally, a consequence of forest fires is their effect on the carbon cycle on the regional and global scales due to carbon emissions into the atmosphere and the following long-range transport. French with co-authors[20] have developed a model of emission to assess the variability in trace gas emission from several factors and to estimate the immediate impact of fire on the carbon cycle. The model was applied to calculation of emissions of three carbon-containing trace gases (CO_2, CO, CH_4) released during fires (1950–1999) in the boreal region of Alaska (area of 223 220 ha). The effects of two factors: the fraction of carbon consumed during fires and the ratio of flaming to smoldering combustion – were investigated in the model. The calculations have shown that an average of 4.5 teragrams of carbon (TgC) has been released annually over the past 50 years. Severe fire years can produce emissions as high as 38 TgC, and the minimal amount was 0.36 TgC in 1989. Wide interannual variations in emissions of total carbon and carbon-based gases are seen. The annual emissions of total carbon therewith almost totally depended on the burned forest area. The flaming/smoldering ratio significantly influenced the levels of CO and CH_4 emissions. These estimates show that natural fires in Alaska's boreal region over the second part of the 20th century have contributed a substantial amount of carbon-based gas to the atmosphere.

In June 1999, within the FROSTFIRE research project, the experiment was conducted with a man-made forest fire covering the area of 11 km^2 in interior Alaska (near Fairbanks), whose major objective was to study the effect of fires on ecosystems of boreal forests and to analyze the possibility of extrapolation of the results obtained on the regional scale. Formation of the post-fire secondary succession is the main process responsible for the change in the structure and species composition of a forest. A significant part of the observed changes in the thickness (density) of stand, live biomass, thermal properties of soil, carbon reservoirs and fluxes, as well as biogenics in ecosystems can be explained as the results of the long-term post-fire evolution.

Fastie with co-authors[19] have undertaken an attempt to reconstruct the history of natural fire on the studied area, using a diversified ground information on the forest state and aerial photographs. The obtained results have shown that between 1896 and 1925, stand-destroying natural fires affected 93% of the regional watershed and 47% of the selected control watershed. No evidence for severe fires during the whole 19th century and later in the 20th century was found. The ignition of some fires may be associated with the early 20th century mining activity. There is no evidence that any part of the studied area has been burned by more than one severe fire in the past 200–250 years, suggesting some overestimation of the fire frequency. In birch forests and black spruce forests the recovery of their pre-fire species composition takes several post-fire decades. However, south-facing birch forests show no evidence of the recovery over 200 years after fire.

The application of the gas chromatographic technique to analysis of air samples for trace gases has opened new possibilities. They were used, in particular, to measure the concentrations of tens of various organic compounds (alkanes, alkenes, alkines, and aromatic trace gases) and helped to find a stable increase in concentrations of many trace gases for the last two decades. Now, a research team of the University of California, Irvine (UCI) performs the monitoring of about 100 volatile organic compounds using both ground-based and airborne samples. Choi with co-authors[13] have discussed the results of analysis of hydrocarbon and halocarbon measurements collected during the second airborne Biomass Burning and Lightning Experiment (BIBLE-B).

To determine the concentration of compounds divorced from each other, the observation data have been processed using the principal component analysis (PCA) in order to quantify and understand the TGC as products of biomass burning and lightning discharges, taking into account their chemical transformation in the atmosphere of the western edge of the Pacific. Urban and industrial tracers (e.g., combustion byproducts, chlorinated methanes and ethanes, xylenes, and long-chain alkanes (to C_7)) dominated in the observed variability along the aircraft courses. Pentane enhancements reflected vehicular emissions.

As a rule, ethyl and propyl nitrate groups indicated oxidation under nitrogen oxide (NO_x) rich conditions and hence urban or lightning influences. Over the tropical ocean, methyl nitrate grouped with brominated compounds and sometimes with dimethyl sulfide and methyl iodide. Biomass burning signatures were observed during flights over the Australian continent. Strong indications of wetland anaerobics (methane) or liquefied petroleum gas leakage (propane) were conspicuous by their absence. One of the most important results of the aircraft experiments was finding in the region under study of the TGC sources attributable to human activity.

7. Fires in savannas

Fires in savannas and substitution of savannas for farm fields or pastures result in short-term and/or long-term changes in the biogenics and carbon cycles. In this connection, from September 1999 through November 2000, Kisselle with co-authors[28] measured the soil–atmosphere fluxes of carbon monoxide (CO) in savanna areas of central Brazil (Cerrado) affected by fires to a variable degree. The studies focused on two vegetation sites covered with *cerrado stricto sensu (ss)* (20–50% canopy cover) and *campo sujo* (scrubland).

The vegetation under consideration was either burned every 2 years or protected from fire for 26 years. The CO emissions in transparent chambers varied seasonally, with highest fluxes during the late dry season and transition to wet season (August–October) and lowest fluxes late in the wet season (February–April). Daytime fluxes in the transparent chambers were always higher than in the opaque chambers. A diurnal behavior was characterized by negative fluxes (from the atmosphere to soil) at all nighttime measurements and positive ones at daytime measurements made with transparent chambers. Deposition velocities observed in the opaque chambers during the night fell in the 0.002–0.0014 $cm\ s^{-1}$ range, which is at the lower end of the range that has been observed in tropical, temperate, and high-latitude regions. No significant differences were found between the daytime annual average fluxes from unburned *cerrado* and unburned *campo sujo* sites ($160\cdot10^9$ and $190\cdot10^9$ $molecules\cdot cm^{-2}\cdot s^{-1}$, respectively).

Fires caused significant soil surface CO emissions in the burned *cerrado* plot. Measurements made 30 days after the fire showed the daytime CO production to be ten-fold higher than that of the unburned *cerrado ss* ($812.8\cdot10^9$ versus $76.8\cdot10^9$ $molecules\cdot cm^{-2}\cdot s^{-1}$). Post-fire CO emissions were greater than pre-fire emissions for both opaque and transparent chambers. This suggests that the fires created both photochemically and thermally reactive precursors. Removal of litter and dead plant material from plots in unburned *campo sujo* and a pasture dramatically decreased CO emissions. CO production in burned plots (using opaque chambers) was similar to previous measurements from Venezuelan and African savannas.

8. Stratosphere–troposphere exchange

The tropopause is usually considered as a barrier for mixing between the troposphere and stratosphere. Though sometimes "towers" of thick cumulus clouds penetrate into the stratosphere, volcanic eruptions are likely the most efficient mechanisms of matter intake from the troposphere into the stratosphere. However, analysis of results of recent satellite observations has revealed a relation between the anomalous aerosol layers in the stratosphere in 1998 and summer forest fires in the Northern Hemisphere. So, Fromm and Servranckx[21] have supposed that a severe convection plays a role in the troposphere–stratosphere transport (TST). An appearance of a similar situation in Canada in summer 2001 stimulated its detailed analysis, which resulted in unambiguous inference on creation of a widespread, dense smoke cloud in the upper troposphere and lower stratosphere (UT/LS) by a Canadian forest fire in May 2001 and the effect of explosive convection on the distribution of fire smokes. Thus, under certain weather conditions, the substantial transport of the matter from the planetary boundary layer into UT/LS can arise due to both vertical advection and the process of destruction of gravitational waves. This phenomenon likely arises quite regularly in the middle and high latitudes of the Northern Hemisphere. However, it is still unclear what heights can be achieved by a smoke cloud and what is its composition.

In connection with the discovered intake of the organic burning products into the upper troposphere and even the stratosphere, Andrianov with co-authors[1] have conducted numerical simulation of a "fire spout" arising sometimes in the atmosphere under the favorable weather conditions.

Conclusions

Analysis of information about forest fires demonstrates a diverse and contradictory nature of this phenomenon. On the one hand, forest fires are disasters of natural (and sometimes anthropogenic) origin causing serious material damage. On the other hand, fires are necessary components of the forest evolution, ensuring their renewal. One more important aspect of the fire activity is connected with atmospheric emissions of various trace gases and aerosols, which affect significantly the chemical and other atmospheric processes (in this context, the climatic effect of the fires caused by nuclear explosions in the atmosphere,[30] as well as the dynamics of the tropospheric ozone[31] are worth mentioning). The problem of heterogeneous chemical reactions on the particles of liquid-droplet (clouds) and solid aerosol deserves particular attention. The crucially important role of the cloud cover dynamics in the climate formation dictates a need in the detailed study of the complex interactions between the atmospheric (in particular, smoke) aerosol and clouds. From the climatic point of view, it is important to take into account not only the effect of natural fire consequences for climate, but also the reverse effect of climate changes on conditions of appearance of natural fires. Thus, we deal with a very complicated problem of understanding the interactive combination of diverse physical, chemical, and biological processes. The main way to solve this problem is to accumulate the needed observations and apply the technique of numerical simulation to the nature–society system. We are still at the very beginning of this way. An important step along this way is the EFEU project, which studies the impact of vegetation fires (natural fires, biomass burning, etc.) on the composition and circulation of the atmosphere. This project is described briefly in Ref. 50.

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