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Impact of Climate Change on Vegetation and Permafrost in West Siberia Subarctic

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/54951>

1. Introduction

The goal of this ongoing study is to examine the impact of climate change on vegetation and permafrost in ecosystems of West Siberia Subarctic. Results of long-term monitoring of northern taiga ecosystem under impact of climatic changes are presented.

The warming of an observable climate from the end of 20th century was accompanied by changes of vegetation and permafrost degradation, especially in the zone of sporadic permafrost. This important problem is examined in works of many researchers (Tyrtikov, 1969, 1979; Belopukhova, 1973; Brown, Pewe, 1973; Nevecherya et al, 1975; Yevseyev V.P, 1976.; Nelson et al. 1993; Ershov et al. 1994; Pavlov 1997, 2008; Moskalenko, 1999; Osterkamp et al. 1999; Parmuzin & Chepurnov 2001; Izrael et al. 2002, Kakunov & Sulimova 2005; Hollister, Webber & Tweedie, 2005; Walker et al. 2006; Perlstein et al. 2006; Oberman 2007; Leibman et al. 2011). They demonstrated that freezing and thawing conditions change in response to the vegetation dynamics. Increases in moss and lichen cover thickness result in the reduction of active layer thickness, and decreases in soil and ground temperatures. However in these works not enough attention was given to estimated impact of climate on the vegetation and permafrost in the ecosystems. In the present report the author tries to fill this deficiency based on long-term monitoring of changes in the northern taiga ecosystem of Western Siberia.

2. Location and parametric considerations

Research on ecosystems were carried out since 1970 on the Nadym stationary site (Fig. 1), located 30 km to a southeast from the town of Nadym (Moskalenko, 2006) in the zone of sporadic permafrost distribution (Melnikov, 1983). Patches of permafrost, occupying up to 50% of areas, are closely associated with peatlands, peat bogs, and frost mounds of III

fluvial-lacustrine plain having elevations ranging from 25 to 30m above sea level. The plain is composed of sandy deposits interbedded with clays, with an occasional covering of peat (Andrianov et al. 1973).

During ecosystem monitoring were used remote and cartographical methods. Office studies and field decoding of remote sensing materials from 1970 up to 2009 was added by land route and detail field descriptions on permanent transects and 10x10m plots, fixed on a terrain. Leveling of permanent marks was carried out by electronic level Sprinter 150M every year. Two times for observation period near plots biomass resources were determined. Repeated mapping of vegetation was performed on 1x1m permanent grids for studying of vegetation structure and dynamics. Annual geobotanical descriptions are made on 28 permanent fixed (10 x 10 m) plots. The structure, average height, phenological and vital condition, frequency and coverage of plant species on 50 registered 0.1m² plots were recorded.

Study of spatial and temporal patterns of active layer thickness, caused with microrelief and vegetation mosaic was carried out on 100x100m CALM (Circumpolar Active Layer Monitoring) grid. On 121-grid nodes detail vegetation descriptions and repeated leveling of microrelief were performed. It would reveal some correlations between active layer thickness, vegetation and microrelief. In 16 10-m boreholes and 1 30-m borehole were established loggers Hobo, and measurements of permafrost temperature were carried out by project TSP (Thermal State of Permafrost). Air and soil temperatures were measured too. Monthly average and mean annual temperatures of air and grounds in a wood and on a peatland are resulted in tables 1 and 2.

3. Investigations and observations

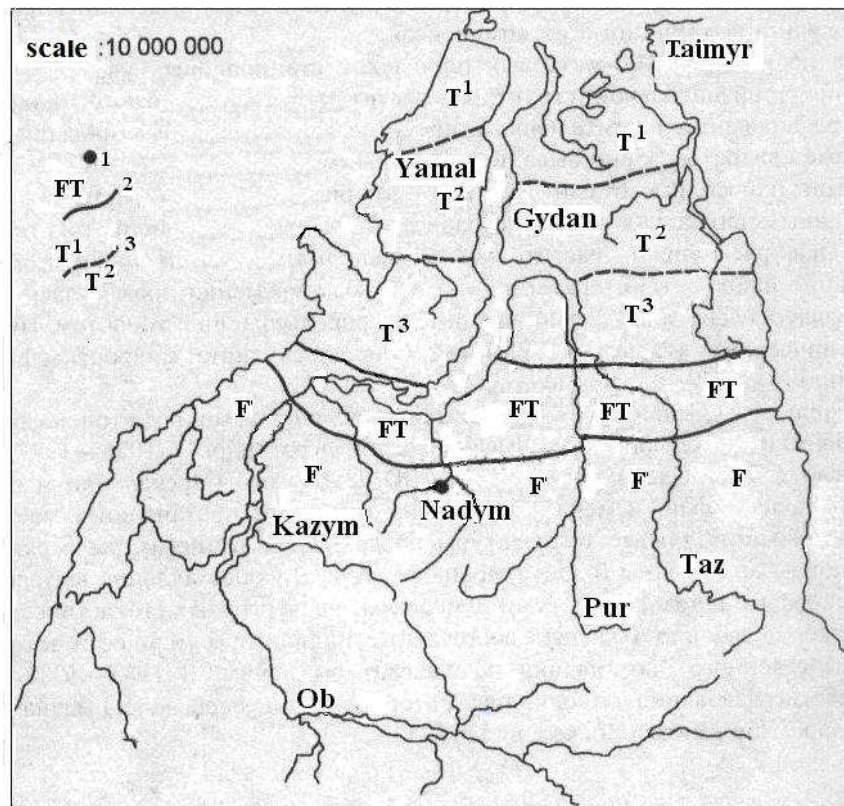
Ecosystem changes have been revealed as a result of 40-years observation over a microrelief, species composition of a vegetation cover, height, frequency and coverage of dominant species of plants, soil and permafrost temperature, thickness and moisture of active layer on permanent plots and transects.

3.1. Impact of increase in amount of atmospheric precipitation on vegetation and permafrost

The analysis of the received data has allowed to revealing tendencies in development of a natural vegetation cover. In wood communities in connection with increase of atmospheric precipitation amount which is marked last decades, the increase in participation of mosses, and change of green moss-lichen sparse forests by lichen-green moss plant communities on drained sites is observed. Changes of atmospheric precipitation (Fig. 2) and *Cladina rangiferina* frequency (Fig. 3) in Birch-pine sparse forest are presented. Coverage of *Pleurozium Schreberi* opposite increases (Fig. 4).

In connection with the increase of atmospheric precipitation process of bog formation on flat poorly drained surfaces of plains becomes more active. As a result hummocky pine

cloudberry-wild rosemary-lichen-peat moss open woodlands were replaced by *andromeda*-cotton grass-sedge-peat moss bogs. Hummocks settled, and the lenses of permafrost under hummocks thawed.



1– site, 2 – boundaries of zones (T – tundra, FT – forest tundra, F – taiga) 3 – boundaries of tundra subzones (T¹ – northern, T² – typical, T³ – southern).

Figure 1. Location of the Nadym site

Depth, m, year		Months												Year
		1	2	3	4	5	6	7	8	9	10	11	12	
Air	a	-17,8	-18,5	-14,6	-9,5	2	-8,7	15,9	11,6	5,9	-3,1	-14	-16,1	-4,1
	b	-24,3	-28,2	-14,5	-6,4	-2,1	10,1	15,1	11,4	8	-2,4	-21,4	-33,8	-7,4
0	a	-2,7	-2,5	-3,1	-2,2	-0,16	7	12,9	11,5	5,8	0,49	-2,4	-1,8	1,9
	b	-1,8	-2,5	-2,2	-1,2	-0,1	5,1	11,8	9,8	7,6	1	-2,6	-3,1	1,3
0,25	a	-0,3	-0,5	-0,9	-1,0	-0,3	0,0	5,5	8,1	6	2,3	0,5	0,1	1,6
	b	0	-0,2	-0,5	-0,5	-0,1	-0,1	5,7	7,8	6,6	3,2	0,4	0	1,8
0,5	a	0,2	0	-0,4	-0,6	-0,1	0,0	3,6	6,8	5,9	2,9	1,2	0,6	1,7
	b	0,4	0,2	0	-0,2	0	0	3,8	6,4	6,2	3,8	1,2	0,5	1,9
1	a	0,5	0,3	0,1	-0,1	-0,1	0,0	2,0	5,3	5,3	3,3	1,7	1	1,6
	b	0,7	0,5	0,2	0,1	0,1	0,2	2,4	4,8	5,6	4,1	1,9	1	2,1
1,5	a	0,8	0,8	0,4	0,2	0,2	0,2	1,3	4,3	4,7	3,5	2	1,3	1,6
	b	1	0,7	0,5	0,3	0,3	0,3	1,5	3,9	4,8	4	2,2	1,3	2,2
3	a	2,1	1,6	1,4	1	1	0,9	0,8	1,5	2,0	2,0	1,5	1,0	1,4

Table 1. Monthly average and mean annual temperatures of air and grounds in the wood (a -2008, b -2009).

Depth, m, year		Months												Year
		1	2	3	4	5	6	7	8	9	10	11	12	
Air	a	-17,2	-18,9	-15,7	-11	0,8	8,5	15,8	11,7	6,1	-2,8	-13,8	-16	-4,4
	b	-24,2	-28,3	-15,4	-8,2	-3,9	9,5	15	13,8	8,3	-2,1	-21,2	-33,3	-7,5
0	a	-2,5	-2,5	-2	-0,9	1,1	7,9	13,3	11,3	5,5	0,12	-1,6	-0,9	2,1
	b	-2,5	-2,5	-2	-0,9	1,1	7,9	13,3	11,3	5,5	0,12	-1,6	-0,9	2,1
0,25	a	-0,5	-0,6	-0,7	-0,5	-0,2	0,8	3,8	5,6	3,9	0,5	-0,1	-0,1	1,0
	b	-0,3	-0,8	-0,8	-0,5	-0,2	0,7	4,2	6,3	4,8	1,6	-0,1	-0,3	1,2
0,5	a	-0,1	-0,1	-0,3	-0,3	-0,1	-0,1	1,0	3,9	3,1	0,5	-0,0	-0,0	0,6
	b	-0,1	-0,1	-0,3	-0,3	-0,1	-0,1	0,8	4	3,8	1,5	0	0	0,8
1	a	-0,0	-0,0	-0,0	-0,0	-0,0	-0,0	-0,0	1,9	1,8	0,3	-0,0	-0,0	0,3
	b	-0,0	-0,0	-0,00	-0,1	-0,0	-0,0	-0,0	1,1	1,6	1,5	0,8	0,2	0
1,5	a	-0,1	-0,1	-0,1	-0,1	-0,1	-0,0	-0,0	0,6	0,7	0,1	-0,1	-0,1	0,1
	b	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	0	0,2	0,6	0,5	0,3	0	0
3	a	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1
	b	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1

Table 2. Monthly average and mean annual temperatures of air and grounds on the peatland (a -2008, b -2009).

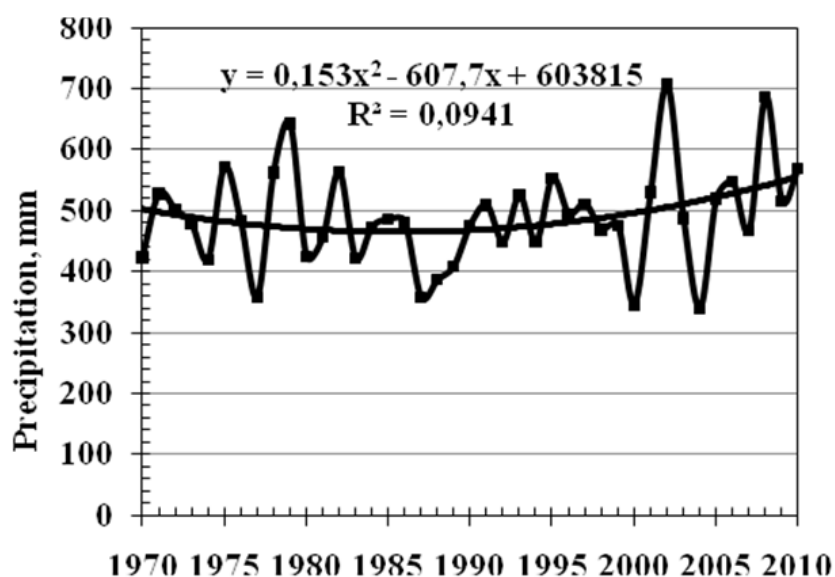


Figure 2. Amount of atmospheric precipitation

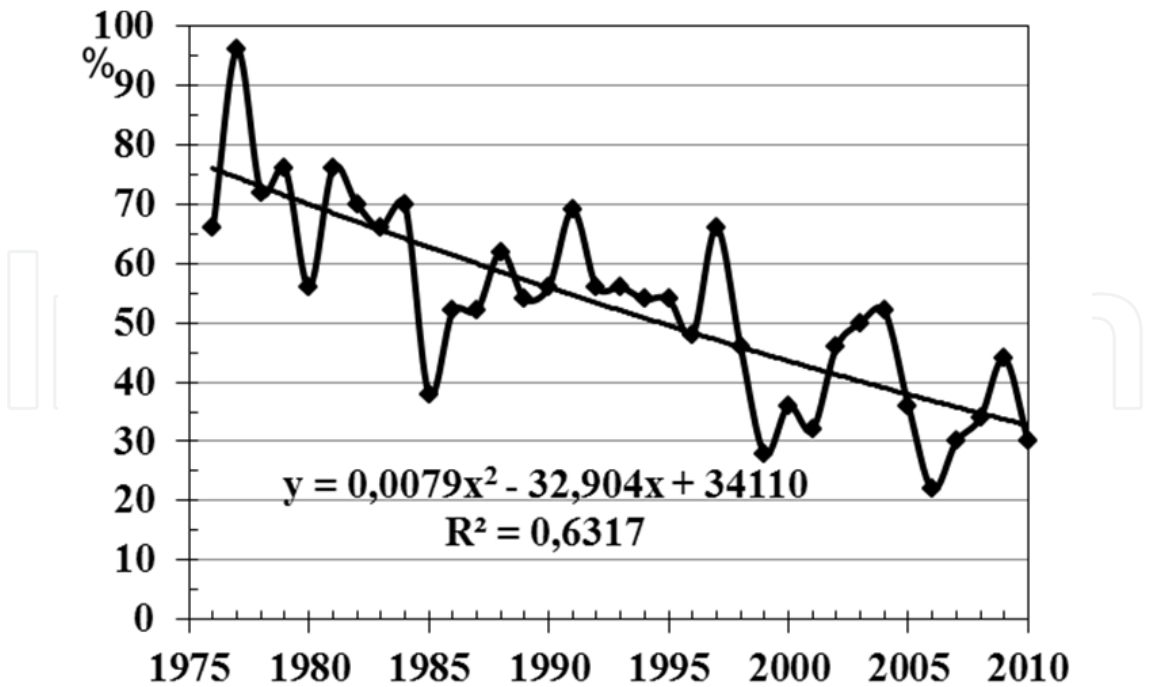


Figure 3. Frequency changes of *Cladina rangiferina* in Birch-pine sparse forest

The frequency of wild rosemary (*Ledum palustre*) which dominated in a cover of the open woodland fell sharply after 1997 (Fig. 5, 2). The frequency of cotton-grass (*Eriophorum angustifolium*) for the past decade increased, and it began to dominate the cover (Fig. 5, 1).

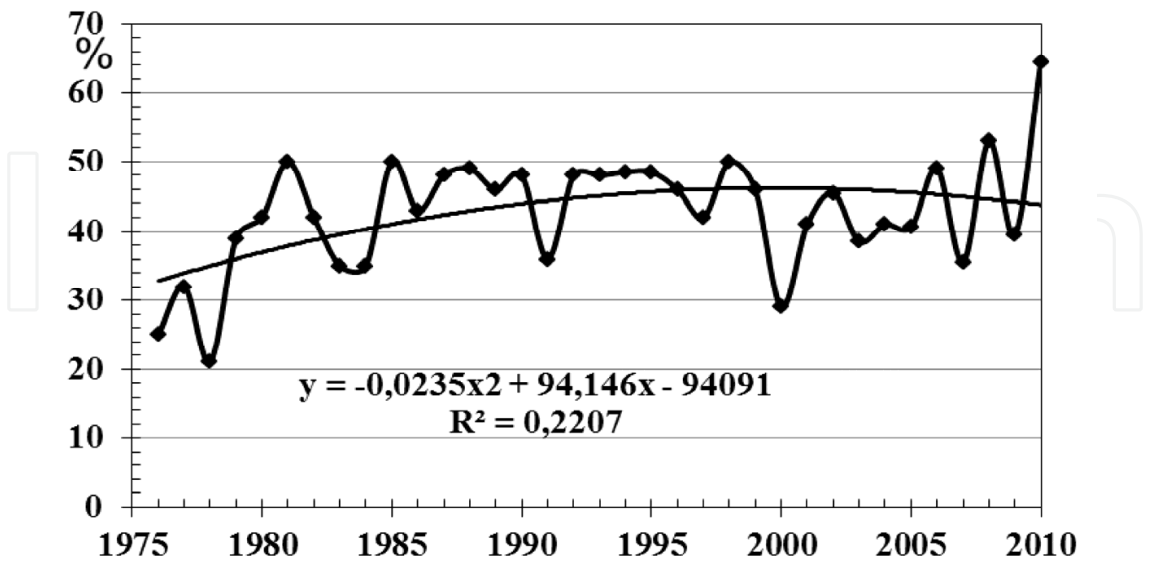


Figure 4. Coverage changes of *Pleurozium schreberi* in Birch-pine sparse forest

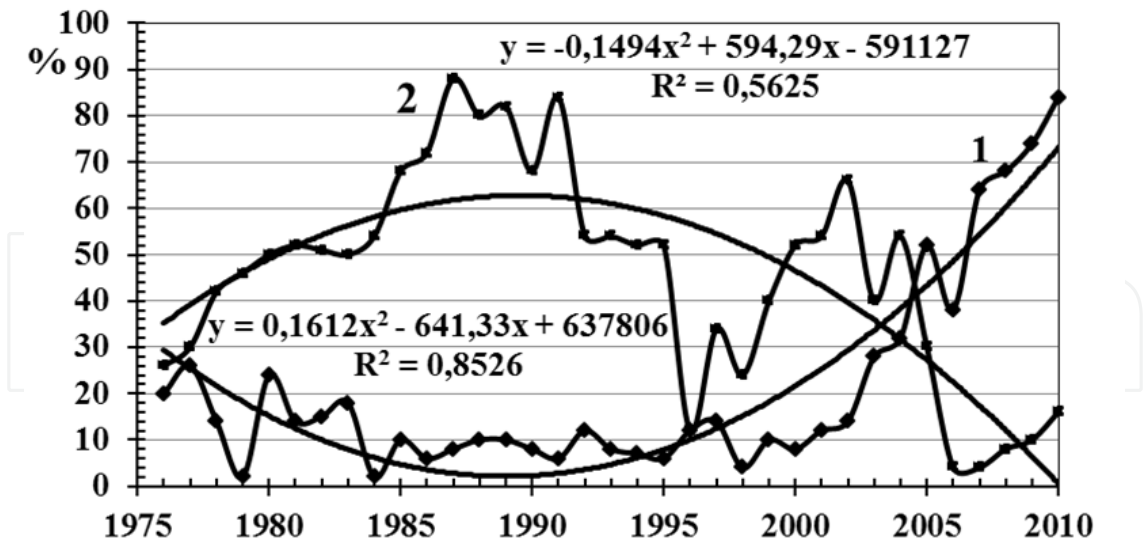


Figure 5. Frequency changes of *Ledum palustre* (2) and *Eriophorum angustifolium* (1) on flat boggy site

Comparison of biomass in wood communities and bog communities shows that by bog formation in wood all aboveground biomass decreases from 2316 to 1715 g/m² and biomass of graminoid and mosses increases (table 3). Comparison of species composition of wood and bog plant communities presents that biodiversity of vegetation cover in process of bogginess decreases in the result of absence mesophyte species of sedges and shrubs (*Carex globularis*, *Empetrum nigrum*, *Vaccinium vitis-idaea*), and also lichens (*Cladina rangiferina*, *C. stellaris*, *Cetraria islandica*, *Cladonia coccifera*, table 4). Common number of species decreases from 27 to 17.

Vegetation		Wood	Bog	Tundra
Deciduous shrubs	Stems	41	84	10
	Live leaves	9	23	1
	Dead leaves	1	0	0
	Berries	0,5	1	0
Evergreen shrubs	Stems	141	141	141
	Live leaves	66	84	33
	Dead leaves	2	4	1
	Berries	0,2	2	1
Graminoid	Live leaves	0.3	3	14
	Dead leaves	0.3	19	46
Forb		2	13	3
Mosses	Live	80	383	1
	Dead	274	272	1
Lichens	Live	812	228	930
	Dead	400	104	524
Litter		490	317	215
All biomass		2316	1715	1926

Table 3. Aboveground biomass (g/m²) of different plant communities on the Nadym site.

Species	Year	Height, cm	Coverage, %	Frequency, %
1. <i>Andromeda polifolia</i>	1	7	2	54
	2	12	4	72
	3	15	5	76
	4	15	3.5	72
	5	15	1	54
2. <i>Betula nana</i>	1	45	2	16
	2	65	1	30
	3	80	2.5	32
	4	80	0.8	14
	5	80	0,1	2
3. <i>Calamagrostis lapponica</i>	1	30	<1	2
	2	70	0.1	12
	3	25	0.5	10
	4	60	<1	<1
	5	50	<1	<1
4. <i>Carex globularis</i>	1	20	4	32
	2	25	7	64
	3	30	4.5	52
	4	35	0.1	2
	5	-	-	-
5. <i>Carex rotundata</i>	1	20	<1	10
	2	30	1	12
	3	60	0.5	4
	4	50	0.1	4
	5	30	1.5	28
6. <i>Empetrum nigrum</i>	1	4	1	6
	2	10	1	10
	3	10	1	14
	4	8	0.1	2
	5	-	-	-
7. <i>Eriophorum angustifolium</i>	1	30	4	20
	2	50	0.2	10
	3	75	1.5	6
	4	100	2	52
	5	60	10.5	84
8. <i>Eriophorum vaginatum</i>	1	30	1	1
	2	60	0.2	10
	3	30	1	14
	4	50	0.1	2
	5	60	3	14
9. <i>Juncus filiformis</i>	1	15	0.1	4
	2	35	0.1	4
	3	40	1	8
	4	30	2	8
	5	40	2	6

Species	Year	Height, cm	Coverage, %	Frequency, %
10. <i>Ledum palustre</i>	1	30	7	32
	2	40	3	48
	3	40	8	60
	4	40	1.5	2
	5	40	1.5	2
11. <i>Oxycoccus microcarpus</i>	1	1	5	44
	2	2	2	30
	3	2	1.5	30
	4	2	0.1	2
	5	2	1	10
12. <i>Pinus silvestris</i>	1	300	<1	<1
	2-4	-	-	-
	5	45	<1	<1
13. <i>Rubus chamaemorus</i>	1	3	14	52
	2	9	3	46
	3	10	8	52
	4-5	-	-	-
14. <i>Vaccinium myrtillus</i>	1	3	1	28
	2	10	3	44
	3	15	1.5	42
	4-5	-	-	-
15. <i>Vaccinium uliginosum</i>	1	20	6-	54
	2	30	10	60
	3	30	15	72
	4	40	0.1	2
	5	40	0.6	16
16. <i>Vaccinium vitis-idaea</i>	1	4	<1	<1
	2	6	1	12
	3	10	1	22
	4-5	-	-	-
17. <i>Cetraria islandica</i>	1	1	0.1	2
	2	2	0.2	8
	3	5	1	6
	4-5	-	-	-
18. <i>Cladonia coccifera</i>	1	1	1	4
	2	1	1	4
	3	3	0.1	4
	4-5	-	-	-
19. <i>Cladina rangiferina</i>	1	6	1	4
	2	7	1	22
	3	7	3.5	26
	4-5	-	-	-
20. <i>Cladina stellaris</i>	1	7	4	10
	2	8	3	22
	3	8	0.2	8

Species	Year	Height, cm	Coverage, %	Frequency, %
	4-5	-	-	-
21. <i>Aulacomnium palustre</i>	1	2	0.1	2
	2	2	0.1	2
	3	2	<1	<1
	4	-	-	-
	5	2	<1	<1
22. <i>Dicranum congestum</i>	1	1	0.1	2
	2	1.5	0.1	2
	3	2	3	6
	4	-	-	-
	5	0.5	0.1	4
23. <i>Pleurozium schreberi</i>	1	1	8	20
	2	2	28	42
	3	4	20.5	40
	4	4	0.1	2
	5	4	2	8
24. <i>Polytrichum commune</i>	1	3	3	38
	2	8	16	60
	3	8	21	70
	4	8	0.2	2
	5	8	25.5	66
25. <i>Sphagnum angustifolium</i>	1	1	11	18
	2	4	7	14
	3	4	6	8
	4	4	0.1	2
	5	5	19	48
26. <i>Sphagnum fuscum</i>	1	2	36	52
	2	2.5	21	24
	3	3	25	28
	4	3	0.1	2
	5	3	9.5	20
27. <i>Sphagnum lindbergii</i>	1	4	23	34
	2	8	8	14
	3	8	5	10
	4	8	<1	<1
	5	8	26.5	36

Table 4. Species composition of vegetation on flat boggy site in 1975 (1), 1985 (2), 1995 (3), 2005 (4) and 2010 (5) years.

3.2. Impact of increase in air temperature on vegetation and permafrost

Last decades in the north of Western Siberia rise in air temperature is observed (Fig. 6). Increase of the air thawing index (the sum monthly mean air temperatures above 0°C) caused the appearance on flat and palsa peatlands separate trees (*Betula tortuosa*, *Pinus sibirica*, *Pinus silvestris*); increase in frequency and height of shrubs (*Betula nana*, *Ledum*

palustre, Fig. 7) and coverage them of a soil surface. These plant species can serve as indicators of climate warming.

Long-term studying of plants communities and active layer thickness in northern taiga has allowed calculating of plant communities frequency with active layer thickness. The smallest values of active layer thickness (67.1 cm) are observed under *Rubus chamaemorus-Ledum palustre-Sphagnum-Cladina rangiferina* cover on flat peatland (coefficient of correlation -0.71). Areas with deepest active layer thickness (173.7 cm) are confined to large sedge-moss pools within peatlands (coefficient of correlation 0.58).

The analysis of the given measurements of the active layer thickness on palsa peatland (Fig. 8) has shown that it has a trend to the increase, caused by increase in the thawing index of air temperature, which trend for 1970-2010 makes 0.2°C in a year. The permafrost temperature at the depth of 10m has increased on 1.4°C. Temperature of permafrost at the depth of 10m (layer with minimum annual fluctuations of temperatures) for the period of researches on the palsa peatland has increased from -1.8°C up to -0.4°C (Fig.9, 2). On flat peatland increase of permafrost temperature was less; here permafrost temperature at the depth of 10m has increased from -0.9°C up to -0.2°C (Fig.9, 1).

Increase in air temperature and rise in amount of atmospheric precipitation promoted faster recovery of a vegetation cover after a fire. For example, on frost mounds with *Pinus sibirica*-wild rosemary-peat moss-lichen open woodland in 35 years after the fire *Betula nana*-wild rosemary-peat moss-lichen community with *Pinus sibirica* in height 2m had developed (Fig.10).

On the permanent plot located on a flat southern slope the frost mound in height of 3 m. In a well-defined microrelief of tussocks and hummocks height up to 0.8m are characteristic. Pools were usual, sometimes filled with water.

Soil is sandy peat-gley, and frozen at 0.5m depth. Average peat horizon thickness is 30cm. A crown density of *Pinus sibirica* is 0.1, its height 7-8m. The coverage of grasses and dwarf shrubs makes up 40-50%.

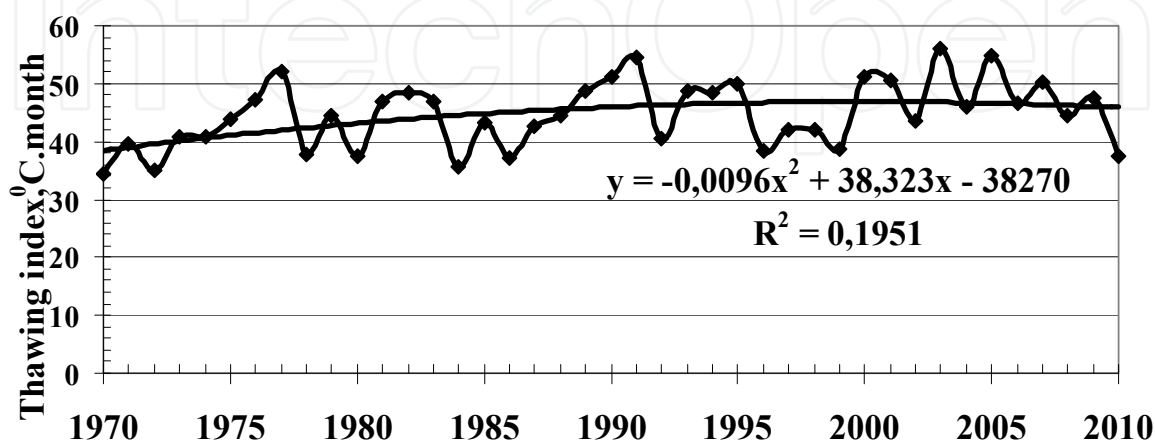


Figure 6. Air thawing index in Nadym

The grass-dwarf shrub cover has two-layer structure: the upper layer in height is 0.3-0.35m composed of wild rosemary and *Betula nana*, and the lower layer in height is 0.05-0.15m with abundant cowberry (*Vaccinium vitis-idaea*), *Chamaedaphne calyculata*, cloudberry and sedge (*Carex globularis*). Peat mosses and lichens make up the continuous ground cover.

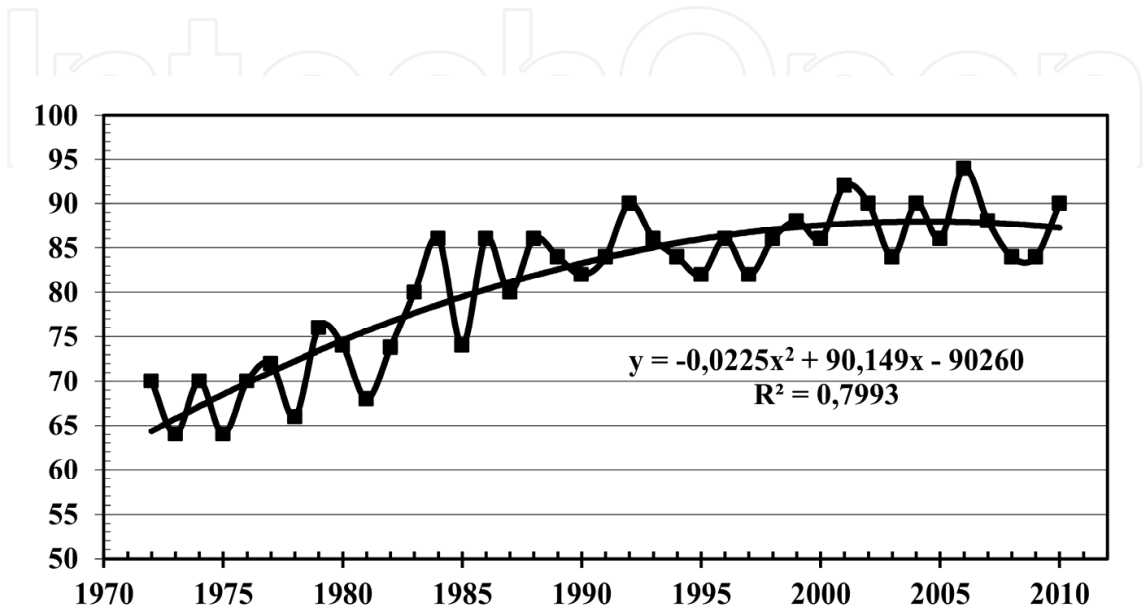


Figure 7. Frequency of *Ledum palustre* on the flat peatland

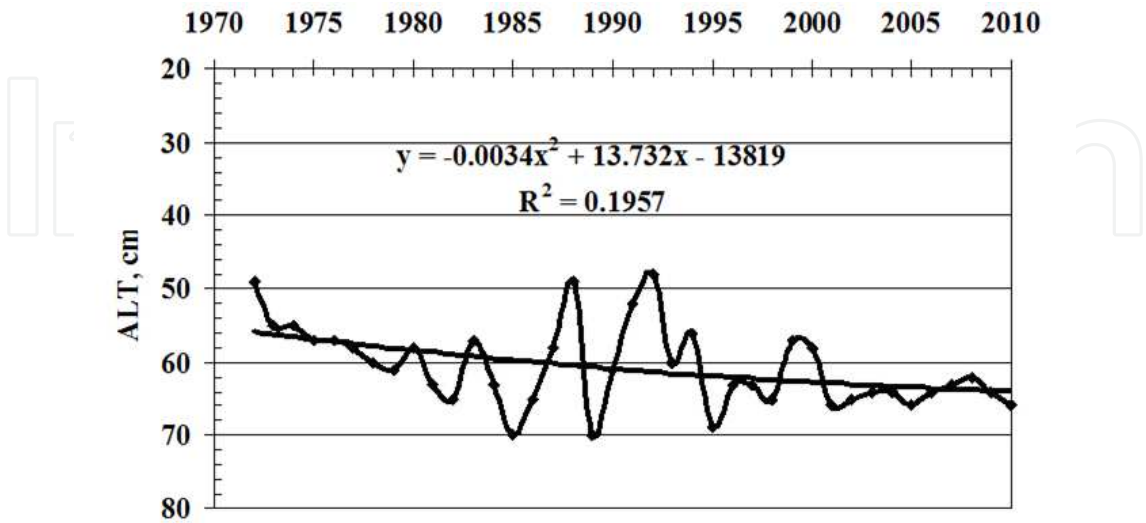


Figure 8. Active layer thickness on the palsa peatland

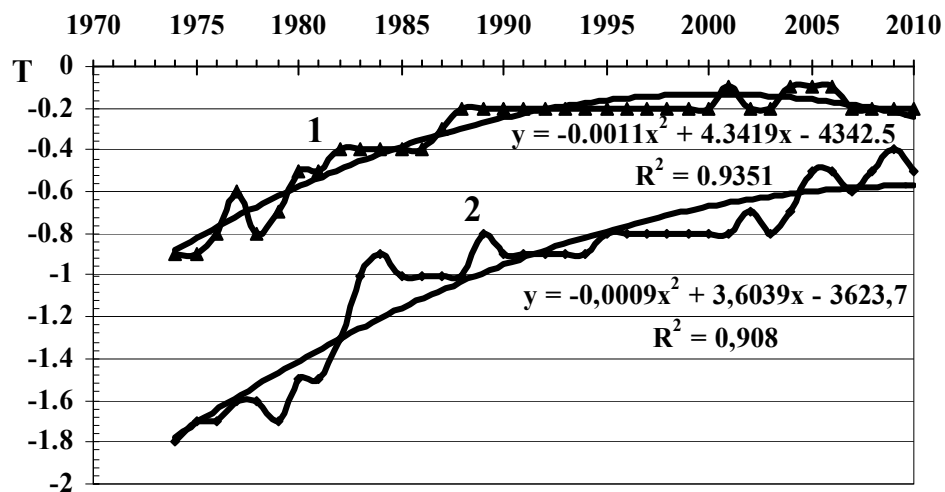


Figure 9. Permafrost temperature (T °C) at the depth of 10m on the flat peatland (1) and the palsa peatland (2)

In June 1976 the plot of grass-dwarf shrub cover, and a forest stand was completely burned. Within two months following the fire the surface cover of 25% consisted of shoots of *Carex globularis*, *Betula nana*, wild rosemary, and cloudberry. In pools the moss coverage of up to 30% was maintained.

One year following the fire the sedge-cloudberry-peat moss grouping was formed, and the next year it was replaced by cloudberry-sedge-wild rosemary-peat moss community. This was the result of the fast recovery of a former role of wild rosemary (Fig.11, 1). In this community the coverage of grasses and dwarf shrubs increased up to 35%, and mosses up to 40%. The next years the coverage of grasses and dwarf shrubs reached its initial value (40-50%), but mosses still covered less than half of plot surface. The frequency of *Betula nana* has increased in 3 times, probably, in connection with the rise in air temperature (Fig. 11, 2).

The occurrence of lichens sharply decreased after the fire, and within 16 years had considerably increased. Only the frequency of *Cladonia coccifera* strongly increased after the fire. The frequency of *Cladonia stellaris* was recovered (Fig. 12, 1), and its reduction last decade is connected to increase of amount of atmospheric precipitation that is observed and in undisturbed conditions. The frequency of *Sphagnum fuscum* (Fig. 12, 2) while remains in 2 times less than in initial community. The increase in height of shrubs (*Betula nana*, *Chamaedaphne calyculata*, *Ledum palustre*) is marked also. Changes in species composition, height, coverage and frequency of plants on frost mound are presented in the table 5.

On the cloudberry-wild rosemary-lichen palsa peatlands n 40 years after the fire the cloudberry- *Betula nana*- wild rosemary-lichen-*Polytrichum* communities are found. These communities differ from the initial communities by ground vegetation composition (smaller percentage of lichens) and increase in presence of *Betula nana*. The last, apparently, is connection to the increase of the air thawing index and a snow thickness over the last decades.

In 1971, plot on palsa peatland on which in 1970 were carried out the detailed description of a vegetation cover, measurements of active layer thickness and permafrost temperature, was burned.

This plot is located at top of peat hillocky with height of 2m and with cloudberry-wild rosemary-lichen plant community. In the microrelief of plot are characteristic small *Dicranum* hummocks with heights of 0.1-0.3m and pools with bog dwarf shrubs (*Andromeda polifolia*, *Chamaedaphne calyculata*) and mosses. The soil of the plot is peaty, and maximum thickness of the active layer is 0.6m. The coverage of grasses and dwarf shrubs equaled 45 %; mosses and lichens - 90%. In a grass-shrub cover two layers are found: an upper layer in height of 0.2-0.4m made up of wild rosemary and *Betula nana*, and a lower layer in height up to 0.15m formed of cloudberry and cowberry. In ground vegetation, lichens predominated over a *Cladina* genus and frequent *Dicranum* mosses but with low coverage.

In 1975, four years after the fire at the top of the peaty hillocky where the vegetation had been described in 1970, a permanent 10 x 10m plot on the soil surface was established. On this plot, since 1975 on present time, annual geobotanical descriptions are performed.

A 10-meter borehole was drilled at the hillocky top near to the geobotanical plot. According to the drilling the peat thickness is 1m, below lies sand with layers of the clay, underlaying with depth 3,75m by clay. From 1975 year-round temperature measurements of soil and permafrost were observed (Fig. 13). Since 2001 year-round measurements of temperature by loggers are obtained. Thickness and moisture of the active layer were measured.

In four years since the fire on hillocky the cotton-grass-cloudberry-*Polytrichum* community is found in which the coverage of grasses made 15%, and mosses 50 %. After the fire the number of species on the plot was 42% of their common number in 1970. Change of species number could be still large, but appearance of new grass species (*Eriophorum russeolum*, *Carex limosa*, *Chamaenerium angustifolium*) and shoots of a birch (*Betula tortuosa*) compensated for significant decrease of species number. It has been related to disappearance of five dwarf shrubs (*Vaccinium uliginosum*, *V. vitis-idaea*, *Empetrum nigrum*, *Andromeda polifolia* and *Chamaedaphne calyculata*), *Eriophorum vaginatum*, one species of lichens (*Alectoria ochroleuca*) and three species of mosses (*Sphagnum fuscum*, *Pleurozium schreberi*, *Hylocomium splendens*). In the first years of vegetation recovery the frequency and coverage of *Polytrichum* mosses strongly increased (Table 6). Occurrence of dwarf shrubs has decreased, bog grasses have appeared absent earlier, and the occurrence of shrubs increased.

In five years after the fire on hillocky landscape with cotton-grass-cloudberry-*Polytrichum* community the coverage of grasses was 20%, and mosses 50%. The next year there was an appreciable increase in occurrence of *Betula nana* that led to changes of the grass-moss community with *Betula nana*- cloudberry-cotton-grass-*Polytrichum* community. The coverage of grasses and dwarf shrubs in this community gradually grew and in 14 years after the fire had reached its initial value. At this time an appreciable role of wild rosemary began to occur. The ground vegetation by this time covered up to 85% of a plot surface, but it still has consisted of *Polytrichum* mosses. The thickness of the active layer in this plant community has increased up to 65-70cm.

The frequency of lichens though has increased, but the coverage on the surface did not exceed 1-3 %. However the coverage of lichens gradually continued to increase, and in 23 years after the fire it has reached 8.5 %. The coverage of lichens has increased for 40th year up to 18.5%, and includes *Betula nana*-wild rosemary-cloudberry-*Cladina*- *Polytrichum* community in which the occurrence of cotton-grass has decreased. The number of dwarf shrubs and mosses by this time has appreciably increased, but remained less than in undisturbed cover due to the absence of bog dwarf shrubs (*Andromeda polifolia*, *Chamaedaphne calyculata*) and one species of mosses (*Hylocomium splendens*). The bog grasses which have appeared at early stages of plant community recovery in 2005 have disappeared from the plant community.



A



B

Figure 10. Frost mound before fire (A) and 35 years after it (B)

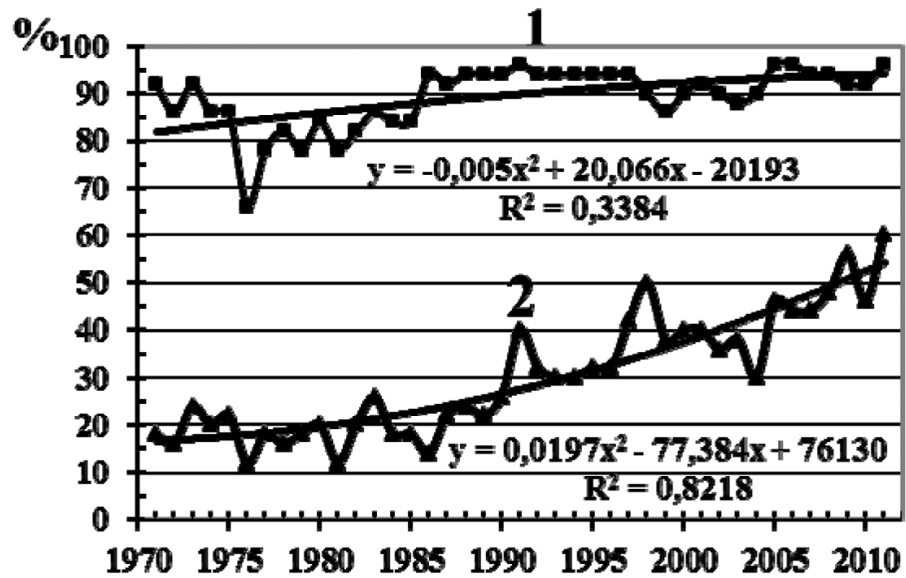


Figure 11. Frequency of *Ledum palustre* (1) and *Betula nana* (2) on the frost mound

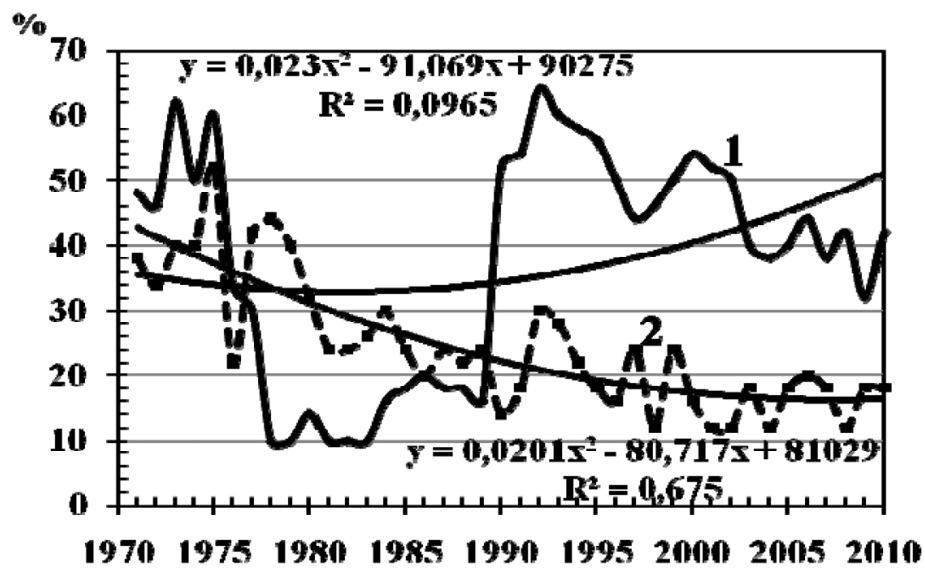


Figure 12. Frequency changes of *Cladina stellaris* (1) and *Sphagnum fuscum* (2) on the frost mound

Species	Year	Height, cm	Coverage, %	Frequency, %
1. <i>Andromeda polifolia</i>	1	10	1	18
	2	13	0.1	8
	3	15	1	14
	4	15	0.1	6
	5	15	0.2	12
2. <i>Betula nana</i>	1	45	2	22
	2	65	1	18
	3	65	1.5	22
	4	80	7	46
	5	100	6	46
3. <i>Carex globularis</i>	1	15	6	64
	2	35	15	80
	3	30	16	86
	4	40	4	96
	5	35	2	84
4. <i>Chamaedaphne calyculata</i>	1	15	4	56
	2	30	1	24
	3	30	7	36
	4	40	2.5	62
	5	40	1	54
5. <i>Empetrum nigrum</i>	1	7	0.1	6
	2	10	0.2	10
	3			
	4	10	0.2	16
	5	10	0.2	10
6. <i>Eriophorum vaginatum</i>	1	10	<1	<1
	2	10	0.4	2
	3	20	0.1	2
	4	20	0.1	2
	5	30	<1	<1
7. <i>Ledum palustre</i>	1	40	15	86
	2	50	9	84
	3	50	20	94
	4	55	21.5	96
	5	55	30	92
8. <i>Oxyccocus microcarpus</i>	1	1	3	46
	2	2	3	30
	3	1	3	30
	4	2	0.9	18
	5	2	0.2	20

Species	Year	Height, cm	Coverage, %	Frequency, %
9. <i>Pinus sibirica</i>	1	800	<1	<1
	2	35	0.1	4
	3	60	<1	<1
	4	170	0.1	2
	5	200	0.1	4
10. <i>Rubus chamaemorus</i>	1	5	5	72
	2	10	11	84
	3	10	6.5	68
	4	12	3	66
	5	10	1.5	46
11. <i>Vaccinium myrtillus</i>	1	10	0.1	2
	2	10	<1	<1
	3	10	0.1	2
	4	12	0.1	4
	5	12	<1	<1
12. <i>Vaccinium uliginosum</i>	1	17	0.1	4
	2	25	0.1	2
	3	25	1	2
	4	25	0.2	8
	5	25	0.1	2
13. <i>Vaccinium vitis-idaea</i>	1	7	5	82
	2	10	11	88
	3	15	4	86
	4	15	6.5	86
	5	20	7	84
14. <i>Cetraria cucullata</i>	1	4	0.2	10
	2	4	<1	<1
	3	4	0.1	2
	4	5	0.1	4
	5	5	0.4	2
15. <i>Cetraria islandica</i>	1	4	0.2	10
	2	4	0.1	6
	3	4	15	16
	4	5	0.1	6
	5	5	0.2	8
16. <i>Cladonia amaurocraea</i>	1	3	0.1	2
	2	3	0.1	2
	3	4	0.2	10
	4	5	1.5	12
	5	8	0.8	8
17. <i>Cladonia coccifera</i>	1	3	0.1	2
	2	2	1	54
	3	4	10	52
	4	5	2.5	32
	5	7	2.5	22

Species	Year	Height, cm	Coverage, %	Frequency, %
18. <i>Cladina rangiferina</i>	1	8	19	60
	2	5	0.5	26
	3	5	0.7	36
	4	9	5.5	32
	5	9	2	32
19. <i>Cladina stellaris</i>	1	8	27	60
	2	4	0.4	18
	3	4	1	56
	4	9	7.5	48
	5	10	12	42
20. <i>Dicranum congestum</i>	1	1	0.1	2
	2	1	2	2
	3	2	0.5	4
	4	2	<1	<1
	5	2	<1	<1
21. <i>Pleurozium schreberi</i>	1	2	2	52
	2	2	0.1	2
	3	3	3	8
	4	3	0.4	2
	5	3	3	12
22. <i>Polytrichum commune</i>	1	5	0.1	4
	2	3	2	24
	3	3	7	20
	4	3	0.2	6
	5	3	3	16
23. <i>Sphagnum angustifolium</i>	1	2	0.1	2
	2	3	14	22
	3	3	8	26
	4	3	10	18
	5	3	6	12
24. <i>Sphagnum fuscum</i>	1	2	23	52
	2	3	14	14
	3	3	6	8
	4	3	16.5	18
	5	3	14.5	18
25. <i>Tomenthypnum nitens</i>	1	1	2	2
	2	1	0.1	2
	3	1	0.8	4
	4	1	0.1	2
	5	2	<1	<1

Table 5. Species composition of vegetation on the frost mound in 1975 (1), 1985 (2), 1995 (3), 2005 (4) and 2010 (5) years.

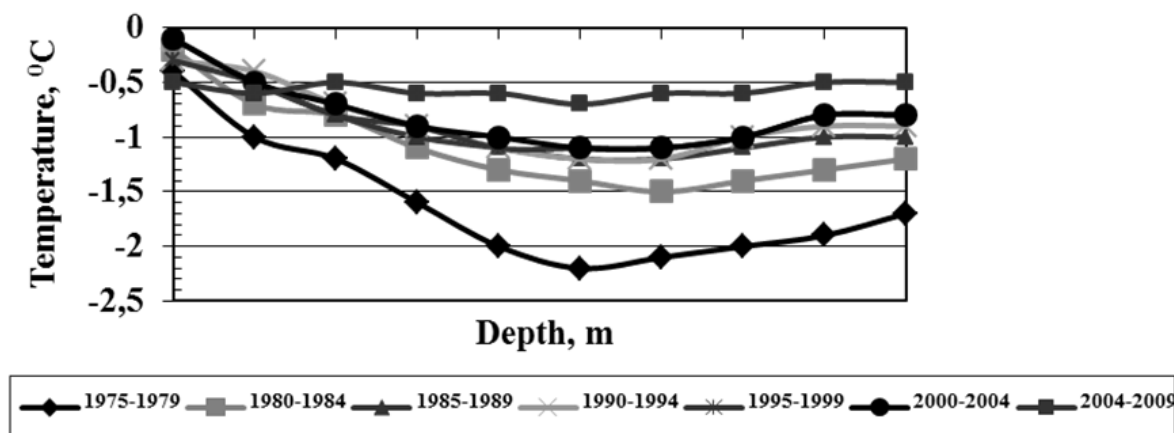


Figure 13. Five-year moving averages of ground temperatures at the depths of 1-10 m on the palsa peatland

Negatively reacted to a fire some shrubs (*Vaccinium vitis-idaea*, *Ledum palustre*), lichens, green mosses and *Sphagnum fuscum*. In 15 years after a fire at the cowberry, the wild rosemary and all before plentiful species of lichens (*Cladina*, *Cetraria*), the frequency and the coverage strongly differed from initial sizes. This distinction was kept and in 23 years after fire. Participation of some species of lichens (*Cladonia coccifera* and *Cladonia amaurocraea*) and blueberries for the investigated period was recovered. At cloudberries sizes of the coverage were made even to initial sizes, but its frequency still was more than 2 times smaller.

In 30 years after the fire the frequency of *Betula nana* has exceeded initial size, the frequency of *Ledum palustre* too has considerably increased and for 40-th year was only a little less, than in not disturbed community. Only at the cowberry and dominant species of lichens (*Cladina stellaris* and *Cladina rangiferina*) the frequency for all period of observations was not recovered. The analysis of frequency diagrams of *Betula nana* and *Ledum palustre* (Fig. 14) shows, that there is a positive trend which will be coordinated to increase of summer air temperatures.

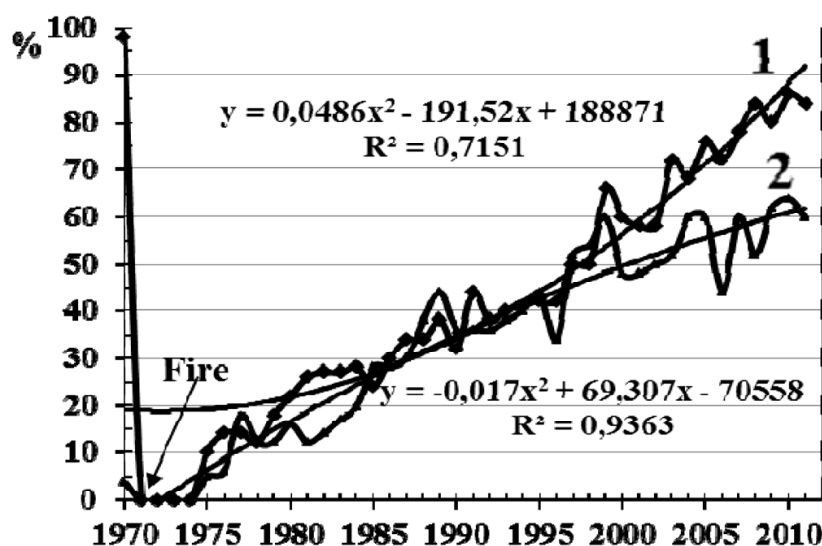


Figure 14. Frequency of *Ledum palustre* (1) and *Betula nana* (2) on the palsa peatland

Species	1970		1975		1980		1985		1990		1995		2000		2005		2010	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Andpol	2	7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	10
Betnan	4	40	5	35	16	50	28	70	36	70	44	70	48	80	60	90	64	100
Bettor	-	-	1	45	1	130	1	200	1	300	1	400	1	500	1	600	4	600
Callap	4	30	-	=	1	30	1	60	1	20	-	-	-	-	-	-	1	40
Carglo	2	25	-	-	-	-	-	-	1	20	1	20	2	35	1	30	1	35
Carlim	-	-	2	20	2	20	-	-	-	-	-	-	-	-	-	-	-	-
Carrot	-	-	-	-	2	20	-	-	-	-	-	-	-	-	-	-	-	-
Chaang	-	-	2	30	1	40	1	35	-	-	-	-	-	-	-	-	-	-
Chacal	2	17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Empnig	2	10	-	-	4	10	-	-	1	10	1	10	2	10	1	10	1	10
Eriang	-	-	-	-	2	20	1	30	-	20	1	20	1	10	-	-	-	-
Erius	-	-	45	35	46	30	64	30	82	30	34	15	-	-	-	-	-	-
Erisch	-	-	-	-	12	20	2	30	-	-	-	-	-	-	-	-	-	-
Erivag	10	12	-	-	2	35	16	30	10	50	54	20	68	30	58	50	38	35
Ledpal	98	20	10	15	22	25	24	30	32	35	42	35	60	40	76	45	86	45
Pinsib	-	-	-	-	1	5	-	-	4	5	4	15	1	20	6	35	10	55
Pinsil	-	-	-	-	-	-	-	-	-	-	-	-	2	6	-	-	1	50
Rubcha	98	10	28	5	22	10	34	12	30	12	34	10	32	15	44	15	42	15
Vaculi	1	10	-	-	2	10	1	20	1	20	1	30	1	30	1	35	1	35
Vacvit	46	5	-	-	6	7	6	7	2	7	4	7	4	7	1	10	1	10
Aulpal	6	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Diccon	10	2	12	1	20	1	1	1	1	2	1	4	2	1	2	1	1	2
Hylspl	2	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Plesch	4	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	2
Polcom	6	2	96	2	96	5	98	6	98	7	96	7	96	7	94	7	98	7
Sphfus	5	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4	3
Aleoch	4	3	-	-	-	-	-	-	-	-	2	2	2	3	6	4	6	5
Cetcuc	28	3	6	1	2	1	1	2	2	3	4	3	8	4	8	5	10	5
Cetisl	6	3	4	1	2	2	2	3	2	3	2	4	1	5	2	5	12	6
Cetniv	94	2	10	1	6	2	1	2	1	2	6	3	2	3	8	4	8	4
Claama	14	3	2	1	1	1	4	2	4	3	26	4	18	4	18	5	22	6
Clacoc	20	3	2	1	12	1	36	2	38	3	48	4	40	4	48	5	40	5
Claran	78	8	2	1	8	2	6	3	14	5	34	6	12	6	20	6	30	6
Claste	98	10	10	1	12	2	22	3	38	4	42	5	30	5	38	6	40	6

Table 6. Frequency (1, %) and height (2, cm) changes of plant species on the palsa peatland in 1970-2010 years.

Plant species. Vascular plants: Andpol – *Andromeda polifolia*, Betnan – *Betula nana*, Bettor – *Betula tortuosa*, Callap – *Calamagrostis lapponica*, Carglo – *Carex globularis*, Carlim – *Carex limosa*, Carrot – *Carex rotundata*, Chaang – *Chamaenerium angustifolium*, Empnig – *Empetrum nigrum*, Eriang – *Eriophorum angustifolium*, Erius – *Eriophorum russeolum*, Erisch – *Eriophorum scheucheri*, Erivag – *Eriophorum vaginatum*, Ledpal – *Ledum palustre*, Pinsib – *Pinus sibirica*, Pinsil – *Pinus silvestris*, Rubcha – *Rubus chamaemorus*, Vaculi – *Vaccinium uliginosum*, Vacvit – *Vaccinium vitis-idaea*.

Mosses: *Aulpal* – *Aulacomnium palustre*, *Diccon* – *Dicranum congestum*, *Hylspl* – *Hylocomium splendens*, *Plesch* – *Pleurozium schreberi*, *Polcom* – *Polytrichum commune*, *Sphfus* – *Sphagnum fuscum*.

Lichens: *Aleoch* – *Alectoria ochroleuca*, *Cetcuc* – *Cetraria cucullata*, *Cetisl* – *Cetraria islandica*, *Cetniv* – *Cetraria nivalis*, *Claama* – *Cladonia amaurocraea*, *Clacoc* – *Cladonia coccifera*, *Claran* – *Cladina rangiferina*, *Claste* – *Cladina stellaris*.

Stages of vegetation recovery after the fire on the frost mound and the palsa peatland are presented in Table 7. Comparison of rates of vegetation cover restoration in these ecosystems demonstrate that on flat weakly drained top of frost mound the vegetation recovery is faster than on better drained palsa peatland. The domination in ground vegetation of *Polytrichum* mosses and the lower occurrence of lichens persists longer.

Stages and their duration (years)	Ecosystems	
	I	II
Grass-moss (1-5)	1a	1б
Shrub-grass-moss (6-15)	2a	2б
Shrub-grass-lichen-moss (16-35)	3a	3б
Grass-shrub-moss-lichen (36-50)	4a	4б

Table 7. Stages of vegetation recovery after the fire in different ecosystems

Ecosystems: I – cloudberry-wild rosemary-lichen palsa peatland, II – frost mound with *Pinus sibirica* wild rosemary- peat moss-*Cladina* open woodland.

Plant communities: 1a – cotton grass-cloudberry-*Polytrichum*, 1б – sedge-cloudberry-peat moss, 2a – *Betula nana*-cloudberry-cotton- grass-*Polytrichum*, 2б – cloudberry-sedge-wild rosemary-peat moss, 3a – cloudberry-*Betula nana*--wild rosemary-*Cladina*-*Polytrichum*, 3б – *Betula nana*-wild rosemary-peat moss-*Cladina*, 4a - cloudberry-*Betula nana*-wild rosemary-*Cladina*-*Polytrichum*, 4б – *Pinus sibirica*- *Betula nana*-wild rosemary-peat moss-*Cladina*.

3.3. Impact of vegetation dynamics on permafrost

On the dwarf shrub-cotton grass-peat moss bogs in the result of vegetation dynamics it is possible to observe formation of new frost heavy hummocks (Fig.16). The height of one of young frost mound, which beginning of formation concerns to 1973, makes by the present moment 80 cm.

The ecosystems are detected, in which the local temperature decrease observed on a background of the general tendency of temperature increase, caused by dynamics of a vegetation cover. It is necessary to allow a possibility of such different tendencies of temperature changes in ecosystems at for the same changes of a climate at geocryological monitoring.

For example, such downturn of permafrost temperatures was observed on dwarf shrub-sedge-peat moss bog, replaced through 25 years by sedge-dwarf shrub- lichen-peat moss

peatland as a result of increase in moss thickness, accumulation of peat and growths of dwarf shrubs (*Andromeda polifolia*, *Chamaedaphne calyculata*). Here permafrost temperatures for the investigated period have gone down on 0.3°C (Fig.15) though in the next flat peatlands surrounding a drained up bog, the permafrost temperature became higher.

On cotton grass-peat moss bogs with the lowered permafrost table on formed on it dwarf shrub-peat moss hummocks after cold winters it is observed formation of new frozen ground. Mean active layer thickness on these hummocks is 80 cm.



Figure 15. New frost heavy hummocks on the dwarf shrub-cotton grass-peat moss bog

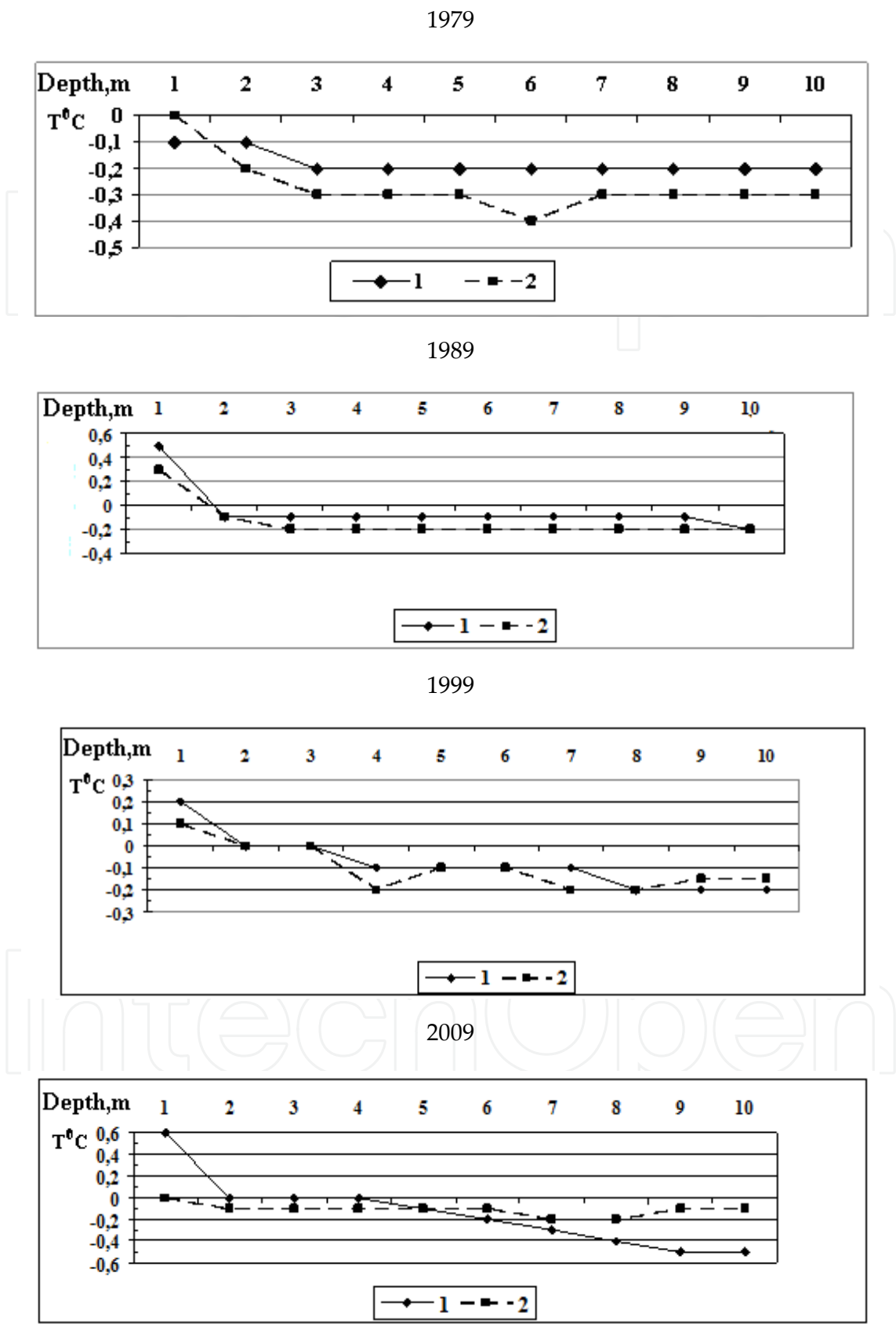


Figure 16. Permafrost temperature ($T^{\circ}\text{C}$) changes on the bog (1) and on the peatland (2) at the depths of 1-10 m in 1979, 1989, 1999 and 2009 years.

4. Results and discussions

Long-term monitoring of the northern taiga ecosystem changes has allowed revealing impact of climatic changes on a vegetation cover and permafrost.

During the last decades in the north of West Siberia the rise in air temperature and the increase in amount of atmospheric precipitation are observed. In wood communities in connection with increase of atmospheric precipitation amount which is marked last decades, the increase in participation of mosses, and change of green moss-lichen sparse forests by lichen-green moss plant communities on drained sites is marked.

On flat poorly drained surfaces of plains process of bog development became more active. As a result of it hummocky pine cloudberry-wild rosemary-lichen-peat moss open woodlands with lenses of permafrost under the hummocks are replaced by andromeda-cotton grass-sedge-peat moss thawed bogs. Comparison wood communities and bog communities show that by bog formation in wood all aboveground biomass decreases on 26% and biodiversity in process of bogginess decreases on 37%.

Increase of the thawing index of air temperature caused the appearance on the flat and palsa peatlands separate trees (*Betula tortuosa*, *Pinus sibirica*, *Pinus silvestris*), increase in the frequency and the height of shrubs (*Betula nana*, *Ledum palustre*) and in the coverage them of a soil surface. These plant species can serve as indicators of climate warming.

The analysis of the given measurements of the active layer thickness on palsa peatland has shown that it has a trend to the increase, caused by increase in the air thawing index, which trend for 1970-2010 makes 0.2°C in a year.

The permafrost temperature at the depth of 10 m has increased on 1.4°C. Temperature of permafrost at the depth of 10 m for the period of research on the palsa peatland has increased from -1.8°C up to -0.4°C. On the flat peatland increase of the permafrost temperature was less; here the permafrost temperature at the depth of 10 m has increased from -0.9°C up to -0.2°C.

In conditions of climate warming fires began to be observed more often. On cloudberry-wild rosemary-lichen palsa peatlands 40 years after a fire are formed cloudberry-*Betula nana*-wild rosemary-lichen-*Polytrichum* plant communities. These plant communities differ from initial communities by ground vegetation composition (smaller participation of lichens) and increase in occurrence of *Betula nana* connected with increase of the air thawing index.

On flat weakly drained top of frost mound the vegetation recovery after the fire is faster than on better drained palsa peatland. Here *Pinus sibirica*-wild rosemary-peat moss-lichen open woodland in 35 years after the fire changed by *Betula nana*-wild rosemary-peat moss-lichen community with *Pinus sibirica* in height 2m.

Stages and rate of vegetation recovery after the fire were revealed.

The ecosystems are established, in which the local temperature decrease observed on a background of the general tendency of temperature increase, caused by dynamics of the vegetation cover.

The carried out researches prove observations of A.P.Tyrtikov (1969), E.B.Belopukhova (1973), V.L.Nevecherya et al. (1975). These researchers marked, that in modern climatic conditions of Western Siberia northern taiga during dynamics of bog vegetation are formed new frost mounds which are considered as some researchers relic formations (Yevseyev, 1976; Brown, Pewe, 1973) for which formation now there are no necessary conditions.

5. Conclusion

In my research the vegetation cover is considered as one of components of the natural ecosystems, closely connected with other components and first of all with soils, underground waters and permafrost for which indication it is used. As the mobile component of ecosystem easily broken at external impact, but capable to self-recovery, vegetation is one of critical components of ecosystems and the major factor of their stabilization.

Long-term monitoring of vegetation cover show that main environmental factors in development of plant communities in the North of West Siberia are water and thermal regime of soil.

Studying of interactions of vegetation with other ecosystem components and revealing of leading factors in vegetation dynamics of region allows more proved to approach to compiling the prediction of vegetation changes in conditions of a varying climate on materials received as a result of long-term monitoring. Use of the interactions existing between the vegetation cover and permafrost, enables to predict on expected tendencies of vegetation development changes of geocryological conditions and to recommend necessary actions on preservation of natural balance in environment.

In all territory of the north of Western Siberia climate changes in time have oscillatory character on a background of the general warming which have begun since 1970th years. On data of Nadym weather station for 1970-2011 the trend to increase of mean-annual air temperature is revealed. Increase of mean-annual temperature has made 0.04°C in a year.

The steady increase in active layer thickness is connected to rise in air temperature in all natural complexes. Extreme reaction to climatic changes natural complexes of bogs and peatlands in the north of Western Siberia possess. Active layer thickness in palsa peatlands for the 40-years period has increased on 30 %.

Despite of climate warming and observed rise in permafrost temperature single instances of permafrost transition in a thawed condition on all thickness of annual heat turn layer are fixed only.

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Acknowledgement

The research was supported by Land-Cover Land-Use Change program, project Circumpolar Active Layer Monitoring (CALM, National Science Foundation, Grant NSF OPP-9732051, OPP-0225603); project Thermal State of Permafrost (TSP, NSF RC-0632400, ARC-0520578) and Council under grant of the President of the Russian Federation (grant NSH-5582.2012.5).

Aleksandar Lazinica is acknowledged for their very useful comments in improving my chapter.

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