Article

Post-pyrogenic dynamics of the vegetation cover of the Barskoe raised bog (Vologda Region, Russia)

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Received: 12.05.2020

Revised: 17.11.2020

Accepted: 27.11.2020

Published online: 11.02.2021

DOI: 10.23859/estr-200512

UDC 581.9+58.02(470.12)

Translated by D.M. Martynova

Abstract. The study deals with the issues of restoration of peat bogs exposed to the pyrogenic factor. The work was carried out in the Barskoe raised bog, at sites unaffected and directly affected by the ground fire of 2002. A decade later, these sites differed in species composition, phytocenosis structure, and biomass accumulation rates. Post-pyrogenic changes in the vegetation cover of the raised bog were associated with a slight decrease in species richness, loss of moisture-demanding bog species and an increase of mesophyte's and xerophyte's roles, simplification of the mire sites structure towards the loss of complexity, reduction of phytocenotic diversity, as well as an increase in the dry biomass stocks with a 1.3–1.4-fold decrease in the photosynthetic phytomass and a 6.4–6.7-fold increase in the mortmass. The restoration rate of the mire exposed to pyrogenic transformation can be accelerated by increasing its water table and the prevention of new fires.

Keywords: peat fire, flora, *Sphagnum*, phytomass stocks, mortmass, mire restoration.

To cite this article. Malashchuk, A.A., Philippov, D.A., 2021. Post-pyrogenic dynamics of the vegetation cover of the Barskoe raised bog (Vologda Region, Russia). *Ecosystem Transformation* 4 (1), 35–52. <https://doi.org/10.23859/estr-200512>

Introduction

Fires are the environmental factor that preconditions the composition, structure and dynamics of phytocenoses (Rabotnov, 1978; Wein and MacLean, 1983), including that at mires and paludified areas (Efremova and Efremov, 1994; Kuhry, 1994; Minayeva and Sirin, 2002). The consequences of each fire in a peatland may be different, from an increase in soil fertility and an improvement in growing conditions to the loss of a number of the main biospheric functions of a mire, depending on the type of fire (crown fire, creeping fire, and underground fire), the water content of the certain site (associated with the degree of its transformation), and weather conditions.

There are several issues received much attention nowadays when studying the effects of fires on the mire ecosystems:

1) searching for the causes and sources of fires, development of general issues (Korchagin, 1954; Kosov, 2012; Panov and Tsymlyakova, 2013; Vomperskiy et al., 2007);

2) study of the fire effects on the peat soils (Efremova and Efremov, 1994, 2006; Glukhova and Sirin, 2018; Sirin et al., 2019; Tsibart et al., 2016; Zaydelman and Shvarov, 2002), waters (Akhmetyeva et al., 2011; Kučerová et al., 2008), vegetation cover (Burenina, 2006; Chumakov, 2013; Grishutkin, 2012; Grummo et al., 2010; Kochubei, 2017; Kopoteva,

1995; Kopoteva and Kuptsova, 2016; Mazing, 1960; Napreenko, 2002; Popov, 2000), invertebrates (Kolesnikov, 2017), protozoans (Kurina and Klimova, 2016), and prokaryotes (Danilova et al., 2015);

3) development of the fire safety issues, including the assessment of potential fire hazard (Khakimov and Sinyutkina, 2014; Ul'baev and Bazaeva, 2012), minimization of consequences (Sirin et al., 2011; Zhukov and Potapov, 2010), monitoring and restoration of disturbed peat bogs (Akhmetyeva et al. et al., 2014; Makarenko, 2013; Medvedeva et al., 2019; Minayeva and Sirin, 2002; Semenova, 2016; Sirin et al., 2018; Sretenskiy, 2004; Zaydelman, 2014).

In the Vologda Region (Russia), the bioecological studies of peat fires and their impact on the environment have practically not been carried out so far (Philippov, 2010), they are limited to a few small notes from different years (Denisenkov, 1980; Lebedeva, 2005; Philippov, 2007; Pyavchenko, 1955; Zaudalov, 2006).

Regard must also be paid to a number of annual cases of peat fires in the studied region and the associated problems. Table 1 summarizes the regional Department of Natural Resources' official information for the period from 2005 to 2016 (Doklad..., 2010, 2012, 2015, 2017). Every year, 37 peat fires on average (from 4 to 122) occur in the region, covering from 0.7 to 47.2 ha (in 2010, 133.5 ha). Although the areas affected by fires, compared to the Vologda Region's total area, seem relatively small, the fires affect the population health and the national economy negatively. They require high extinguishing costs, which may reach up to 15–25 million Russian roubles in the seasons with the worst fire, and the total damage may exceed dozens of millions of Russian rubles, exceeding hundreds of millions in some years.

The study aims to identify the main changes in the species composition, coenotic structure, and in the stock of aboveground biomass in the raised bog after the fire. The work was carried out as part of the preparation of the graduation thesis of A. Malashchuk, defended successfully at Vologda State University (Russia) in 2014, some results were presented as an abstract at the conference, same year (Malashchuk, 2014).

Materials and methods

The research took place in the Sukhonskaya Lowland, located at a pre-glacial tectonic depression and a lacustrine-glacial reservoir with terraces (117–145 m above sea level) in the basin of the upper reaches of the Sukhona River (Lyapkina, 1985). The territory is heavily paludified (up to 25% of the total area, see: Filonenko and Philippov, 2013), which is facilitated by the general flatness of the relief, low relative elevation of the area, shallow groundwater, temperate continental climate, and the proximity of large water bodies, the Lake Kubenskoe and the

Sukhona River (Abramova, 1965; Lyapkina, 1985). The raised bogs are smaller than low moors and transitional types of moors, they are located mainly in the Sukhonskaya Lowland watersheds. Most of the raised bogs of this area, especially in the vicinity of Vologda, Sokol, and Kadnikov cities and a number of large villages, were transformed as a result of forest reclamation, drainage and peat extraction (Shevelev and Komissarov, 1994).

A model object is the Barskoe raised bog (Fig. 1), which is one of two “isolated areas” of the Vakhtyuzhskoe peatland (Torfyanoi Fond..., 1955). The mire is elongated northeasternwards along the southeastern edge of the Olarevskaya ridge (a moraine formation in the marginal zone of the Upper Valdai glaciation). It serves as the source of the Voz'ma River. It belongs to pine-cottongrass-dwarf shrub-sphagnum raised bogs dominated by *Sphagnum magellanicum* coll. According to the detailed studies carried out in 1944 and 1947 by the State Institute for Exploration of Coal and Peat Deposits of the Fuel Industry (Gipromesttop), the mire has an area of more than 10 km², the average depth of peat deposits is 3.36 m (maximum, > 6.0 m). Raised-bog peat deposits of medium peat and complex raised-bog peats prevail: degree of decomposition is 10–50% (avg. 29%), ash content, 0.7–12.4% (avg. 3.6%), moisture content, 88.8%, stumpiness, 1.2% (Torfyanoi Fond..., 1955). According to our data, the mire area is 11.1 km².

The southwestern part of the mire is located within the Vologda District's boundaries; the northeastern part belongs to the Sokol District. The southwestern extremity of the mire near the Mezhdurech'e village was drained in 1944–1948; the peat was extracted on about 10 hectares. In the second half of the XX century, an amelioration ditch was dug along the eastern and southeastern edges of the mire, and the forest reclamation was carried out in several forested areas (for example, near the villages of Volkovo and Konanovo). Considering the proximity of cities (15–20 km to Vologda, 10–15 km to Sokol), transport accessibility (the Northern Railway line locates in 0.5–1.5 km), and the attractiveness of the facility for picking berries, hunting and recreation, the mire is exposed to strong seasonal recreational impact and associated risk of peat fires. The fires are creeping and local. The last most severe fire here occurred in 2002 was anthropogenically induced and damaged about 8–10% of the mire area.

Botanical studies of the mire were carried out in 2010, 2012–2014, and 2019. The most material was collected during the 2012 vegetative season near the stopping point of 515 km of the Northern Railway on three model sites: S1, “natural”, i.e. not exposed to direct fire effects, located closer to the centre of the mire (N 59°22'31" E 39°58'48") (Fig. 1C); S2, “pyrogenic”, exposed in 2002 to the influence of ground fire (N 59°22'30" E 39°59'29") (Fig. 1H); S3,

Table 1. Characteristics of wildfires on the territory of the Vologda Region in 2005–2016. Disbenefit and extinguishing costs have been rounded to the nearest hundredth; * – no data.

Wildfires	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Number of fires	209	223	72	91	90	308	189	65	130	157	46	177
– incl. peat-bog	42	41	13	4	26	42	37	15	40	51	12	122
Area, ha	105.5	349.3	65.6	117.6	69.0	979	296.1	48.3	198.9	266.4	26.6	43.0
– incl. peat-bog	17	51	6.7	0.7	1.6	133.5	19.9	11	35.1	47.2	*	*
Extinguishing costs, 10 ⁶ Russian roubles	2.27	2.28	0.49	1.18	1.60	25.52	15.10	2.61	8.01	9.96	0.39	2.27
Disbenefit, 10 ⁶ Russian roubles	6.33	27.36	2.33	10.54	5.30	211.04	71.90	7.33	21.26	26.63	1.81	4.37

Fig. 1. The raised bog Barskoe. **A** – general view of the bog; **B** – general view of the pyrogenically transformed site of the mire; **C** – pine-dwarf shrub-cottongrass-*Sphagnum* undisturbed site; **D** – *Oxycoccus*-cottongrass-*Sphagnum* communities; **E** – traces of fire; **F–H** – pyrogenically transformed part of the bog: **F** – dying pines after a fire; **G** – peat outcrops and the beginning of burnt-out overgrowth with birch and *Polytrichum* mosses; **H** – birch-*Polytrichum* post-pyrogenic communities.

“marginal”, the forested edge of the mire, not affected by the direct anthropogenic load (N 59°22'20" E 39°59'31") (Fig. 1B). The emphasis was given to the analysis of changes in flora composition, coenotic diversity and production characteristics of natural and pyrogenically disturbed areas.

In the field, floristic lists were compiled for the entire mire and each part separately (central and marginal natural and pyrogenically disturbed areas), the plants were collected in a herbarium, and the photographs of plants, communities, and the mire areas were taken (Philippov et al., 2017). Geobotanical descriptions were carried out on the plots (10 × 10 m) to characterize phytocoenoses. When describing the phytocoenoses, geographic coordinates were recorded (using a Garmin eTrex Vista H GPS receiver), the microrelief shape was described, the water level was determined, the species list was compiled (emphasizing the vascular plants' abundance using the 7-point Brown-Blanquet scale), and the percentage of bryophyte projective cover was assessed. The descriptions were carried out, taking into account the microrelief (ridges, carpet, and hollows were described separately). In order to determine the stock of aboveground biomass, the mowing method was applied (Golovatskaya and Porokhina, 2005). The plots (a metal frame 50 × 50 cm; five replicates) were analyzed for each microrelief element on natural (hummocks and carpet) and disturbed areas. At each plot, plants were cut at the moss surface level and placed in the plastic bags with labels indicating the site's number, the plot, and the type of microrelief.

The identification of plants, the herbarium setting, compilation of a checklist, digital processing of field materials and their analysis were carried out in the laboratory. Herbarium materials were deposited in the Herbarium of the Department of Biology and Chemistry of the Vologda State University (VO) and the Herbarium of the Mire Research Group, Papanin Institute for Biology of Inland Waters, Russian Academy of Sciences (MIRE). Also, the quantitative samples were grouped by certain species, dried to an air-dry state, then the phytomass and mortmass were weighed (for dwarf shrubs, the photosynthetic (leaves) and non-photosynthetic (branches) parts were weighed separately). The primary data were summarized in tables and analyzed following the data processing recommendations by Golovatskaya and Porokhina (2005).

The plant nomenclature is given in accordance with the recent reviews (Ignatov et al., 2006; Konstantinova et al., 2009; Tsvelev, 2000). Recently, *Sphagnum magellanicum* Brid. was divided into three species (Hassel et al., 2018), in northern Eurasia, two of them (*S. medium* Limpr. and *S. divinum* Flatberg & Hassel) occur in approximately equal proportions

in relatively similar mire biotopes. Considering that these species are sister species, they have not been differentiated during our analysis, so in this study, we follow the accepted approach (Bengtsson et al., 2021) and consider them as *S. magellanicum* coll. Peat of the medium type is also composed of the remains of this “composite” species.

Floras were compared using the ExcelToR program (Novakovskiy, 2016).

Results and discussion

Effect of fires on the flora of higher plants

In the Barskoe raised bog, 55 species of higher plants were recorded, in particular, Magnoliophyta (32 species), Bryophyta (18), Marchantiophyta (2), Pinophyta (2), and Polypodiophyta (one species), belonging to 36 genera, 26 families, 8 classes, and 5 divisions (Table 2). In the mire flora, the families Sphagnaceae (10 species), Cyperaceae (9), Ericaceae (6), and Salicaceae (four species) dominated. Almost a third of the species list (15 species of vascular plants and 2 moss species) were recorded only at the edge of the mire, and only one species (*Pinus sylvestris*) was found in all analyzed areas (natural, pyrogenic, and marginal).

As a rule, in the natural areas of the raised bogs, microrelief is well-developed, and the species richness is lower compared to the flora of other types of mires and the combined species list of mire flora (16 species of bryophytes, 13 species of vascular plants). *Pinus sylvestris* (h = 2.5–3.5 m), heather dwarf shrubs, *Eriophorum vaginatum*, *Rubus chamaemorus*, peat moss (*Sphagnum magellanicum* coll., *S. angustifolium*, and *S. fuscum*) and *Polytrichum* mosses (*Polytrichum strictum* Dum) grow on hummocks and ridges (h = 2.5–3.5 m), *Drosera rotundifolia* and *Melampyrum pratense* are found less often. *Eriophorum vaginatum*, *Oxycoccus palustris*, *Scheuchzeria palustris*, *Carex limosa*, peat mosses (*Sphagnum balticum*, *S. angustifolium*; rarely, *S. cuspidatum*, *S. majus*, and *S. fallax*) grow on the low carpet and in hollows.

During a fire, complete or partial destruction of the soil and vegetation cover occur, as well as the surface enrichment with ash elements and nitrogen. As a result, the microrelief of the mire area changes; it becomes hummocky with unexpressed complexity. In the Barskoe mire, charred trunks (up to 5–6 m high) and pine stumps remained in the burnt areas. Post-pyrogenic successions are associated with the emergence of shoots of *Betula pendula* and *B. pubescens*, the development of *Polytrichum* mosses (*Polytrichum commune*, *P. strictum*), *Eriophorum vaginatum*, and *Calluna vulgaris*. *Chamaenerion angustifolium* is found as single specimens. There are

Table 2. Species richness and coenotic significance of plants in natural (S1), disturbed by fire (S2), and marginal (S3) areas of the raised bog: 1 – single specimens, 2 – not very abundant, 3 – moderately abundant, 4 – co-dominants, 5 – dominants (very abundant), “–” – the species was not found.

Taxon	Site		
	S1	S2	S3
Phylum Marchantiophyta			
Family Myliaceae Schlijakov			
<i>Mylia anomala</i> (Hook.) Gray	1	–	–
Family Odontoschismataceae (Grolle) Schlijakov			
<i>Cladopodiella fluitans</i> (Nees) H. Buch	1	–	–
Phylum Bryophyta			
Family Aulacomniaceae Schimp.			
<i>Aulacomnium palustre</i> (Hedw.) Schwägr.	2	1	–
Family Bryaceae Shwägr.			
<i>Bryum</i> sp.	–	1	–
Family Calliergonaceae (Kanda) Vanderp. et al.			
<i>Warnstorfia fluitans</i> (Hedw.) Loeske	2	–	2
Family Dicranaceae Schimp.			
<i>Dicranum undulatum</i> Schrad. ex Brid.	1	–	–
Family Hylocomiaceae (Broth.) M. Fleisch.			
<i>Pleurozium schreberi</i> (Brid.) Mitt.	2	–	2
Family Mielichhoferiaceae Schimp.			
<i>Pohlia nutans</i> (Hedw.) Lindb.	1	1	–
Family Polytrichaceae Shwägr.			
<i>Polytrichum commune</i> Hedw.	–	5	–
<i>P. strictum</i> Brid.	3	3	–
Family Sphagnaceae Martynov			
<i>Sphagnum angustifolium</i> (C.E.O. Jensen ex Russow) C.E.O. Jensen	4	2	–
<i>S. balticum</i> (Russow) C.E.O. Jensen	4	–	–
<i>S. cuspidatum</i> Ehrh. ex Hoffm.	2	–	–
<i>S. fallax</i> (H.Klinggr.) H. Klinggr.	2	–	2
<i>S. fuscum</i> (Schimp.) H. Klinggr.	4	–	–
<i>S. girgensohnii</i> Russow	–	–	2
<i>S. magellanicum</i> coll.	5	1	–
<i>S. majus</i> (Russow) C.E.O. Jensen	2	–	–
<i>S. rubellum</i> Wilson	1	–	–
<i>S. russowii</i> Warnst.	–	–	1
Phylum Polypodiophyta			
Family Dryopteridaceae Ching			
<i>Dryopteris carthusiana</i> (Vill.) H.P. Fuchs	–	–	1

Taxon	Site		
	S1	S2	S3
Phylum Pinophyta			
Family Pinaceae Lindl.			
<i>Picea abies</i> (L.) Karst.	–	–	1
<i>Pinus sylvestris</i> L.	5	2	2
Phylum Magnoliophyta			
Family Betulaceae S.F. Gray			
<i>Alnus incana</i> (L.) Moench	–	–	2
<i>Betula pendula</i> Roth	–	5	3
<i>B. pubescens</i> Ehrh.	–	3	2
Family Cyperaceae Juss.			
<i>Carex acuta</i> L.	–	–	1
<i>C. canescens</i> L.	–	–	2
<i>C. echinata</i> Murr.	–	–	2
<i>C. limosa</i> L.	3	–	–
<i>C. pauciflora</i> Lightf.	2	–	–
<i>C. rostrata</i> Stokes	–	–	2
<i>C. vesicaria</i> L.	–	–	1
<i>Eriophorum vaginatum</i> L.	5	4	–
<i>Scirpus sylvaticus</i> L.	–	–	1
Family Droseraceae Salisb.			
<i>Drosera rotundifolia</i> L.	2	3	–
Family Ericaceae Juss.			
<i>Andromeda polifolia</i> L.	5	2	–
<i>Calluna vulgaris</i> (L.) Hull	–	4	–
<i>Chamaedaphne calyculata</i> (L.) Moench	5	2	–
<i>Ledum palustre</i> L.	2	4	–
<i>Oxycoccus palustris</i> Pers.	4	4	–
<i>Vaccinium uliginosum</i> L.	3	3	–
Family Onagraceae Juss.			
<i>Chamaenerion angustifolium</i> (L.) Scop.	–	1	2
Family Pediculariaceae Juss.			
<i>Melampyrum pratense</i> L.	1	1	–
Family Poaceae Barnhart			
<i>Deschampsia caespitosa</i> (L.) Beauv.	–	1	1
Family Ranunculaceae Juss.			
<i>Ranunculus repens</i> L.	–	–	2
Family Rhamnaceae Juss.			
<i>Frangula alnus</i> Mill.	–	–	1

Taxon	Site		
	S1	S2	S3
Family Grossulariaceae DC.			
<i>Ribes nigrum</i> L.	–	–	2
Family Rosaceae Juss.			
<i>Rubus chamaemorus</i> L.	4	2	–
Salicaceae Mirb.			
<i>Populus tremula</i> L.	–	2	2
<i>Salix caprea</i> L.	–	–	2
<i>S. cinerea</i> L.	–	1	2
<i>S. pentandra</i> L.	–	–	2
Family Scheuchzeriaceae F. Rudolphi			
<i>Scheuchzeria palustris</i> L.	4	–	–
Family Typhaceae Juss.			
<i>Typha latifolia</i> L. s.l.	–	–	2
Total number of species	29	24	27

practically no hygrophilic species (peat mosses), but some species characteristic for the marginal areas and adjacent mineral lands (*Salix cinerea*, *Populus tremula*) begin to occur. In total, 17 species of vascular plants and 7 species of mosses were found in the flora of peat bog areas recovering from a fire. The leading families are Ericaceae (6 species), Polytrichaceae, Sphagnaceae, Betulaceae, and Salicaceae (2 species each). The similarity of the natural and pyrogenic areas' floras based on the Sørensen–Czekanowski coefficient is low (0.56), and the similarity of these two areas with the marginal flora is even lower (0.20). In the marginal areas of the raised bog, 27 species were found (22 species of vascular plants, 5 species of mosses). The marginal flora is mostly presented by forest, mire-forest, and mire-meadow species; this is also typical for other mires in the region (Philippov, 2015) and is associated with the edge effect, but not with anthropogenic transformations of the territory.

In general, after the fire in the raised bog, the number of species decreases insignificantly (from 29 to 24); however, the proportions of certain groups change: the share of typical mire plants, hygrophytes (*Sphagnum* spp., *Carex* spp.) decreases, the share of meso- and xerophilic species increases, and such species as *Betula* spp., *Populus tremula*, *Calluna vulgaris*, *Chamaenerion angustifolium* appear. Similar trends (leaving the regional characteristics) were reported by other researchers (Denisenkov, 1980; Grummo et al., 2010; Napreenko, 2002; Pyavchenko, 1955, etc.).

Effect of fires on the coenotic diversity

Not all the plant species play the same role in plant communities' composition (Table 2). The analyzed areas are characterized by low species similarity. Thus, the natural and pyrogenic sites are similar in terms of species abundance and composition (Sørensen–Czekanowski index is 0.36), and the similarity of these two sites with the mire margin is even lower (0.13).

Out of 29 species of higher plants growing in natural sites, only 8 species are the most coenotically significant (considering the microrelief); these are *Pinus sylvestris*, *Eriophorum vaginatum*, *Andromeda polifolia*, *Chamaedaphne calyculata*, *Sphagnum magellanicum* coll., *S. balticum*, *S. angustifolium*, and *S. fuscum*. On hummocks, they form pine-*Chamaedaphne-Sphagnum* and pine-*Andromeda-Sphagnum* communities, in hollows, *Scheuchzeria-Sphagnum*, sedge-*Scheuchzeria-Sphagnum*, *Scheuchzeria-Oxycoccus-Sphagnum*, on the carpet, cottongrass-*Sphagnum-Oxycoccus* communities.

At the initial stages of the post-pyrogenic restoration of the peat bog, the central role is played by *Polytrichum commune*, as well as *Eriophorum vaginatum* and two species of birch trees (*Betula pendula* and *B. pubescens*). Depending on specific conditions, they form *Polytrichum*, cottongrass-*Polytrichum*, and/or birch-*Polytrichum* communities. Meantime, in the studied areas, birch should be considered only as undergrowth, but not as a tree layer,

since the height of *B. pendula* reaches an average of 1.5–1.8 m, *B. pubescens*, usually no more than 0.6 m. Liverworts were not found in disturbed areas of the mire, although *Marchantia polymorpha* L. aggr. may be found on the burnt places according to some authors (Napreenko, 1996).

In general, under the influence of the pyrogenic factor, the coenotic structure of the Barskoe raised bog has simplified significantly:

1) in the tree layer, pine is replaced by birch (mainly *B. pendula*);

2) in the grass-dwarf shrub layer, the importance of some heather dwarf shrubs (*Calluna vulgaris*, *Ledum palustre*) increases, while *Andromeda polifolia* and *Chamaedaphne calyculata* are almost absent;

3) environment-forming plant species of natural mires (*Sphagnum* spp.) are almost entirely replaced by *Polytrichum* mosses (*Polytrichum commune*, *P. strictum*); this reduces the rate of carbon accumulation in peat deposits due to the loss of the main peat-forming species.

Similar results were obtained by other scientists. The research performed in 1951 in the Totma District of the Vologda Region evidenced that the tree layer also underwent restoration mainly due to birch and aspen, the moss cover was represented by *Polytrichum commune*, while in the wetter sites of the burnt places, *Sphagnum capillifolium* (Ehrh.) Hedw., *S. fallax*, and *S. balticum* could be found (Pyavchenko, 1955). When studying pyrogenic successions in the Cherepovets District of the Vologda Region, it was also noted that after some time, shoots of *Betula* ssp. and *Ledum palustre* developed on the burnt places; *Eriophorum vaginatum*, *Vaccinium uliginosum*, and *Andromeda polifolia* were fruiting actively; *Calluna vulgaris*, *Chamaenerion angustifolium*, and *Epilobium palustre* appeared; and peat mosses were replaced by *Polytrichum strictum* and *Marchantia polymorpha* (Denisenkov, 1980).

Such a birch-dwarf shrub-moss stage may last for 30–40 years, but it may be shortened when the total humidity increases, which, in turn, initiates the beginning of the restoration of the *Sphagnum* cover (Sejbutis, 1961). Other authors believe that the restoration of oligotrophic mire vegetation is associated with a decrease in the amount of nitrogen accumulated in the upper layers of peat after a fire (Popov, 2000). However, only a slight increase in the content of nitrogen and phosphorus is noted in post-pyrogenic peat soils; therefore, an increase in the mire soil fertility is mostly due to a decrease in moisture, destruction of moss cover, and an increased concentration of ash elements (Akhmetyeva et al., 2011; Efremova and Efremov, 1994). Further overgrowth of these areas reduces the trophicity of the upper soil layers. Improving mineral nutrition

promotes active regeneration; for example, this is true for *Eriophorum vaginatum* (Grishutkin, 2012).

Fires in the mires of the Kaliningrad Region (Napreenko, 2002) and Belarus (Grummo et al., 2010) lead to a depletion of the species composition, thinning of the tree layer, active development of deciduous forest-forming species, an increase in the coenotic significance of *Calluna vulgaris* and *Polytrichum strictum*, and a weak renewal of hygrophytes. All researchers noted an increase in mires vulnerability to fires with a decrease in their moisture supply.

Effect of fires on the aboveground plant biomass

Biological productivity (the ability of living organisms to create, preserve, and transform organic matter) consists of three main indicators: biomass stock, dynamics of phytomass growth, and net primary production (Golovatskaya and Porokhina, 2005). During our research, the primary attention was paid to the stock of aboveground biomass at three sampling sites (their geobotanical description is given in Table 3).

In oligotrophic mire areas with a ridge-carpet microrelief (S1a, Table 3), the aboveground biomass stock in the pine-*Chamaedaphne-Sphagnum* community of the ridge is 1225 g/m² (Table 4). The most important role is played by *S. magellanicum* coll. (417 g/m²) and *S. fuscum* (134 g/m²), *Chamaedaphne calyculata* (82 g/m², photosynthesizing part; 242 g/m², non-photosynthesizing part), *Oxycoccus palustris* (32 and 43 g/m², respectively). *Andromeda polifolia*, *Ledum palustre*, *Vaccinium uliginosum*, and *Aulacomnium palustre* have a minor contribution to the total biomass (from < 1 to 3 g/m²). Mortmass (litter) is 174 g/m²; its share in the total biomass stock is 14.2%. The phytomass of the moss layer (572 g/m²) in the ridge communities of the Barskoe raised bog is 1.5 times higher than the phytomass of grasses and dwarf shrubs (384 g/m²). The non-photosynthesizing phytomass exceeds the photosynthetic phytomass in the grass-dwarf shrub layer almost twofold (branches, 254 g/m²; leaves and grasses, 130 g/m²).

In the same ridge-carpet complex, in the cottongrass-*Oxycoccus-Sphagnum* carpet community (S1b, Table 3), the biomass stock is 963 g/m² (Table 4). The highest biomass is typical for *S. angustifolium* (623 g/m²), *Eriophorum vaginatum* (53 g/m²), *Oxycoccus palustris* (photosynthesizing part, 42 g/m²; non-photosynthesizing part, 55 g/m²). The minimum biomass was recorded in *Andromeda polifolia* (photosynthesizing part, 6 g/m²; non-photosynthesizing part, 3 g/m²). There are practically no species characteristic of hummocks and ridges of raised bogs among the plants that form the bulk of biomass in carpet communities. Mortmass (litter) is 182 g/m²,

Table 3. Vegetation of natural (S1a – ridge, S1b – carpet) and disturbed by fire (S2) areas of the raised bog. For vascular plants, the abundance is indicated in points; for bryophytes, as projective cover, %; for woody plants, the height (m) is given in brackets.

	Community		
	S1a	S1b	S2
Total projective cover, %	95	95	75–80
Phreatic line, cm	–18...–20	–7...–8	–20...–25
Number of species	17	10	20
Tree and dwarf shrubs layer			
<i>Betula pendula</i>	–	–	3 (1.5–1.8)
<i>Betula pubescens</i>	–	–	1 (0.5–0.6)
<i>Pinus sylvestris</i>	1 (2.5–3.5)	–	+ (0.5)
<i>Populus tremula</i>	–	–	+ (0.3–0.4)
<i>Andromeda polifolia</i>	+	+	+
<i>Calluna vulgaris</i>	–	–	r
<i>Chamaedaphne calyculata</i>	3	+	+
<i>Ledum palustre</i>	–	r	–
<i>Oxycoccus palustris</i>	2	2	+
<i>Rubus chamaemorus</i>	2	+	+
<i>Vaccinium uliginosum</i>	1	–	1
Grass and moss layer			
<i>Drosera rotundifolia</i>	r	–	–
<i>Eriophorum vaginatum</i>	1	4	2
<i>Melampyrum pratense</i>	–	–	r
<i>Aulacomnium palustre</i>	2–3	–	3–4
<i>Bryum</i> sp.	–	–	1–2
<i>Dicranum undulatum</i>	1–2	–	–
<i>Pleurozium schreberi</i>	1–2	–	1–2
<i>Pohlia nutans</i>	1–2	–	1–2
<i>Polytrichum commune</i>	–	–	65–70
<i>Polytrichum strictum</i>	5–7	–	25–30
<i>Sphagnum angustifolium</i>	15	15	10–12
<i>S. balticum</i>	–	65	–
<i>S. fuscum</i>	30	2–3	–
<i>S. magellanicum</i> coll.	30	5–7	1–2
<i>Mylia anomala</i>	1–2	–	–

and its share of the total biomass stock is 18.9%. In carpet communities, the phytomass value of the moss layer (623 g/m^2) exceeds that in the grass-dwarf shrub layer almost fourfold (158 g/m^2). Meantime, the photosynthesizing phytomass is 1.6 times higher than that of non-photosynthetic phytomass (leaves and grass, 97 g/m^2 ; branches, 61 g/m^2).

In the pyrogenically disturbed site of the mire, in the birch-*Polytrichum* community (S2, Table 3), the biomass stock is 1725 g/m^2 , which exceeds that in the mire areas untouched by the fire in 1.4–1.8 times (Table 4). *Polytrichum commune* (473 g/m^2) and *Eriophorum vaginatum* (50 g/m^2) play the central role in these communities. The other species (*Andromeda polifolia*, *Oxycoccus palustris*, *Vaccinium uliginosum*, *Aulacomnium palustre*, *Sphagnum angustifolium*, and *S. fuscum*) are characterized by minimal biomass stock ($1\text{--}10 \text{ g/m}^2$). Mortmass (mat) is 1173 g/m^2 ; its share in the total biomass stock is 68%. The phytomass of the moss layer in the pyrogenically disturbed communities (488 g/m^2) is 8.1 times higher than that of the grass-dwarf shrub layer (60 g/m^2). Meantime, the proportion of photosynthesizing phytomass exceeds that of non-photosynthesizing elevenfold (leaves and grass, 55 g/m^2 ; branches, 5 g/m^2).

In addition to absolute biomass values, it is necessary to pay attention to the aboveground biomass stocks' distributional pattern, i.e. their fraction composition (Table 4). In the natural part of the mire, the central role in the biomass structure belongs to the photosynthetic phytomass. In particular, its share exceeds 60% (754 g/m^2) on the ridges and almost 75% (720 g/m^2) on the carpet. The main difference in the biomass structure between these elements of the ridge-carpet complex is that there are practically no heather dwarf shrubs on the carpet. Accordingly, the share of non-photosynthesizing phytomass on the ridges (298 g/m^2) is 4.9 times higher than that on the carpet (61 g/m^2). The mortmass in the mire area undisturbed by the fire is insignificant and ranges as 14–19% of the total biomass stock (174 g/m^2 on the ridges, 182 g/m^2 on carpet). A completely different distribution of biomass is observed in the communities of pyrogenically disturbed areas when only one third belongs to photosynthetic phytomass (543 g/m^2 , mainly due to *Polytrichum commune*), and mortmass accounts for up to 68% of the total biomass stock. In the disturbed areas, the role of peat mosses, the main peat-formers in the raised bogs, decreases to almost zero.

In general, peat fires also change the production parameters of the raised bog communities. Thus, the stock of dry biomass of pyrogenically disturbed areas increases in 1.4–1.8 times compared to the biomass of ridges and carpet of natural communities, but the share of photosynthetic phytomass decreases by 30–40%, and the share of mortmass increases in 6.4–

6.7 times. Since the photosynthesizing phytomass of undisturbed raised bogs is presented mainly of peat mosses, its reduction leads to a decrease in the rate of peat accumulation and an increase in carbon emission.

Similar trends were reported by other authors. Long-term observations of the dynamics of the aboveground phytomass in the post-pyrogenic period in a mesotrophic dwarf shrub-*Sphagnum* mire in the Far East Region of Russia evidenced that the structure of the living phytomass of vascular plants in an undisturbed area was constant: dwarf shrubs, 87%; herbaceous, 13% (Kopoteva and Kuptsova, 2016). When omitting the microrelief and considering the natural mire area as a whole in our studies, the ratio of dwarf shrubs to herbaceous plants was 9 to 1. There was also indicated that the share of herbaceous plants began to increase in the burnt place compared to that of dwarf shrubs (Kopoteva and Kuptsova, 2016); this was due to grasses' ability to grow annually, while dwarf shrubs tended to restrict growth after they reached 5–6 years.

A tendency to an increase in the share of mortmass in the total biomass was noted both when studying the effects of fires on the mires of the Far East Region of Russia (Kopoteva and Kuptsova, 2016) and in our study; however, absolute values obtained for the Barskoe raised bog were significantly higher (1173 g/m^2 versus 42 g/m^2). It was probably due to a different understanding of the scale and interpretation of the term “mortmass” rather than the mire type or geographical position of the mire.

Possible scenarios for further community succession

At this point, we cannot unambiguously determine further changes in the three analyzed areas. However, in many respects, they will depend on climatic factors, since the raised bog has an atmospheric type of water-mineral nutrition, and anthropogenic factors, such as the strength of possible fires and nature of the further mire use.

We assume that the natural site will continue to progress towards differentiation of the surface into microforms, forming ridge-hollow complexes, will continue as well. The water content in the hollows (and their further evolution into lakelets) will largely depend on the region's climate (primarily humidity). Global warming will have a negative impact on this process; however, it will contribute to an increase in biological productivity and the degree of participation of tree species in mire coenoses.

The pyrogenic site will continue to recover, but in many respects, the rate of this process will be pre-conditioned by the water content and by a decrease of the trophicity of the site (due to a decrease in the ash content of peat, which increases during a fire). Likely, the main observed changes are associated

Table 4. Biomass stock (g) of natural (S1a – ridge, S1b – carpet) and fire-disturbed (S2) sites of the raised bog. The values are given to the nearest 1 g; "+" – the component is identified, its mass is less than 1 g; "-" – the component was not found.

	Plot no.										Plot no.										Mean	g/m ²	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1	Mean	g/m ²	5	4	3	2	1
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	Plot no.					Plot no.					Plot no.					Mean	g/m²	1	2	3	4	5	Mean	g/m²
	1	2	3	4	5	Mean	g/m²	1	2	3	4	5	Mean	g/m²										
Trees																								
<i>Pinus sylvestris</i> (shoots)	-	+	+	-	-	+	+	-	+	+	-	+	+	+	-	-	-	-	-	-	-	-	-	
<i>Betula pubescens</i> (shoots)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	-	-	-	-	-	-	1.0	4.0	
Mosses																								
<i>Aulacomnium palustre</i>	1	-	-	-	+	0.2	0.8	-	-	-	+	-	+	+	-	2	-	+	-	-	0.4	1.6		
<i>Sphagnum angustifolium</i>	-	-	4	11	11	5.2	20.8	159	149	192	125	154	155.8	623.2	-	-	1	-	11	2.4	9.6			
<i>Sphagnum magellanicum</i> coll.	107	106	87	117	104	104.2	416.8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
<i>Sphagnum fuscum</i>	15	60	70	17	5	33.4	133.6	-	-	-	-	-	-	-	-	-	-	5	-	1.0	4.0			
<i>Polytrichum commune</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	40	146	154	117	134	118.2	472.8			
<i>Polytrichum strictum</i>	62	1	2	-	1	13.2	52.8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
Mortmass (litter, mat, rags), g	46	10	36	59	66	43.4	173.6	20	18	70	94	26	45.6	182.4	250	237	352	341	286	293.2	1172.8			
Non-photosynthesizing phytomass (branches), g	113	62	33	66	89	74.4	298.0	15	23	16	12	10	15.2	60.8	1	0	1	0	4	1.2	4.8			
Photosynthesizing phytomass (leaves, grasses, mosses), g	231	192	179	180	160	188.4	753.6	194	167	218	153	168	180.0	720.0	43	151	159	174	152	135.8	543.2			
Wet weight, g	1900	1800	2000	1800	1700	1840	7360	2300	2100	2900	2500	2100	2380	9520	1300	1500	2300	2200	1900	1840	7360			
Dry weight, g	390	264	248	305	324	306.2	1224.8	229	208	304	259	204	240.8	963.2	299	388	512	515	442	431.2	1724.8			

with the introduction of peat mosses and *Pinus sylvestris* into the coenoses, as well as with the loss of *Betula pubescens*, *B. pendula*, and other species uncharacteristic for the raised bogs (*Populus tremula*, *Salix cinerea*, *Chamaenerion angustifolium*, and *Deschampsia caespitosa*) from the communities.

The marginal area of the mire is least susceptible to global processes; therefore, its further development depends on the local factors only. For example, in the case of increasing recreational load, the introduction of weed or invasive species is possible.

Conclusions

Fires in the raised bogs affect the species richness, the structure of phytocoenoses, and the rate of biomass accumulation. By the example of the Barskoe raised bog, we argue that in 10–12 years after the ground fire has occurred, the pyrogenically disturbed areas differ from the natural mire complexes, which have not been directly exposed to fire. Post-pyrogenic changes in the canopy cover of the raised bog are associated with a slight decrease in the species richness, the loss of moisture-demanding mire species, a simplification of the structure of the mire areas, a decrease in coenotic diversity, an increase in dry biomass accompanied by a decrease in photosynthetic phytomass by 30–40%, and with an increase of the mortmass in 6.4–6.7 times. Accelerating the rate of restoration of the raised bog ecosystem is possible due to the prevention of new fires and increasing the overall water content of the mire.

Acknowledgments

The authors are grateful to A.V. Ivanov for his help with sorting of cut samples by fractions and V.V. Yurchenko (IBIW RAS) for her help during the fieldwork in 2010, as well as anonymous reviewers for valuable comments and advices.

Funding

The research of D.A. Philippov completed in the framework of the state assignment of Papanin Institute for Biology of Inland Waters Russian Academy of Sciences (project no. AAAA-A18-118012690099-2).

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