Post-fire ecological consequences within the drained site of the Great Vasyugan Mire: retrospective water-thermal regime and pyrogenic disturbance estimation

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Abstract. The aim of this research is to carry out an assessment of pyrogenic load after the fire event in 2016 within the drained site of Great Vasyugan mire (Bakchar bog, North-East part of The Great Vasyugan mire). Specifically, the objectives of this study were to: 1) perform a retrospective analysis of the water-thermal regime of the area under study according to monitoring data on the nearby site for estimation of development emergence of a fire-dangerous situation conditions; 2) determine the quantitative characteristics of vegetation and microtopography fire transformation based on field data; 3) estimate zone of contamination by combustion products and 4) estimate the hydrocarbons composition of mire and river water, peat and typical plants of the pyrogenic disturbed bog. The water-thermal retrospective analysis confirmed that in August 2016, the most favourable conditions for the emergence of a fire-dangerous situation were developed. The area of fire spread was 5.54 km², including within the mire of 4.44 km². The area of Zn and Pb pollution covers an area of 8 km, which is consistent with the prevailing wind direction and atmospheric deposition data for 2016. The zone of extreme pollution of heavy metal peat deposits is limited mainly by the zone of intensive burning of the surface, however, and beyond it, there was also a significant (2 times) Zn, Cd and Pb concentration (except Cu) increase, mainly due to the migration of elements with water flow. Carbon losses for the burned area of 1 square metre to a depth of 30 cm were about 3,800 gC/m². Against the background of a decrease in the content of n-alkanes, their share in the composition of peat lipids of the burnt area increases slightly, and among them the content of homologues C23–C25 increases, C29–C33 decreases and the CPI value decreases.

1. Introduction
In natural mires permanently waterlogged conditions prevent the complete decomposition of dead plant material, leading go the accumulation of carbon [1]. Interplay in gas exchange within the mires has played a major role in the regulation and maintenance of global climate. Disturbed drainage mires due to the lowering of the mire water level, become a source of carbon dioxide emissions into the atmosphere due to the activation of microbiological processes in the peat deposit [2]. In addition,
drainage of mires is the main cause of peat fires. Emissions associated with the drainage of peat lands and organic soil and peat fires potentially release 0.9–3 Gt of carbon dioxide to the atmosphere annually [3, 4]. The average carbon loss from peat to atmosphere is 3.2±0.4 kgf/m² due to the biomass combustion [5].

Fires within the mires lead to changes in their vegetation cover, water-physical properties of peat deposits, transformation of biogeochemical cycles of elements, contribute to the removal of a significant amount of pollutants (heavy metals, polycyclic aromatic hydrocarbons, etc.). This problem is relevant both for the Russian Federation and for the whole world [6, 7]. The reason for the significant increase in fire activity since the second half of the 20th century was the growth of cities and the increase in anthropogenic load [8]. At the same time, the observed climate changes, which are associated with a significant increase in air temperature and a change in the nature of atmospheric circulation [9], lead to an increase in the frequency of dry fire periods.

The aim of this research is to carry out an assessment of pyrogenic load after the fire event in 2016 within the drained site of Great Vasyugan mire (Bakchar bog, North-East part of The Great Vasyugan mire). Specifically, the objectives of this study were to: 1) perform a retrospective analysis of the water-thermal regime of the area under study according to monitoring data on the nearby site for estimation of development emergence of a fire-dangerous situation conditions; 2) determine the quantitative characteristics of vegetation and microtopography fire transformation based on field data; 3) estimate zone of contamination by combustion products and 4) estimate the hydrocarbons composition of mire and river water, peat and typical plants of the pyrogenic disturbed bog.

2. Materials and Methods
The objects of field research are three sites (point 1, 2, 5) within the burnt area, one unburned site within the main contour of the fire (point 3), two background sites at 100 m from the contour of the fire (point 4) and on the pristine bog and the site of long-term monitoring at 8 km (point 6) (figure 1).

The retrospective analysis of the water-thermal regime of the drained bog was carried out using the monitoring data on the nearby site preserved after the fire and data of Russia Hydrometcenter. Mire water levels data were obtained using an Autonomous differential pressure sensor (IMCES SB RAS). The level of mire water was measured in centimetres relative to the average surface of the mire with an interval of 4 hours. Data on precipitation amounts were obtained using the sensor RainCollectorII (Davis Instruments, USA) installed within the mire. The data of Hydrometcenter on the annual amounts of precipitation and average annual air temperature at the meteorological station in Bakchar village for the period of 1970–2017 were used. The analysis used data of air temperature
measurements at two levels of 0.1 and 2 m, and in the peat deposit to a depth of 3 m, obtained from automatic monitoring systems (IMCES SB RAS) installed within the mires. Sensor DS18B20 was used for temperature measuring.

Field geobotanical studies included an assessment of the intensity and fire damage area to each layer of vegetation and the characteristics of vegetation restoration. The assessment of the proportion of surface burnout and transformation of the microlief was carried out by total station survey of 25 m² model sites with a step of 0.5 m in 2017. The plant samples were taken along the transects from 5–10 registration sites on the tussock and in the depression to determine the production of grass-shrub and moss-lichen layer and direct calculation of the loss of organic matter during the fire. Underground production of grass and shrubs identified in the growth of roots, rhizomes and tillering nodes of the current year.

The assessment of the pollution zone was carried out by analysing the content of Cu, Pb, Zn and Cd in atmospheric deposition using the methodology of the United State Geological survey, the content of Cu, Pb, Zn and Cd and hydrocarbons in peat and plants, mire and river waters. Sample analysis of the content of Cu, Pb, Zn and Cd, produced after the pre-acid decomposition method of mass spectrometry with inductively coupled plasma (ICP-MC) in the Chemical-analytical centre "Plasma". Determination of the composition and content hydrocarbons in mire waters, peat and plants w carried out by IR and chromato-mass spectrometric methods at the Institute of petroleum chemistry SB RAS.

3. Results and Discussion

3.1 Retrospective analysis of water-thermal regime

The analysis of the long-term period data (1970-2017) showed a statistically significant increase in mean annual air temperature in the atmospheric surface layer at the nearest meteorological station at Bakchar village. Significant increases in the annual amounts of precipitation is not detected. A retrospective analysis of the water-thermal regime allowed us to attribute 2016 to the average annual air temperature and the amount of precipitation for the year (figure 2), but the summer period was characterized by extremely high temperatures.

The summer of 2016 was characterised by warm and hot weather in some periods, with heavy rainfall and thunderstorms [10]. The average air temperature (June–August) in the Tomsk region averaged 17–19 °C, which is higher than the climatic norm by 2–3 °C. Similar warm summer was observed in 1965 and 2012 over the past 65 years. The hottest months of the year were June–July, when the temperature rose to 30–35 °C, and the average monthly air temperature varied in the range of 18.6–19.7 °C. The air temperature decreased to 16.8 °C and 10.6 °C, respectively, in August and September, mainly due to a decrease in night air temperature. However, during the day, the air warmed up significantly, and the maximum temperature in August was 33.3 °C and in September,
28.2 °C. High temperatures and very little rainfall, only 5 mm per month, remained until mid-September which contributed to the preservation of the fire situation.

The maximum air temperature within the drained mire at an altitude of 2 m was 35 °C, and within the natural mire, 33 °C, in summer 2016. The analysis of the data showed a significant increase in the summer temperature of the peat deposit of the drained mire (site 4) in comparison with the pristine mire (site 6). Warming of peat deposits is observed with a shift to July–August, and the maximum temperatures in the layer 0–10 cm were noted: site 4—28 °C and in the site 6—23.5 °C, in July.

Thus, the drained mire is characterised by more contrasting temperature conditions, which are determined by the lower heat capacity of the peat deposit, significant amplitudes of temperature fluctuations and a rapid reaction to changes in air temperature.

Analysis of the dynamics of mire water levels showed that drained site levels values are statistically significant lower (5–17 cm) in comparison with the natural site. The average mire water level within drained site was -30 cm below the mire average surface in 2016, and the amplitude of the oscillation was 44 cm (figure 3).

3.2 Area of fire spread and pyrogenic load classes

The area of fire spread was 5.54 km², including within the mire of 4.44 km². The burning lasted during August–October 2016. The spread of fire in the Eastern and North-Eastern parts is limited by the main channels, in the Southby the boundary of the drainage network and in the Northby the road. In the central part of the allocated area, it is not subject to pyrogenic load, and the contour of which coincides with the boundary of moister hummock-hollow and grass-moss mire areas (figure 4). Three classes of pyrogenic load differentiate which differ damage of the soil and vegetation cover based on Landsat 8 satellite data and field research materials. Sites differ in the type of damage to the soil and vegetation cover: 1) areas with completely burnt vegetation (1.84 km²); 2) areas with partially burned vegetation (2.34 km²) and 3) the sites of soil fire in forests and swamp (1.16 km²). The spatial
distribution of the area’s first and second pyrogenic load classes have a spotted pattern, and often the sections of first class are characterised by an elongated shape and stretch along the drainage channels. Partial burnout of vegetation is characterised for interchannel spaces. The third class of the pyrogenic load is located in the Northern and Western parts of the pyrogenic area and corresponds to forests and swamp within the marginal part of the mire (figure 5).

3.3 Microtopography and vegetation transformation of post fire site

First class pyrogenic load is characterised by the complete burn-moss and herb-dwarf shrub layers. Tree trunks and crowns of trees are completely charred. Complete burning of moss hummock led to the alignment of the positive forms of microtopography, with the formation of decreases due to the burning of the moss and the top layer of peat with a capacity of about 5 cm, which is most pronounced around the trunks of burnt trees. The indicators of the surface fragmentation are close to the values typical for the drained site, but unlike them, the mosaic of the surface does not form the growth of the accumulative forms of the microtopography due to the increase in the productivity of the vegetation cover, but rather the formation of depressions as a result of the burning of moss and peat, in particular around the tree trunks (table 1).

The area corresponding to the second class of pyrogenic load is characterised by partial burnout of the surface within 40–60 %. Trees burned on all forms of microtopography, and living specimens are not preserved. The transformation of the microtopography occurred mainly due to the burnout of negative forms and slopes of moss hummock. The proportion of burning on positive forms was 13%, and on negative 62%, of the surface. Increasing of all parameters of microtopography fragmentation was on average 36% compared to natural areas and was by 22% in comparison with the areas of drained sites are marked. In the distribution of heights relative to the average surface there was a significant decrease in the proportion of heights in the range -5–5 cm to 22%, due to the burning of the slopes of moss hummock and the formation of steep slopes between negative and positive forms (table 1).
Areas of the third class pyrogenic load are characterised by partial burning of the mineral soil and peat, which is associated with the burning of roots and felling of trees.

Table 1. Microtopography parameters of pine-dwarf-shrub-sphagnum bogs.

| Parameters | Pristine bog (average means) | Drained bog (site 4) | Partial burning bog (site 2) | Complete burning bog (site 1) |
|------------|------------------------------|----------------------|-----------------------------|------------------------------|
| Amplitude, cm | 37,2 | 44,3 | 51,10 | 49,70 |
| The interval of altitudes at a significance level of p=0.05, cm | 27,7 | 31,4 | 35,80 | 31,80 |
| Quartile scale, cm | 13,0 | 14,1 | 18,90 | 12,00 |
| The standard deviation, σ | 8,61 | 9,79 | 11,60 | 9,37 |
| The proportion of heights at the mid-plane (-5-5 cm), % | 43,5 | 37,10 | 28,0 | 45,0 |
| The skewness, λ | 0,12 | 0,22 | 0,63 | 0,51 |

The transformation of the microtopography in post-pyrogenic areas is determined by the intensity of the fire. The greatest deviation from natural bog indicators of surface fragmentation and distribution of altitudes relative to the mean surface is characteristic of the partially burnt sites. For a completely burnt area, despite the close values of quantitative indicators with natural areas, there is almost
complete absence of accumulative forms in the form of moss hummock, and the mosaic surface is determined by the uneven burning of the moss and peat within the area under study.

3.4 Carbon losses within post fire site

After the fire, the amount of mortmass increases twice, and the burning of the combs causes the compaction of the peat layer, which leads to an increase in the total amount of plant matter from 10,000 to 15,000 g/m$^2$.

Carbon losses for the burned area of 1 square meter to a depth of 30 cm were about 3,800 gC/m$^2$. The mortmass amount increased 2 times after the fire from 7,237 g/m$^2$ on the background site to 13,234 g/m$^2$ on the completely burned. Production increases on partially burnt sites, at the expense of the overgrown roots of bushes and on completely burned sites at the expense of the not-died-out, the roots of a pine which remained after a fire. In the post-fire succession, the productive activity of the shrub tier on the partially burned experimental site increases in two times. Photosynthetic mass of shrubs increases from 45 to 70 g/m$^2$. The fire frees the surface of the mire from low-yielding plants, which leads to an increase in stocks and production of more productive groups of plants.

3.5 Contamination by combustion products and estimation of the hydrocarbons composition

Analysis of atmospheric deposition showed a significant increase in the amount of Zn 2 times, Pb 14 times, Cu 4 times and Cd up to 9 times in their composition. The area of Zn and Pb pollution covers an area of 8 km, which is consistent with the prevailing wind direction and atmospheric deposition data for 2016. Significant increasing of Cu, Zn, Cd and Pb concentrations in the upper layer peat deposit (0–5 cm) in 3–6 times relative to the background area 100 m from the border is observed. The zone of extreme pollution of heavy metals peat deposits is limited mainly by the zone of intensive burning of the surface, however, and beyond it there was also a significant (2 times) Zn, Cd and Pb concentration (except Cu) increase, mainly due to the migration of elements with mire waters. High concentrations of Cu, Zn, Cd and Pb (1.5–4 times higher than background) remain in mire waters and waters of Gavrilovka river 2 years after the fire. Excess of background content of Zn, Cd and Pb throughout the year and Cu in June, August and September in mire waters is marked. The content of heavy metals increases with increasing influence of pyrogenic factor in Sphagnum fuscum and Pinussylvestris (2–10 times higher than background). These species can serve as an indicator of the degree of mire pyrogenic disturbance.

Analysis of the composition and content of hydrocarbons compounds showed that in the upper layers of the peat deposit, there is a decrease in the content of the main groups of compounds: di - and triterpenoids, steroids, phytone, n-alkanes, n-alkane-2-ones, n-aldehydes, squalene, tocopherols (about 2–5 times), carboxylic acids and phytol (1.1 times). Against the background of a decrease in the content of n-alkanes, their share in the composition of peat lipids of the burnt area increases slightly, and among them the content of homologues C23–C25 increases, C29–C33 decreases and the CPI value decreases. According to IR spectrometry data, the high hydrocarbon content of up to 7 MAC for domestic water supply was observed, and the CPI index decreased, which is evidence of the transformation of the hydrocarbon composition and is consistent with the increase in n-alkanes.

4. Summary and Conclusion

The retrospective analysis of the water-thermal regime of the drained site of the Great Vasyugan mire confirmed that in August 2016, the most favourable conditions for the emergence of a fire-dangerous situation were developed. The summer period of 2016 was characterised by extreme temperatures, which in early August increased to 30–33.5 °C, which was observed previously 2 times over the past 50 years. The levels of mire water fell below the level of 40 cm from the surface. Therefore, in the future, we should expect the re-emergence of fire-dangerous seasons, and the results obtained indicate that the mire areas where there is a decrease in the level of mire water to 40 cm are potentially fire-hazardous areas.

The area of fire distribution is determined by the moisture content of the mire. The fire did not spread to the outside of the hummock-hollow mire inside the main contour of the fire. The areas of pine-shrub-sphagnum bogs in near to drainage channels were exposed to the most intensive burning.
Carbon losses for the burned area of 1 square metre to a depth of 30 cm were about 3,800 gC/m$^2$. The area of pollution covers an area of 8 km, which is consistent with the prevailing wind direction and atmospheric deposition data for 2016.

**Acknowledgments**

This study was funded by RFBR, research project no. 18-44-700005.

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