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Polygonal patterned peatlands of the White Sea islands

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Abstract. The summits and slopes of some islands along the northeastern and northern coasts of the White Sea are covered with dried out peatlands. The thickness of the peat deposit is 30–80 cm and it is separated by troughs into gently sloping polygonal peat blocks up to 20 m^2 in size. On some northern islands the peat blocks have permafrost cores. The main components of the dried out peatlands vegetation are dwarf shrubs and lichens. The peat stratigraphy reveals two stages of peatland development. On the first stage, the islands were covered with wet cottongrass carpets, which repeated the convex relief shape. On the second stage, they were occupied by the xeromorphic vegetation. We suggest that these polygonal patterned peatlands are the remnants of blanket bogs, the formation of which assumes the conditions of a much more humid climate in the historical past. The time of their active development was calculated according to the White Sea level changes and radiocarbon dates from 1000–4000 BP.

1. Introduction

There exist islands covered with dried out peatlands in the White Sea, the appearance of which resembles the shape of ice-wedge polygonal mires of arctic lowlands. The peat deposit is separated by troughs into gently sloping polygonal peat blocks 4–20 m^2 in size. A layer of withered peat with a thickness of 30–80 cm repeats the convex relief shape covering the summits and slopes of the land. The islands are far beyond the zone of the Arctic polygon mires, and the ice wedges, which are typical for the polygon mires, appear to be always absent in the troughs of the peatlands. The xeromorphic vegetation, that covers the peatlands, consists mainly of dwarf shrubs and lichens. The purpose of this work is to give brief essay on the current vegetation, to survey the peat deposit stratigraphy and to reconstruct the Holocene history of these peculiar peatlands.

2. Study area

The White Sea is located in the northeastern part of Europe along the boundary of Fennoscandia. In the period from 2006 to 2016 more than 750 km of the coastline were observed between the mouths of the Ponoi and Kem' rivers (figure 1). All studied islands are located along the coast with a maximum distance of 14 km. The polygon patterned peatlands were found on 9 islands. Additionally peatland with hummocky-hollow surface pattern was observed on Veshnyak island (table 1).

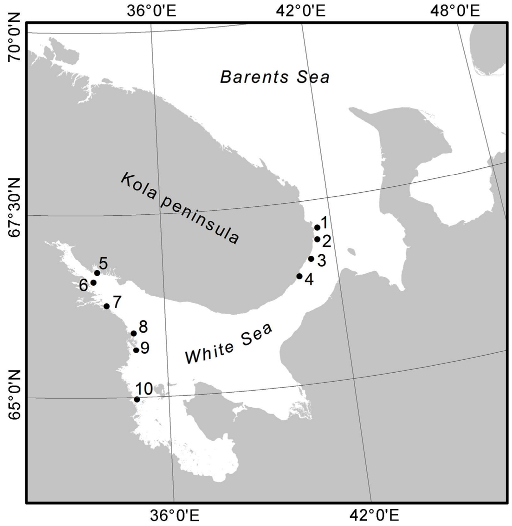

Figure 1. Study islands: 1 – Veshnyak, 2 – Unnamed island near the Goryainov island, 3 – Danilov, 4 – Sosnovetz, 5 – Stolbovaya Luda, 6 – Bol'shaya Srednyaya Luda, 7 – Sharapikha, 8 – Zelenaya Luda, 9 – Bol'shoi Rob'yak, 10 – Terroikha.

Figure 2. Polygon patterned peatland on Danilov island.

The surveyed territory is located within Belomorian fold belt – the southeastern part of the ancient Precambrian Fennoscandian shield [1]. Bedrocks dominated by acid gneisses and granite gneisses, lacking in almost all biogenic elements, some richer basic rocks cover smaller areas [2]. Islands in southern and western part are bare fractured rock outcrops whereas in the northeastern part, they have a thin layer of loose marine deposits [3].

Table 1. Study islands.

Island	Geographic coordinates N	E	Altitude above sea level, m	Size, km²	Peatlands mineral basement
Veshnyak	67°06'25"	41°24'07"	20.1	0.621	soft sediments above rock
Unnamed near Goryainov	67°01'40"	41°20'48"	< 5.0	0.008	soft sediments above rock
Danilov	66°44'20"	41°05'33"	6.3	0.036	soft sediments above rock
Sosnovetz	66°29'22"	40°40'59"	16.2	0.491	soft sediments above rock
Stolbovaya Luda	66°40'42"	33°47'02"	19.1	0.024	bare rock
Bol'shaya Srednyaya Luda	66°36'03"	33°41'04"	15.5	0.050	bare rock
Bol'shoi Rob'yak	66°37'31"	34°54'26"	16.8	0.269	bare rock
Sharapikha	66°13'41"	34°03'09"	31.8	0.112	bare rock
Zelenaya luda	65°53'39"	34°48'40"	11.0	0.058	bare rock
Terroikha	65°02'40"	34°59'25"	22.5	0.232	bare rock

Among the most important factors in the history of the formation of coastal peatlands during the Holocene are the isostatic land uplift and oscillations of the White Sea level [4, 5]. The rate and sometimes the direction of vertical movements in different parts of the studied territory are different [6, 7]. Since the highest middle Holocene transgression (ca. 6250 BP, Tapes phase), the sea level along the west coast has dropped by 20–25 m, while in the northeast it has dropped to 10 m. The most distinct coast paleoline, corresponding to the sea level 4100 years ago traced at 17 m a.s.l., is on the western coast and it is 8 m a.s.l. on the northeastern coast. The modern uplift is 1–2 mm per year in the west and the fall is 1.4–2.5 mm in the northeast [7].

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The climatic regime of the White Sea region may be described as intermediate between marine and continental types. The winters are relatively warm but lengthy whereas summers are short and cold. Additional specific climate features include significant cloudiness, high air humidity, abundant precipitation, and generally unstable weather conditions throughout the year. The intensive cyclonic activity and relatively rapid shifts of synoptic processes create high variability of the values of meteorological parameters [8]. The long-term mean annual air temperature along the studied area ranges from –0.67 in the northeast (Sosnovetz island weather station) to +1.4 °C (Kem' weather station) in the south-west. The annual precipitation is 343 mm (Sosnovetz) and 467 mm (Kem'), 71–75% of them fall in the warm period of the year [8].

The studied islands are mainly covered by heaths, which vary based on geographic location. The southern and western islands are situated within the north taiga subzone [9]. As a rule, *Empetrum hermaphroditum* is the most abundant species of these heaths, *Vaccinium vitis-idaea* and *V. uliginosum* are common. On the well-drained substrates *Arctostaphylos uva-ursi* and *Arctous alpina* are important. *Vaccinium myrtillus*, *Avenella flexousa,* and *Luzula pilosa* are confined to the snow-protected habitats. *Andromeda polifolia*, *Rubus chamaemorus,* and *Carex rarifolra* are significant in the paludified heathlands. Mosses (mainly *Pleurozium schreberi*), lichens (*Cladonia* spp., *Flavocetraria nivalis*, etc.) and liverworts (chiefly *Ptilidium ciliare*) are common. The peculiarity of these island heaths is the presence of some boreal, and even hemiboreal, plants (*Rubus saxatilis*, *Luzula pilosa*, *Dicranum polysetum*, etc.) and the absence of some arctic-montane or hypoarctic species (*Betula nana*, *Alectoria ochroleuca*, *Thamnolia vermicularis*, etc.), which are common on the northern islands. The other vegetation types of the southern and western islands are the supralittoral coastal meadows, salt marshes, fragments of mires, and pine forests, which occupy a negligible area.

The northern islands are lying within the south tundra (low arctic) subzone [9]. The Veshnyak island flat summit is mainly covered by chionophobous heath with lichens *Cladonia arbuscula* and *Flavocetraria nivalis* predominate. *Empetrum hermaphroditum*, *Betula nana* and prostrate *Salix glauca* prevail among the vascular plants. On the steep shore slopes there are *Empetrum hermaphroditum*, *Betula nana*, *Chamaepericlymenum suecicum* dominating heath and willow (*Salix glauca*, *S. lanata*) thickets. The Danilov and the small unnamed islands are entirely covered by dried out peat deposits with *Empetrum hermaphroditum* heath with abundance of *Rubus chamaemorus* (figure 2). The Sosnovetz island covered by peat deposits that have the form of a palsa peatland and in some places of a slightly differentiated plateau. The mounds and plateau are mainly covered by *Cladonia arbuscula*, *Flavocetraria nivalis* dominated heath with a high significance of *Rubus chamaemorus* and *Empetrum hermaphroditum*. *Eriophorum scheuchzeri*, *Carex aquatilis*, *C. rariflora* and *Sphagnum lindbergii*, *S. riparium* predominate in the hollows. The other vegetation types (mainly coastal meadows and herbs coenoses) of the northern islands are of little significance.

The polygon patterned peatlands are separate massifs on most of the islands. On some islands the polygonal structures are combined with extensive permafrost peat plateaus. On the Danilov island the polygonal relief turns into a more homogeneous plateau with permafrost at the northern foothill. The hilltop of Sosnovetz is entirely occupied by a permafrost peatland with an undulating relief, by the edges of which a polygonal structure is developing along the slopes and on the foothill. The studied peatlands on Veshnyak island are spotted by flat summits and they have hummocky-hollow relief.

3. Methods

3.1. Vegetation studies

The peatlands vegetation was recorded with about 100 relevés, which were made in homogeneous stands from sample plots 25 m² in 2011–2016. The abundance of each taxon was recorded by means of a cover percentage scale. The location in mesorelief, nanorelief pattern, exposure and slope angle were recorded for each sample plot.

3.2. Peat studies

Peat samples were taken manually from small pits to the full depth usually every 5 cm if a uniform layer or by visible limits if noticed. In Stolbovaya Luda and Bol'shaya Srednyaya Luda the thickness of samples was 2 cm. In Bol'shoy Rob'yak, Sharapiha, Zelenaya luda it was from 5 to 15 cm. For the most part of the islands the peat samples were taken only from one point, but on bigger islands they were taken from several sampling points. For the Danilov island we laid stratigraphical geological cross-section based on 5 sampling points through the whole peatland. Altogether 151 peat samples from 14 pits were analyzed in this study.

Botanical macrofossil analyses and degree of decomposition evaluation of samples were made with a microscope method at the precision of 5% in the Laboratory of mire ecosystem IB KarRC RAS in Petrozavodsk by N. Stoikina. The radiocarbon dating was performed in the conventional ^{14}C laboratories at the Geological Institute of the Russian Academy of Sciences (Moscow) (GIN) and Herzen State Pedagogical University of Russia (St.Petersburg) (SPb).

3.3 Meteorological data

The main sources of meteorological data of Hydrometeorological Service in Russia are Raspisaniye Pogodi Ltd. (rp5.ru) and hydrometeorological database (http://ib.komisc.ru/climat) [10].

4. Results

4.1 Essay on the current vegetation

The main components of the dried out peatlands vegetation are the dwarf shrubs (chiefly *Empetrum hermaphroditum*, also *Vaccinium uliginosum*, *V. vitis-idaea*, *Arctous alpina*), lichens (*Cladonia arbuscula*, *C. rangiferina*, *Flavocetraria nivalis*, *Cetraria islandica*, etc.) and *Rubus chamaemorus*. The moss floor is poorly developed usually and consists of *Dicranum elongatum*, less often *Polytrichum strictum*. Liverworts are common: *Ptilidium ciliare* grows mainly on the top of polygons; *Calypogeia* spp. and *Cephalozia* spp. are confined to the polygon slopes. There are deflation scars on the most windswept sites on the polygon surface, which are overgrown by *Ochrolechia frigida* and cup-shaped *Cladonia* species. As a rule, the troughs between polygons are occupied by the same dwarf shrubs and sometimes also by the same lichens. The narrowest troughs lack any vegetation. The mire hygrophilous species and the ice wedges, which are typical for the Arctic polygon mires [11], are always absent in the troughs of the dry polygon peatland. Another difference from palsa and polygon mires is the absence of *Andromeda polifolia*, *Carex rariflora*, *Eriophorum vaginatum*, *Sphagnum* spp., etc. in the communities of the top of the polygons. Such communities with some variations in structure and floristic compositions are typical for the dry peatlands of the studied islands, except for Veshnyak Island. On the latter island, the studied peatlands have hummocky-hollow relief. The hummocks 40–60 cm high are covered by heath with abundance of *Empetrum hermaphroditum*, *Rubus chamaemorus*, *Betula nana* and sometimes of lichens (*Cladonia* spp., *Cetraria islandica*); *Carex rariflora* is constant. The hollows are dry with mineral substrate or a thin peat layer on the bottom. There are scattered *Polytrichum* spp., lichens, liverworts and solitary *Salix glauca* or *S. lanata* in them.

4.2 Peat stratigraphy

The peat deposits are dry. The fragments of permafrost are observed only on the northeastern islands (Danilov, Sosnovetz). It occurs in the central parts of peat blocks at the depth of 40 cm and penetrates deeper into the sand. The basal layer of the deposit is dense dark brown peat while the upper layer is more bulk, have lighter brown tint and permeated with living roots of shrubs.

The basal layer of the deposits is composed of cottongrass peat with decomposition degree 35% or more. Besides *Eriophorum*, remnants of Ericales, *Rubus chamaemorus*, *Salix*, *Betula*, *Spagnum* sect. *Cuspidata*, *Dicranum*, *Polytrichum* are common. The remnants of *Carex rariflora*, *C. aquatilis*, *Equisetum* and herbs are less seen. Almost pure cottongrass deposit was observed only once – at the foothill of Danilov island (figure 3a), where it was overlapped with a layer of logs, brought by the sea (not shown on the graph). In addition, the basal peat layer is frozen here; both of these factors prevent the penetration of shrub roots into the underlying deposit. In addition to the *Eriophorum*, there are remnants of *Salix*. The maximum thickness of the cottongrass basal peat is 25–30 cm (figure 3b, l). In some cases *Eriophorum* is not absolute dominant of basal peat, although it is present in significant amounts (figure 3c, h, k).

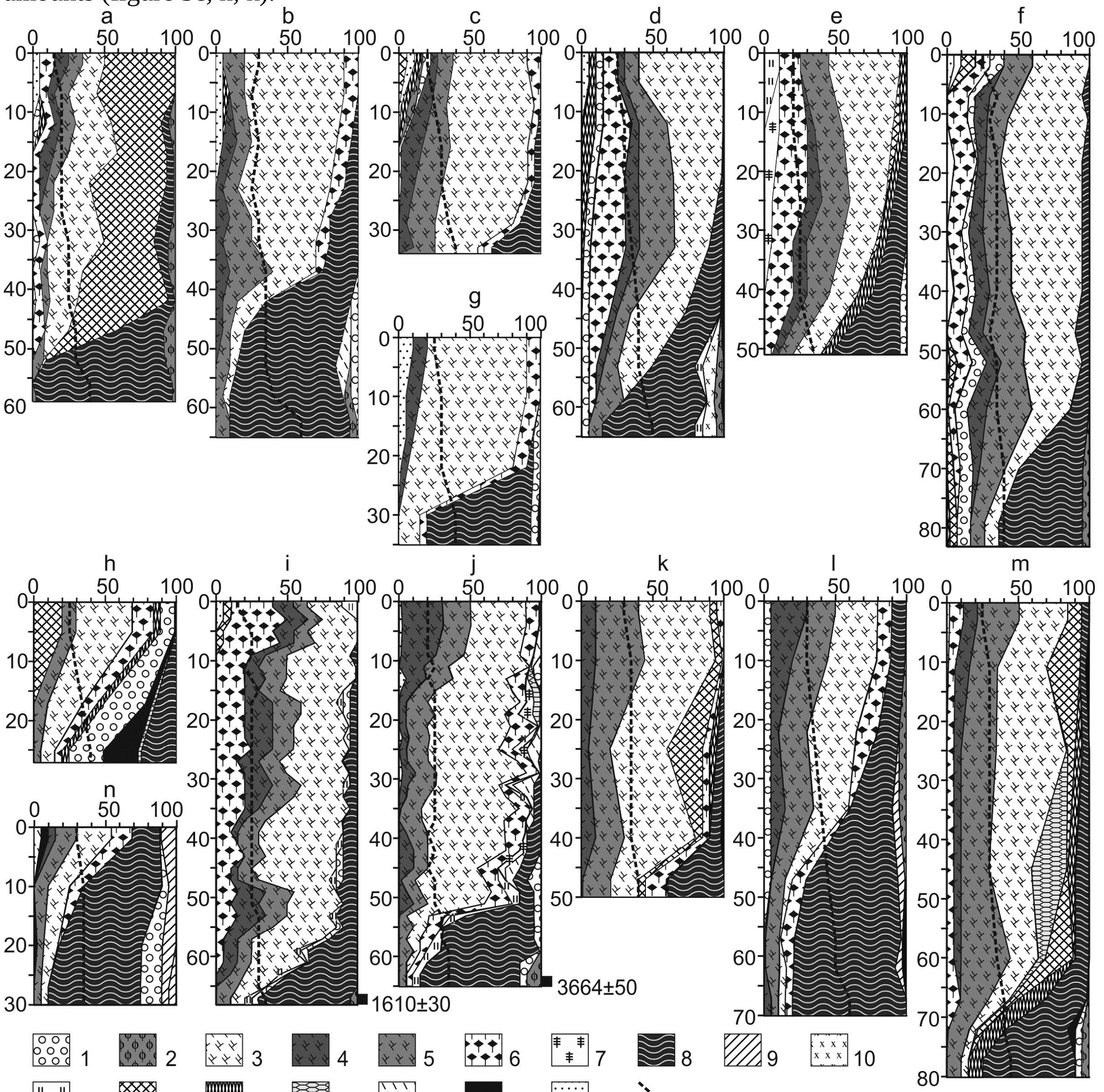

Figure 3. Peat macrofossil composition columns (a–n – Islands: a–c – Danilov (a – foothill, b – seaside slope, c – hilltop); d–f – Sosnovetz (d – shoreside slope, e – foothill, f – seaside slope); g – Unnamed island near Goryainov island; h, n – Veshnyak (hilltops); i – Stolbovaya Luda; j – Bol'shaya Srednyaya Luda; k – Bol'shoy Rob'yak; l – Sharapikha; m – Zelenaya luda. 1–17 – Macrofossils: 1 – *Betula nana*, 2 – *Salix*, 3 – *Empetrum*, 4 – *Vaccinium*, 5 – Ericales (undetected), 6 – *Rubus chamaemorus*, 7 – *Chamaepericlymenum suecicum*, 8 – *Eriophorum*, 9 – *Carex* (*C. rariflora* – i, l, n; *C. aquatilis* – i (bottom)), 10 – *Equisetum*, 11 – Herbs (undetected), 12 – *Dicranum*, 13 – *Polytrichum*, 14 – *Pleurozium*, 15 – Bryales (incl. *Loeskypnum badium* – b, i), 16 – *Sphagnum* (*S.* sect. *Cuspidata* – d, g, k, l; *S. lindbergii* – h; *S. riparium* – n; *S. capillifolium* – m), 17 – Lichens; 18 – Decomposition degree (%).

The cottongrass peat is overlapped by dwarf-shrubs one with decomposition degree of 20–35%. There are deposits with both sharp and slightly more smoothed boundary of dwarf-shrub peat. The most detailed study was carried out at Stolbovaya Luda and Bol’shaya Srednyaya Luda, the transition is relatively smooth on the first one, and on the second island *Eriophorum* content abruptly decreases from 65 to 10%. In the above mentioned Danilov island deposit with artificial boundary in the form of logs the transition of peat layers is quite sharp. *Empetrum* remnants is the dominant of dwarf-shrub peat layer, *Vaccinium* is also usual, some of the shrubs cannot be determined, but most likely they also belong to these genera. *Rubus chamaemorus* is common. Peculiar remnants are of *Dicranum* (probably, *D. elongatum*) and *Polytrichum* species, in some cases, the former plays an essential role (figure 3a). Small cottongrass content (5–10%) can be found close to the surface (up to 5–15 cm); in a few cases, it completely disappears at the depth of 25–30 cm (figure 3j, k). Sometimes there are remnants of *Chamaepericlymenum suecicum*. The thickness of the dwarf-shrub peat layer in the deeper deposits may reach up to 60 cm, in shallow – 15–30 cm.

Commonly, there is no cottongeass at all in the surface layer of peat as well as in the current communities. The other peat forming plants are supplemented with the remnants of lichens and hepatic mosses. The degree of decomposition decreases to 15%. The stratigraphic profile from the Danilov island demonstrates the stratification of these layers over the entire area of the peatland (figure 4).

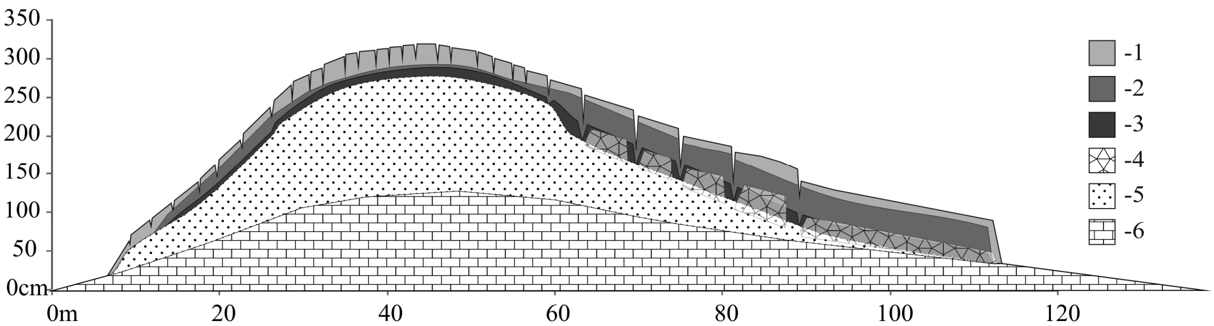

Figure 4. Stratigraphical geological cross-section (west-east direction) of the peatland on Danilov island. 1 – dwarf-shrub peat, 2 – dwarf-shrub peat with cottongrass, 3 – cottongrass peat, 4 – permafrost, 5 – sand, 6 – rock basement (sand/rock boundary is suppositive).

In addition to the typical polygonal patterned peatlands we studied some similar formations. For example, in figure 3 h, n, the stratigraphy of shallow peat deposits of the hummocky-hollow complex from Veshnyak island are given. The main features of the deposit structure are similar to those of the other deposits. The peculiarities are the presence of *Sphagnum lindbergii* remnants in the basal layer in one case and *Carex aquatilis* in the second one as well as the larger role of *Betula nana*.

There are two radiocarbon datings of basal cottongrass peat layers: from the islands Stolbovaya Luda 1610±30 BP (GIN-15057) and Bol’shaya Srednyaya Luda 3664±50 BP (SPb-1928).

5. Discussions

5.1 Paleocommunities

The stratigraphy of the deposit of all polygonal patterned peatlands is rather similar. In all cases two main layers of peat are identified – the basal layer, with the degree of decomposition of 35–50%, consisting predominantly of the remnants of cottongrass and the overlapping layer of dwarf-shrub peat with a degree of decomposition of 20–30%, in which the remnants of cottongrass are found in small amounts close to the surface. Thus, the stratigraphy of the peat deposits identifies two stages of vegetation development. At the first stage the islands were covered by wet cottongrass carpets repeating the convex shape of the relief. In addition to *Eriophorum*, Ericales, *Salix*, *Betula nana*, *Sphagnum* sect. *Cuspidata*, *Carex rariflora*, herbs and some Bryales species were in paleocommunity composition. In conditions of a slow water flow on flat plateaus, as on Veshnyak island, *Sphagnum* and sedges (including *Carex aquatilis*) were abundant.

Currently there are no such communities on the convex relief forms in the region. On some islands of the east of the Kola Peninsula on the mires with permafrost, some thawed hollows occupied by a carpet of cottongrass (*Eriophorum scheuchzeri*, *E. russeolum*, *E. media*) can still be found, but this relates only to the depressions of micro-relief. Mires of convex relief forms with mostly atmospheric nutrition are known as blanket bogs which global distribution today is confined to cool, extremely oceanic climate [12, 13, 14, 15]. The cottongrass is the main peat-forming plant of the blanket bogs in the oligotrophic (acid) conditions [12]. Based on our studies of the deposits, similar paleocommunities occupied large areas on some islands, often being the main type of vegetation in the historical past.

The second stage of peatlands vegetation development was its xeromorphisation. Cottongrass paleocommunities were changed by dwarf-shrub–moss and, later, in some places, by dwarf-shrub–lichen. Most species of cottongrass paleocommunities are absent in the modern flora of peatlands.

5.2 Time frame
The comparison of the current absolute hypsometric position of peatlands with the history of the White Sea level fluctuations during the Holocene allows us to determine to some extent the time of the beginning of the formation of peatland on the islands.

The sea level in the western part during highest middle Holocene transgression (ca. 6250 BP) exceeds present time level for 20–25 m [7] and all studied islands were below sea level or in the zone of active wave action. In the eastern part, the sea level was 10 m higher than the current and some of the islands were under water as well. The sea level experienced weak oscillation till 4000–4100 BP, when it reached 15–17 m [4, 7]. After that, the last significant regression of the sea started (Trivia-Ostrea stages transition). Finally, the White Sea level fell to an absolute 10 m only 2000 years ago. At that time, the lowest of the studied islands in the western part of the sea came to the surface. Thus for the most of the studied peatlands the age of origin cannot exceed 2000–4000 years. The time of peatland initiation on the Bol'shaya Srednyaya Luda (3664 ± 50 BP) is close to that assuming the sea level oscillations.

5.3 Climatic envelopes
The blanket bogs existence in the past in the White Sea region is a remarkable fact. Currently, the nearest active blanket bogs are located in the north of the central part of Norway [13, 14] which is more than 800 km to the northwest from the White Sea coast. The existence of blanket bogs is limited by narrow climatic envelopes [15, 16, 17]. There are several climatic indexes delineating blanket bog formation conditions. Further we compare them with modern conditions along the coast of the White Sea obtained by long-term observations at the weather stations.

The first one is the mean annual temperature (MAT) > −1°C [15]. In this study region the MAT is –0.67 °C (for Sosnovetz island) and 1.4 °C (for Kem' river estuary), thus, throughout the region, the MAT does not exceed the climatic limits for the blanket bogs. Accordingly [16] blanket bogs occur in Fennoscandia in areas where the annual temperature varies from 1.5 to 6.7 °C, but in their opinion, temperature variables here appear not to be as important climate determinants.

Another temperature parameter, the mean temperature of the warmest month (MTWA) varies from 8.5 (Sosnovetz) to 14.2 (Kem'), which corresponds to MTWA < 14.5 °C [15] and MTWA 10.0–14.1 °C [16]. The last important temperature parameter is continentality (yearly thermic interval, max.–min. of monthly mean temperatures); for Sosnovetz (21.0) and Kem' (27.2) it exceeds the upper climatic limit of 18.9 [16] due to low winter temperatures.

The second important group of parameters relates to precipitation. In accordance with [16] the mean annual precipitation (P) explained almost 60% of variation in blanket bog occurrence in Fennoscandia. The greatest discrepancy between the current climatic conditions of the White Sea area and the blanket bog regions is in much lower precipitation amount. Blanket bogs occur in Fennoscandia in the areas where P exceeds 1018 mm [16], whereas the long-term mean for Sosnovetz

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and Kem' is 2–3 time less.

The moisture index, MI (ratio of P to equilibrium evapotranspiration) might be expected to capture the distribution of peatlands better than merely P because the latter neglects the large differences in evaporative demand between climates at different latitudes and with differing degrees of cloudiness [17]. MI for blanket bogs occurrence area is > 2.1. The gross evaporation for Ponoi river watershed is 236 mm and for Kem' river is 356 mm, the calculation model demonstrates similar values [18]. So, accordingly to gross evaporation MI is 1.45 for Ponoi–Sosnovetz and 1.19 for Kem' area, which is also significantly lower than MI of blanket bogs region. It turns out that with the same evaporation rate, to create conditions for the initiation of blanket bogs, the amount of precipitation should increase by 152 mm (30%) in the Ponoi–Sosnovetz and 322 mm (43%) in the Kem' area.

5.4 Past climatic possibilities for blanket bog initiation

For the eastern Fennoscandia there are a number of spore-pollen diagrams for organic deposits of mires, on the basis of which the quantitative characteristics of the paleoclimate were determined using the information statistical method based on a nonlinear statistical relationship of current climate conditions with the surface (subrecent) pollen spectra [19]. One of such pollen-based climatic reconstructions was made for Lovozero mire from inner part of Kola Peninsula [20]. It allows tracing possible climatic circumstances for the initiation of blanket bog formation during the Holocene.

The most favorable conditions for the blanket bogs inception initiations were during the climatical optimum in the Atlantic period (higher amount of precipitation, lower rate of climate continentality). At that time, the most massive formation of blanket bogs over Great Britain started [12, 15]. However, the studied islands were hidden by the waters of the White Sea.

At the transition of the Atlantic and Subboreal periods 4500 BP there was a significant global cooling during which palsa mires started to form on the Kola Peninsula about 4000 BP [20]. The next warming maximum occurred in 3500 BP. Precipitation exceeded the current level by 50 mm, the temperature - by 2 °C, the climate continentality decreased. The radiocarbon date of the basal cottongrass peat layer from Bol'shaya Srednyaya Luda (3664 ± 50 BP) exactly corresponds to this climate shift. We suppose that during this warming in the middle of the Subboreal the blanket bogs started to form on the White Sea islands. At the same time, the extension of blanket bogs on the British islands is traced [15], as well as peatland formation on the fells of Finnish Lapland [21]. So, the climate of Northern Europe at this time contributed best to the expansion of the blanket bogs.

However, some of the studied islands at this time were still below the sea level. The last warming event occurred in the lesser climatic optimum of the Medieval period, with the maximum about 1000 years ago. Radiocarbon dating from the Stolbovaya Luda (1610±30 BP) is of a slightly older age. The amount of precipitation exceeded then the current level by 75 mm, temperature - by 1–2 °C [20]. By that time all the surveyed islands already appeared. The above comparative climate data show that an increase in MAT and MTWA by 1–2 degrees would not exclude these areas beyond the climatic optimum for the development of blanket bogs. The continentality decline is due to a greater increase in winter temperatures; it could even approach the upper optimum limit.

To the greatest extent, the climatic optimum is not matched by precipitation. The above calculations show that at the same rate of evaporation, the amount of precipitation required for blanket bog initiations should have exceeded the current ones by 150–300 mm. The calculated precipitation rate [20] refers to the inner part of the Kola Peninsula; perhaps the increase in precipitation at the seashore was significantly greater. Moreover, the islands might have inherent lower evaporation due to higher permanent air humidity on the sea coast in comparison with the inner regions of the continent. The average annual air humidity at Sosnovetz is 89%, whereas at the Kanevka weather station located in the interior of the mainland at 80 km from Sosnovetz is 82%. In the warm months the difference is even more significant (89% and 78%). There are 60–70 days with fog during year in the northern part of the White Sea and in the summer months fogs occur every 3 days [22]. These factors reduced the evaporation and led to an increase of the substrate humidity.

It is known that the climate of the White Sea is unstable both on a short-term and on a long-term scale [8, 23]. Currently, the increase in precipitation is observed, i.g. for Kem' annual precipitation grows from 425 (1968 yr) to 514 (2014 yr), i.e. at 89 mm, significant growth is also observed at the other stations along the White Sea [23]. It is caused by the intensification of cyclonic activity and the increase in the intensity of precipitation [24]. Thus, it can be assumed that the amount of precipitation on the White Sea coast in the past could also be significantly higher than the current level and conditions for the blanket bogs development might well exist.

The warm period was replaced by a "small Ice Age" with an extreme at about 800 BP, when precipitation and temperature were lower than the present-day values by 50 mm and by 3–4 °C (2 °C in July) and the climate continentality increased. That cooling event led to degradation of Sphagnum on palsas and the formation of dwarf shrub and lichen communities, which still persist in the area [20]. We assume that at the same time the blanket bogs of the White Sea islands might dry up.

Indirectly, it is indicated by the position of the lower boundary of the peatlands at about 10 m a.s.l. in the western part of the sea. The slopes of the islands appeared less than 1000 years ago were never occupied by cottongrass communities. In the northeastern islands, which are currently experiencing subsidence [7], the peatlands extend to supralittoral grass communities.

The existence of permafrost fragments in blocks of some northern peatlands is an interesting fact. There is a suggestion that the permafrost as waterproof horizon, can contribute to the blanket bogs development [25]. However, the studies of climatic envelops [15, 16] show that palsa mires and blanket bogs in the north of Europe have a clear thermal disjunction, which means that they cannot be at one time in one place. Suggesting, the development of permafrost in the peatlands of the White Sea islands occurred later or during the changes in their plant communities. As in the case of Fennoscandia palsa mires [26], the existence of permafrost is currently maintained in them due to strong winds, which are drying the peat surface and keeping it clear of snow in winter.

6. Conclusion

The drying out polygonal patterned peatlands of summits and slopes of the White Sea islands are the evidence of blanket bog existence during a more humid climate periods of 1000–4000 years ago. The amount of precipitation on the White Sea coast required for their existence at that time had to exceed significantly the previously assumed value. To the present time, these peatlands stopped their development and the erosion processes are prevailing. This study provides only a general idea about the history of their development. Relict peatlands of the islands of the White Sea are quite unique formations and undoubtedly require further investigations.

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References

[1] Slabunov A I, Stepanova A V, and Sibelev O S 2008 Geological characteristics *Rupestrian Landscapes of the White Sea Karelian Coast: Natural Characteristics, Economic Utilization, Conservation* ed A N Gromtsev (Petrozavodsk: Karelian Research centre of RAS) chapter 1.2 pp 8–15

[2] Systra Y I 2003 Geologic characteristics *Biotic Diversity of Karelia: Conditions of Formation, Communities and Species* ed A N Gromtsev et al (Petrozavodsk: Karelian Research centre of RAS) chapter 1.2 pp 7–12

[3] Pozhilenko V I, Gavrilenko B V, Zhirov D V and Zhabin S V 2002 *Geology of mineral areas of the Murmansk Region* (Apatity: Kola Science Centre RAS) p 359

[4] Elina G A 2008 Mires and paludified lands characteristics *Rupestrian Landscapes of the White Sea Karelian Coast: Natural Characteristics, Economic Utilization, Conservation* ed A N Gromtsev (Petrozavodsk: Karelian Research centre of RAS) chapter 2.1 pp 28–50
[5] Zaretskaya N E, Shevchenko N V, Simakova A N and Sulerzhitsky L D 2011 *Geochronometria* **38 (2)** 116–127
[6] Kaplin P A and Selivanov A O 1999 *Changes in the Sea Level of Russia and the Coast Development: Past, Present, Future* (Moscow: GEOS) p 288
[7] Koshechkin B I 1979 *The Holocene Tectonic of the Eastern Part of Baltic Shield* (Leningrad: Nauka) p 158
[8] Filatov N N, Pozdnyakov D V, Johannessen O M, Pettersson L H and Bobylev L P 2005 *White Sea. Its Marine Environment and Ecosystem Dinamics Influenced by Global Change* (Chichester: Springer-Praxis Publ.) p 472
[9] *Vegetation of the European Part of the USSR* 1980 ed E M Lavrenko et al (Leningrad: Nauka) p 236
[10] Novakovskiy A B and Elsakov V V 2014 *Data Science Journal* **13** 57–63
[11] Boch M S, Gerasimenko T V and Tolchelnikov Yu S 1971 *Botanical Journal* **56 10** 1421–1435
[12] Moore P D, Merryfield D L and Price M D R 1984 The Vegetation and Development of Blanket Mires *European Mires* ed P D Moore (London: Acad. Press) 203–235
[13] Moen A 1999 Vegetation *National Atlas of Norway* (Hønefoss: Norwegian Mapping Authority) 200
[14] Pajunen H 2005 Mires *The Physical Geography of Fennoscandia* ed M Seppälä (Oxford: Oxford University Press) 77–95
[15] Gallego-Sala A V, Charman D J, Harrison S P, Li G and Prentice I C 2016 *Clim. Past* **12** 129–136
[16] Parviainen M and Luoto M 2007 Climate envelopes of mire complex types in Fennoscandia *Geogr. Ann.* **89 (2)** 137–151
[17] Gallego-Sala A V, Clark J, House J I, Orr H G, Prentice I C, Smith P, Farewell T and Chapman S J 2010 *Clim. Res.* **45** 151–162
[18] Salo Yu A, Nazarova L E and Balagansky A F 2016 *Trans. Karelian Research Centre RAS* **9** 95–101
[19] Klimanov V A 1976 *Vestn. Moscow State University* Ser 5 Geography **2** 92–98
[20] Elina G A, Arslanov Kh A, Klimanov V A and Usova L I 1995 *Bot. J.* 80 (3) 1–16
[21] Luoto M and Seppälä M 2000 *The Holocene* **10 (2)** 229–241
[22] Vasilyev L Yu and Vodovozova T E 2010 Climate *The White Sea system* ***1*** *Natural environment of the catchment area of the White Sea* ed I A Nemirovskaya and V P Shevchenko (Moscow: Scientific World) pp 16–39
[23] Tolstikov A V 2016 *Variability of the Surface Layer Temperature of the White Sea* (Moscow: GEOS) p 212
[24] Filatov N N, Nazarova L E, Georgiev A P, Semenov A V, Anciferova A R, Ozhigina V N and Bogdan M I 2012 *Arctic: Ecology and Economy* **2(6)** 80–93
[25] Neshatayeva V Yu and Neshatayev V Yu 2006 *Proc. Int. Symp. Mire Ecosystems in Nothern Europe: Diversity, Dynamics, Carbon Balance, Resources and Conservation (Petrozavodsk: aug. 30 – sept. 2 2005)* (Petrozavodsk: Karelian Research centre of RAS) pp 181–192
[26] Seppälä M 2011 *Quaternary Research* **75 (2)** 366–370