Phytomass and organic carbon stocks in the mountain tundra communities of the Khibiny Mountains, Murmansk Region, Russia

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Abstract

This article presents the results of a field-measured monitoring study on the structure and productivity of two widespread community types within the mountain tundra belt of the Subarctic (Kola Peninsula, Khibiny Mountains). The data cover the period 2000 to 2023, during which the mean annual air temperature increased by 2.2°C. In 2023, the dwarf shrub community had an average aboveground phytomass of 908 g m^{-2} and an annual production of 128 gm^{-2}, values 1.5–2 times higher than in the lichen community. The composition of aboveground phytomass was as follows - dwarf shrub community: 72% dwarf shrubs, 10% mosses, 18% lichens; lichen community: 32% dwarf shrubs, 6% mosses, 62% lichens. In the dwarf shrub community during the past two decades (2000–2023), the contribution of dwarf shrubs to the aboveground phytomass remained unchanged. However, a compositional change occurred: the proportion of evergreen dwarf shrubs nearly doubled, the moss component increased fivefold, while the lichen fraction decreased by a factor of 1.5. Aboveground phytomass increased by 22%, whereas annual production showed a slight decrease of 7%. The aboveground phytomass of the lichen community decreased by 15% over a twenty-year period. Its structural composition also changed: the moss contribution increased 21 times, while the proportion of lichens decreased by a factor of 1.1 in 2023. The results demonstrate a significant response of the Khibiny mountain tundra ecosystem to ongoing global warming during the study period. The rise in temperature at this stage of global climate change has led to an alteration in the structure of vegetation, namely an increased contribution of evergreen dwarf shrubs and mosses to the plant communities of the Khibiny Mountains.

Key words: climate change, phytomass stocks, primary production, carbon, tundra, Khibiny Mountains, Subarctic

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Introduction

Mountain tundra ecosystems are already experiencing climate-dependent shifts in their distribution, structure, and productivity (Henry and Molau 1997, Everett and Fitzharris 1998, Schuur et al. 2009, Craine et al. 2010, Romanovsky et al. 2010). Recent research on the impacts of atmospheric and climatic changes has demonstrated that high-latitude ecosystems are among the most sensitive to these shifts and, in turn, play a critical role in the global biosphere balance (Callaghan et al. 2011, Sergienko and Konstantinov 2016, Brodsky and Safronova 2017). The primary source of uncertainty regarding the atmosphere as a driver of change in the Arctic is precipitation. Future changes in its spatial and seasonal distribution are unclear, as are its effects on the sea-ice mass budget, marine primary productivity, and vegetation. A better understanding of precipitation effects will only be gained through developing and sustaining a more robust observing network (Callaghan et al. 2011).

Yet, the direction and drivers of these changes remain unclear. Some studies report increased woody vegetation and shrub expansion (Tape et al. 2006, Frost and Epstein 2014), greater canopy height, biomass, and productivity (Verbyla 2008, Day et al. 2008, Hudson and Henry 2009, Hill and Henry 2011, Epstein et al. 2012, Tishkov et al. 2018), and subsequent shifts in carbon stocks. Others, however, find no significant structural or productivity changes (Chapin et al. 1995, Hobbie and Chapin 1998, Wahren et al. 2005) or even a decline in biomass (Gorbunova 2021). These discrepancies may be a consequence of local topography, microclimate variability (Niittynen et al. 2020). Shifts in snow cover and phytopathogen prevalence may play a role (Olofsson et al. 2011), as well as soil moisture and permafrost dynamics (Elmendorf et al. 2012). Another reason for undistinguishable clear trend in plant productivity response might be differences in monitoring duration and methodologies (Chapin et al. 1995, Epstein et al. 2004, Wahren et al. 2005, Olofsson et al. 2011, Elmendorf et al. 2012, Gorbunova 2021, Niittynen et al. 2020).

When vegetation monitoring is done by a remote sensing, NDVI-based assessments often yield unsatisfactory results in mountain tundra ecosystems due to fine-scale spatial heterogeneity (Fung 1997, Tape et al. 2006). Thus, *in situ* studies remain indispensable for accurate biomass estimation (Epstein et al. 2012, Rangwala and Miller 2012, Zona et al. 2023). While NDVI is widely used for biomass estimation in vascular plants plant, its applicability is limited in moss-dominated ecosystems (Cunliffe et al. 2020). Plot-based studies provide essential fine-scale data on vegetation composition and structure that cannot be obtained through other methods (Hudson and Henry 2009).

Long-term ecosystem monitoring is crucial for identifying linkages between abiotic factors, climate change, and vegetation dynamics (Hudson and Henry 2009, Elmendorf et al. 2012, Natali et al. 2012, Henry et al. 2022), as well as potential feedback mechanisms (Berner et al. 2018). However, even extensive datasets may not always be extrapolated to broader spatial scales (Leuzinger et al. 2011).

Tundra ecosystems are among the most significant terrestrial biomes in terms of carbon storage, owing to the slow decomposition of organic matter. Despite their low primary productivity, tundra soils accumulate the highest carbon stocks per unit area among all terrestrial ecosystems Bolin 1986, Billings 1987, Melillo et al. 1993). Aboveground biomass is a key contributor to soil organic matter, making the study of biomass accumulation essential for understanding carbon sequestration in these systems. Within the vast body of scientific literature on the carbon cycle, a prominent hypothesis posits a positive

feedback loop between global warming and a change in the carbon balance of tundra biogeocenoses: from a carbon sink to a source for the atmosphere. The core of this hypothesis is that Arctic warming and aridification could significantly accelerate the decomposition of organic matter stored in tundra soils. A potential increase in primary production would likely be insufficient to offset the increase in ecosystem respiration, resulting in the release of substantial amounts of currently sequestered carbon into the atmosphere. Detailed studies of the carbon cycle in Arctic Alaska (USA) led researchers to conclude that tundra in this region has already transitioned from a carbon sink to a source (Oechel et al. 1995, Grogan et al. 1999, 2000). Given the central role of plant productivity in energy and nutrient flows, monitoring its changes is particularly critical in low-productivity biomes like the tundra.

While extensive research has been conducted in the European Arctic and North America (Epstein et al. 2008, Walker et al. 2012), comparable studies in Russia remain scarce. Despite the vast expanse of Russian Arctic tundra and documented climate shifts (McBean et al. 2005, Anisimov et al. 2011, Bukvareva et al. 2015, Gorbunova 2021), these regions are underrepresented in global meta-analyses (Elmendorf et al. 2012, Rixen et al. 2022, Berner et al. 2024). Existing Russian studies focus on southern hypoarctic tundra's (Murmansk Region) (Manakov 1972, Ushakova et al. 2003), arctic tundra the Taymyr Peninsula, northeastern Siberia (Bazilevich 1993), Yamal, Trans-Ural forest-tundra, Polar Urals tundra's (Andreyashkina and Peshkova 2003), and mountain tundra's of Tyva (Sambyla 2010).

Mountain tundra ecosystems are not confined to high latitudes but also occur in high-altitude regions, enabling comparative studies across geographies. While extreme abiotic conditions often produce functionally similar communities, their responses to environmental changes may vary significantly (Zhang and Welker 1996, Walker et al. 1999, Myers-Smith and Hik 2013, Saccone et al. 2013, Ernakovich et al. 2014).

This study presents a 23-year ground-based monitoring of vegetation in the Khibiny mountain tundra, as rapid shifts in Arctic plant communities are often detectable only after major environmental disturbances (Sumina 2017). The objectives were to: to estimate biomass reserves and productivity in typical communities of the Khibiny mountain tundra (shrub, lichen) in relation to the warming trend over a 20-year period; quantify phytomass stocks in dwarf shrub and lichen communities (2023); compare phytomass, species composition, and dominant functional groups with 2000 baseline data (Shmakova et al. 2008); assess carbon stocks in Khibiny mountain tundra ecosystems. In light of significant recent warming (a temperature increase over the past two decades), Arctic tundra vegetation may experience increased productivity, though likely within a limited range that can be defined experimentally. Beyond this initial phase, a change in community composition can occur, potentially leading to the loss of individual species between different functional groups of plants.

Material and Methods

Study area

The study area is situated in the Khibiny Mountains (Fig. 1), a mountain range in the central part of the Murmansk Region (67°30′ – 67°50′ N, 33°10′ – 34°10′ E). The Khibiny massif spans 1 327 km^2, with peak elevations ranging between 1 000 and

1 200 meters above sea level. The Khibiny Mountains are characterized by unique geological features. They are primarily composed of alkaline igneous rocks, particularly nepheline syenites and associated rocks such as foyaite and pulaskite. These rocks formed during the intrusion of magma into the Earth's crust approximately 350 million years ago, in the late Devonian to early Carboniferous period (Arzamastsev 1994).

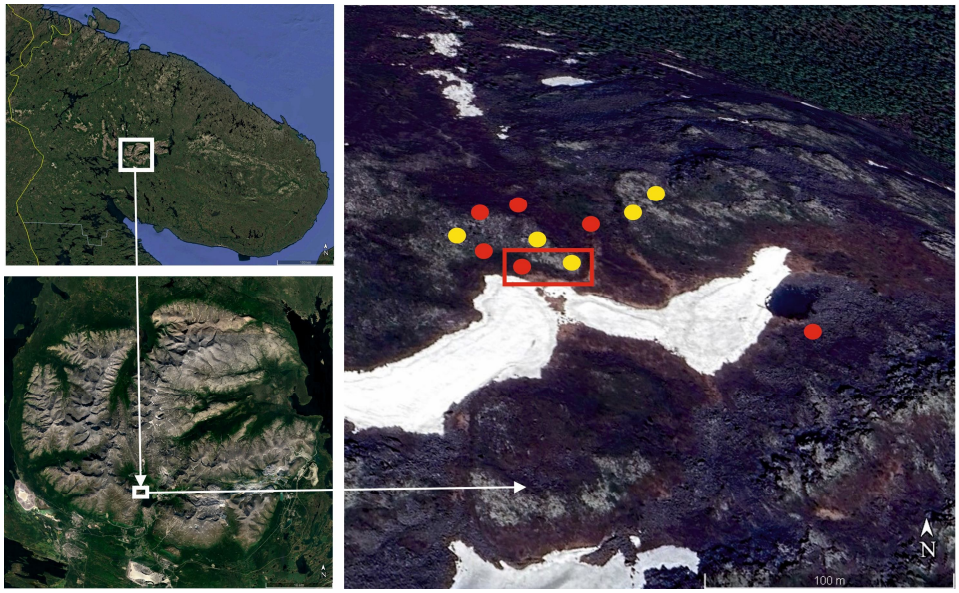


Fig. 1. Location of the sample plots in the Khibiny Mountain tundra (red dots – dwarf shrub communities, yellow dots – lichen communities, red square – the sample plots in 2023 and 2000 are the same). The product of ESRI satellite were used to reproduce the map.

The investigated site encompasses the northeastern slope of the Vudjavrchorr Mountain, specifically within the Botanical Circus – a well-defined glacial saddle in the tundra belt. This area is characterized by a Quaternary glaciation-formed depression, surrounded by convex, steep slopes with inclines reaching 30–40°. The local topography consists of dome-shaped bedrock outcrops and a saddle filled with boulder deposits.

The climate of the Khibiny Mountains is determined by: position north of the Arctic Circle, proximity to the ice-free Barents Sea (which is influenced by the warm Gulf Stream), and orographic effects of the mountainous terrain. The average monthly air temperature in January is –12.5°C, in July it is 12.9°C; the annual precipitation total is 928 mm, the duration of the growing season is 100–105 days, the duration of the period with a stable snow cover is 209 days, and the snow cover depth is 122 cm (Zyuzin 2006). The zonal vegetation in the Khibiny Mountains belongs to the subzone of the northern taiga. The vegetation is characterised by distinct zonation: there are the forest belt; the belt of birch twisted forests, and the mountain-tundra belt.

Sample plots characteristic

The selected study area represents a typical hypoarctic mountain-tundra ecosystem, characterized by a composition of widely distributed plant species characteristic of this biome. The spatial organization of the site provides sufficient environmental heterogeneity to incorporate multiple association types with an appropriate number of replicates for local-scale investigations.

In 2023, we established ten permanent monitoring plots (10×10 m each, with five replicates) in two community types within the mountain tundra of Vudjavrchorr Mountain (Khibiny Massif). For each plot, we recorded: geographic coordinates (WGS-84 system) of boundary points, absolute elevation markers (Table 1). Notably, the coordinates of plot 5 (dwarf shrub community), plot 1 (lichen community) matched exactly with plots surveyed in 2 000. Sampling was conducted on slopes with gradients varying between 5° and 30°, representing the dominant geomorphological features of the study area.

Number of sample plot	Coordinates		Elevation m a.s.l.
Dwarf shrub communities			
1	67.643108	33.652061	552.1
2	67.643313	33.654015	540.8
3	67.643453	33.652892	542.2
4	67.64227	33.654854	553.6
5[1]	67.642835	33.652778	552.8
Lichen communities			
1[1]	67.64287	33.653668	549.0
2	67.643304	33.656214	560.9
3	67.64358	33.655021	545.4
4	67.643295	33.651512	557.7
5	67.643204	33.652952	550.7

Table 1. Coordinates of centers of sample plots in communities of the mountain tundra of the Khibiny Mountains, NW Russia. *Note*: [1]The coordinates of the sample plots in 2023 and 2000 are the same.

Selection was haphazard, but it was intended to identify a representative set of sites for each of the typical habitats in the mountain tundra belt. Individual sites were relatively homogeneous in terms of microtopography and plant composition and unequivocally attributable to a single habitat type. Complete phytosociological descriptions using the Braun-Blanquet cover-abundance scale (Westhoff and Van Der Maarel 1973) have been conducted. The projected coverage of layers and species was assessed in relative shares. The syntaxonomic affiliation of the communities was determined using modern taxonomic sources (Mucina et al. 2016).

Methods

Changes in climate parameters (average annual air temperature; average air temperature during the warm (snow-free, June –September) and cold (October–May) periods of the year) were assessed based on data from the PABGI meteorological station, located within the forest belt. In accordance with the World Meteorological Organization decision, standard norms for most meteorological parameters are calculated for consecutive 30-year periods with a 10-year step. In that way, current norms are for 1981–2010, then 1991–2020, and so on, while the period 1961 – 1990 remains the baseline for assessing long-term climate changes (Demin and Volkov 2017). Therefore, the period 1991 – 2020 was selected for climate monitoring in the study area and for evaluating current weather anomalies. Air temperature in the ground layer during the growing season in the monitoring years were determined as follows: in 2000, using thermographs installed at a height of 30 cm; and in 2023, using DS1921G-F5 loggers (iButton). Precipitation amounts were measured using precipitation collectors.

Reserves and structure of aboveground biomass was determined by the method of registration sites, the underground biomass was determined using the monoliths method (Alexandrova 1958, Bazilevich et al. 1978). Aboveground biomass of deciduous dwarf shrubs was separated into leaves, current-year shoots, and previous-year shoots. The biomass of evergreen dwarf shrubs was separated into leaves and current-year shoots, and leaves and previous-year shoots. All green aboveground parts were collected and counted at peak phenological development.

The entire green aboveground mass of mosses was determined. For species, where possible, annual growth was estimated based on colour and morphological markers. When this was not feasible, the annual growth was estimated to be 20% of the green aboveground mass, based on values from the established literature. The entire mass of the living thallus of lichens was included in the above-ground biomass. Annual growth was not measured directly; instead, a standard literature-derived value of 5% of the aboveground mass was applied.

Biomass evaluations were conducted in the first half of August during the maximum seasonal plant development on plots measuring 0.25 × 0.25 metres with a fourfold repetition. In 2000, 20 such accounting plots were described, and in 2023, 40 plots were documented. The biomass was sorted by plant species, separating living parts from dead ones. The boundary between aboveground and belowground phytomass was defined at the transition zone where living (green) moss tissues changed to non-living (brown) parts. For shrubs and dwarf shrubs, the current year's shoots were separated from the previous year's shoots, with a division into leaves and stems. In mosses and lichens, the living parts of the thalli were considered in the assimilative mass. Total plant biomass estimates were obtained per plot by sum of the shoot mass for each species.

Primary production of shrubs and dwarf shrubs was considered to be the sum of the mass of current year's shoots and the mass of previous year's shoots (accounting for branch thickening), not exceeding 4% (Andreyashkina 1971). Annual production of mosses was assumed to be 20%, and that of lichens 5%, of their living aboveground biomass (Levina 1960, Richardson and Finegan 1973). Growth of underground organs was not considered. The material was dried to an air-dry state at +40°C. The organic matter stocks in the communities were calculated taking into account the projected coverage, in grams of absolute dry matter per square metre of soil surface occupied by the community.

The carbon contents were measured using absolutely dry material with a Unicube® Elementar elemental analyser (Elementar GmbH, Germany). The analyses were conducted using the scientific equipment of the Shared Research Facilities Centre of the Federal Research Centre "Karelian Scientific Centre of the Russian Academy of Sciences." Carbon stocks in the phytomass of ground cover plants (g C m^{-2}) were calculated by multiplying the carbon content (%) by the phytomass stock. The total carbon stock for the community was determined as the sum of the carbon stocks of all fractions.

Statistical analysis

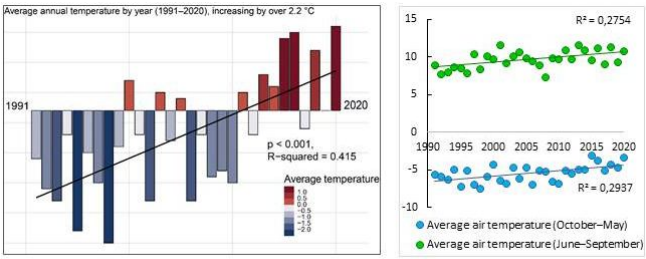
Statistical data processing was performed using the Statistica 10 software. Community distribution analysis was carried out using the indirect ordination method – non-metric multidimensional scaling (NMDS) – based on the Bray–Curtis distance, implemented in the *vegan* package in the R environment (Oksanen et al. 2019). The statistical significance of differences in mean values was assessed using Student's *t*-test. Significance of differences: * – $p \leq 0.1$; ** – $p \leq 0.01$; *** – $p \leq 0.001$.

Results

Characteristics of major climate change trends in the study area

Figure 2a shows changes in average annual air temperatures recorded by the PABGI weather station in the Khibiny forest belt over the period from 1991 to 2020. It can be observed that from 1991 to 2010, average annual temperatures were below 0°C, averaging – 0.9°C, whereas from 2011 to 2020 they were positive, averaging 0.6°C, with temperatures falling below 0°C only in 2012 and 2017. Analysis of the obtained time series of average annual temperatures revealed a significant linear trend toward warming, with an increase of 2.2°C ($R^2 = 0.42$, $p \leq 0.001$).

The time series of average air temperatures during the warm (snow-free, June – September) and cold (October – May) periods of the year from 1991 to 2020 were analyzed separately (Fig. 2b). The coefficient of variation (CV) was 12.4% for the warm period and 21.6% for the cold period. A lower CV in the warm period indicates greater stability of average air temperatures, while a higher CV in the cold period reflects more pronounced fluctuations over the study period. Correlation analysis showed that the average annual temperature was more strongly correlated with the air temperature during the cold period ($r = 0.90$) than with that during the warm period ($r = 0.65$). An analysis of changes in average monthly temperatures (Fig. 3) revealed unevenly distributed warming within a year. It was more pronounced in the spring months (April and May), as well as in August and November, and least evident during the winter months (December – February).



(**a**) (**b**)

Fig. 2. Time series and linear trends of (**a**) average annual air temperature and (**b**) average air temperature during the warm (snow-free, June – September) and cold (October – May) periods of the year at the PABGI (Khibiny Mountain) site from 1991 to 2020.

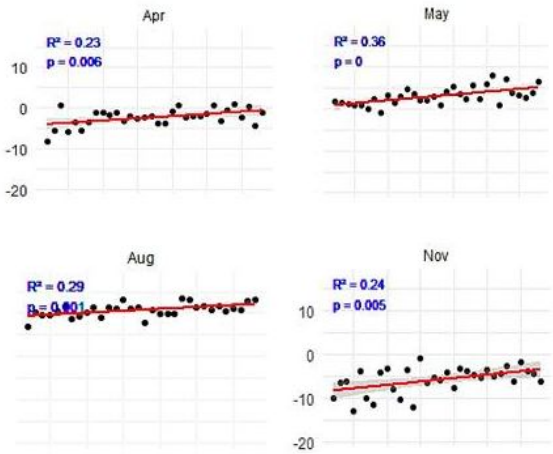


Fig. 3. Dynamics of average monthly temperatures by month for the period 1991 – 2020 (months with a confidence level of $p < 0.01$ are shown).

Climatic characteristics of the growing season

Temperature regimes during the vegetation period in the Khibiny mountain tundra in different monitoring years (2023 and 2000) differ significantly. All indicators of average daily air temperatures were higher in 2023: the sum of effective temperatures was 1.2 times greater (1107 *vs.* 899°C), active temperatures were 1.5 times higher (919 *vs.* 612°C), and the average temperature for the vegetation period was 1.3 times higher (12.5 *vs.* 9.7°C). During the vegetation period (*see* Fig. 4a), the difference between the average monthly temperature in June and July was 0.5 – 0.9 °C, while in August and September, it reached 5°C.

The amount of precipitation (Fig. 4b) in 2023 was 1.8 times higher than in 2000 (340 *vs.* 188 mm). As poikilohydric organisms, mosses responded to higher precipitation during the 2023 growing season with a substantial increase in annual production – 77% higher than in the drier year of 2000. Although moss growth initiates

under the snowpack, growth rates peak during the active growing season (July–August), particularly when regular precipitation occurs and prolonged dry spells are absent (Ermolaeva and Shmakova 2020). Consequently, the 7-day extension of the growing season in 2000 due to earlier snowmelt did not result in a significant increase in annual production. During the 2023 growing season, the highest precipitation was recorded in August (132 mm) and September (162 mm). Mean annual precipitation in the study region ranges from 730 to 1250 mm. On average, up to 37% of this (approximately 376 mm) falls during the growing season (June–September). July and September are typically the wettest months, with average precipitation reaching up to 114 mm.

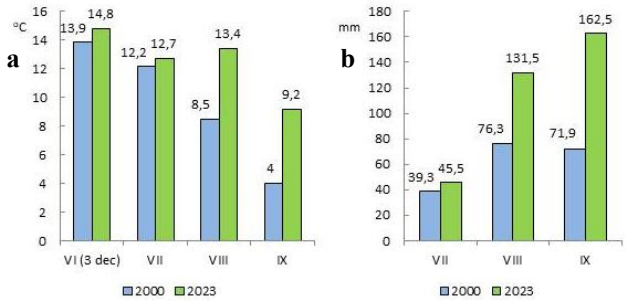


Fig. 4. Average monthly air temperature (**a**) and precipitation amount (**b**) during the growing season in the Khibiny mountain tundra in the monitoring years.

The vegetation cover was completely cleared of snow on June 1 in 2000 and on June 7 in 2023. In lichen communities, the depth of snow cover was four times less than in dwarf shrub communities, so the release of sample plots from snow in lichen communities occurs earlier, which somewhat extends the duration of the growing season. The growing season in the Khibiny mountain tundra averages 90 to 95 days. In recent years, we have observed an extension of the growing season to up to 118 days, attributed to high September temperatures. The growing season typically begins between June 3rd and 5th.

It was observed that the period of active vegetation (July) was accompanied by a small amount of precipitation in both years of monitoring. Overall, the vegetation period of 2023 is characterized as warm and relatively humid, while 2000 was relatively warm but dry.

Description of plant communities

The vegetation the mountain tundra belt of the Khibiny Mountains is characterised by significant diversity, resulting from the influence of meso- and microrelief and the heterogeneity of microclimatic conditions. The most common and characteristic assemblages that occupy a large part of the mountain-tundra belt are two types of plant community (Fig. 5). The diversification of vegetation cover is consequently the topographic gradient, which determines different levels of snow accumulation and moisture.

Fig. 5. Vegetation ground cover in different tundra types in a subarctic mountains tundra (Khibiny Mountains): (**a**) dwarf shrubs community; (**b**) lichen community.

The first type are dwarf shrub communities (Fig. 5a). They are located on gentle slopes of the cirque in the trans-eluvial landscape element under the conditions of mountain placcor and transit of nutrients and water. During the winter, the slopes are protected from drying winds by a sufficiently thick snow cover (0.7-2.5 m), which fully melts in mid-June. The vegetation season is of moderate duration and the microclimatic conditions are optimal for the formation of dwarf shrub communities classified as ***Empetro-Betuletum nanae*** Nordh. 1943 and ***Phyllodoco-Vaccinietum myrtilli*** Nordh. 1943 alliance ***Phyllodoco–Vaccinion myrtilli*** Nordh. 1936 oder ***Deschampsio flexuosae-Vaccinietalia myrtilli*** Dahl 1957 class ***Loiseleurio-Vaccinietea*** Eggler ex Schubert 1960. These plant communities have a close cover (100%).

The species diversity of the dwarf shrub communities comprised 18 vascular plant species. The herb-shrub layer is dominated by *Empetrum hermaphroditum* Hagerup, *Vaccinium uliginosum* L., *V. myrtillus* L., *V. vitis-idaea* L., *Betula nana* L. A characteristic feature of these communities is their well-developed moss-lichen mat, forming continuous ground cover.

The mosses are represented by nine species, consisting mainly of mesophytic species *Pleurozium schreberi* (Willd. ex Brid.) Mitt. and *Dicranum majus* Turner. Among the six lichen species present, *Cetraria islandica* (L.) Ach. and *Flavocetraria nivalis* (L.) Kärnefelt & A. Thell are dominant taxa.

The second type is lichen-dominated communities (Fig. 5b). They are located on gentle mountain slopes, moderately snowy in winter (up to 40 cm of snow cover high) and moderately moist in summer, as well as on elevated micro- and mesorelief elements: on outcrops of bedrock, dome-shaped peaks, and slopes of morainic hills. Within these communities, autochthonous well-drained soils are formed with a significant content of bouldery material. These are xeromesophythic communities that form under conditions of blowing snow in winter and poorly moistened in summer. The communities are characterised by significant share of bare ground, vegetation cover exhibits pronounced horizontal mosaicity. In the ground cover a bushy snow-adapted lichens dominate. The association identified ***Loiseleurio-Diapensietum*** (Fries 1913) Nordh. 1943 alliance ***Loiseleurio-Arctostaphylion*** Kalliola ex Nordhagen 1943 oder ***Deschampsio flexuosae-Vaccinietalia myrtilli*** Dahl 1957 class ***Loiseleurio-Vaccinietea*** Eggler ex Schu-

bert 1960. The vegetation cover is not closed, the proportion of bare ground is on average 30%.

The species diversity of the plant cover in the lichen communities is represented by 11 vascular plant species. Only four shrub species significantly contribute to the aboveground biomass" *E. hermaphroditum*, *V. uliginosum*, *B. nana*, and *Loiseleuria procumbens* (L.) Desv. The height of the dwarf-shrub vegetation is constrained by snow cover depth. Among moss species, *Racomitrium lanuginosum* (Hedw.) Brid., *P. schreberi*, and *D. majus* are dominated. The greatest ground coverage among from 50 to 5% the identified 20 lichen species is occupied by *Flavocetraria nivalis* and *F. cucullata* (Bellardi) Kärnefelt et A. Thell, *Alectoria ochroleuca* (Hoffm.) A. Massal., and *Cetraria islandica.*

Reserves and structure of biomass in dwarf shrub communities

Aboveground phytomass of the dwarf shrub community (Table 2) in 2023, accounting for projective cover, averaged 908 g m^{-2}. Due to high vegetation patchiness, the aboveground phytomass distribution across sampling plots was uneven, with productivity values varying up to twofold (615 and 1262 g m^{-2}). The differences in aboveground biomass reserves are primarily related to the proportion of perennial plant organs. In terms of species composition, the aboveground phytomass of the dwarf shrub community is represented by the following life forms (Fig. 6): 72% vascular plants (48% evergreen and 24% deciduous shrubs), 18% lichens, and 10% mosses. Among vascular plants, the greatest contribution to the above-ground phytomass is made by dwarf shrubs: *Empetrum hermaphroditum* – 39%, *Betula nana* – 9%, *Vaccinium uliginosum* – 8%, *V. myrtillus* – 5%, and *V. vitis-idaea* – 3%. Among green mosses, two species dominate: *Pleurozium schreberi* (6%) and *Dicranum majus* (3%). In the lichen group, the highest phytomass is observed in *Cetraria islandica* (16%). Among herbaceous perennials, the following species were recorded: *Arctostaphylos alpina* (L.) Spreng., *Festuca ovina* L., *Avenella flexuosa* (L.) Drejer, and *Juncus trifidus* L. Among club mosses, *Diphasiastrum alpinum* (L.) Holub was found on the plots. However, their contribution to the aboveground phytomass was minimal, not exceeding 2.5 g m^{-2} (less than 0.3% of the total above-ground phytomass). The largest reserves were recorded in habitats with favorable moisture and mineral nutrient conditions. The proportion of assimilating organs to the above-ground phytomass in different plots ranged from 31% to 60%. Their reserves vary within a relatively narrow range; the coefficient of variation (CV) was the lowest among all components of total phytomass – 24% (Table 2).

The average annual increment was 128 g m^{-2} (ranging from 72 to 223 g m^{-2} across sample plots), which corresponds to 5% of the total reserve and 14% of the above-ground phytomass. Underground biomass constitutes a large and highly variable portion of the total phytomass (55 – 67%), averaging 1383 g m^{-2}. The ratio of above-ground to below-ground phytomass is approximately 1:1.5, indicating a predominance of underground organs in shrub communities. However, there were sample plots where the mass of underground organs was comparable to that of the aboveground ones.

Sample plots	The aboveground biomass[1]				Underground biomass	Total phytomass
	total	assimilation organs	stems	primary production		
			Dwarf shrubs community, 2023			
1	1074.7±154.5	470.0±94.3	604.7±71.5	155.0±26.7	1312.5±78.1	2387.2±125.5
2	1261.8±80.2	389.0±43.6	872.8±114.1	223.1±62.5	2325.9±241.7	3587.7±197.5
3	697.7 ±227.8	418.1±136.4	279.6±94.8	71.8±22.8	1411.6±109.8	2109.3±167.1
4	890.6 ±152.6	477.7±115.6	412.9±41.8	108.5±12.6	1112.4±160.2	2003.0±48.2
5	614.7±128.7	240.7±71.2	374.0±64.6	80.5±12.9	753.5±146.3	1368.2±170.2
< > (CV, %)	**907.9±119.1** (29.3)	**399.1±42.9** (24)	**508.8±105.2** (46.3)	**127.8±27.9** (48.8)	**1383.2±261.2** (42.2)	**2291.2±364.5** (35.6)
			Lichen community, 2023			
1	691.6±132.8	510.9±120.2	180.7±83.6	56.1±16.6	951.2±101.4	1642.8±151.2
2	540.0± 164.1	468.9±148.3	71.1±31.5	54.5±4.7	815.2±103.8	1355.2±171.3
3	666.9± 106.8	525.1±105.9	141.8±49.5	66.0±14.5	836.0±156.1	1502.9±143.8
4	665.7 ±161.8	546.1±184.2	119.6±37.9	68.1±10.0	1173.3±102.3	1839.0±154.9
5	544.6 ±140.2	352.3±122.7	192.3±41.1	48.2±12.0	1071.5±116.4	1616.1±128.9
< > (CV, %)	**621.8±32.8** (11.8)	**480.7±34.5** (16)	**141.1±21.9** (34.6)	**58.6±3.7** (14.2)	**969.4±68.5** (15.8)	**1591.2±80.1** (11.2)
			Dwarf shrubs community, 2000			
< > (CV, %)	**745.8±49.7** (14.9)	**328.1±20.7** (14.1)	**417.7±21.3** (11.4)	**137.2±8.4** (13.7)	**1650.0±182.7** (24.8)	**2395.8±143.3** (13.4)
			Lichen community, 2000			
< > (CV, %)	**732.9±31.8** (9.7)	**593.6±26.4** (9.9)	**139.3±25.6** (41.1)	**72.8±10.8** (33.1)	**423.5±12.2** (5)	**1156.4±23.1** (2.7)

Table 2. Stocks and structure of phytomass (g m^{-2}) in mountain tundra communities of Khibiny Mountains in different years of monitoring. *Note*: [1]Data – arithmetic mean ± standard error; CV – coefficient of variation.

Reserves and structure of biomass in lichen communities

The aboveground phytomass of the lichen community in 2023, taking into account the projective cover averaged 622 g m^{-2} is shown in Table 2. This type of community is characterized by a severely sparse ground vegetation cover. In terms of species composition, the aboveground phytomass of the lichen community was represented by the following life forms (Fig. 6): 32% vascular plants (21% evergreen and 11% deciduous shrubs), 62% lichens, and 6% mosses. The aboveground phytomass was primarily composed of lichens: *Flavocetraria nivalis* (34%), *Cetraria islandica* (13%), *Alectoria ochroleuca*, *Cladonia arbuscula* (Wallr.) Flot., and *Cladonia mitis* Sandst. (4% each). Among vascular plants in the lichen community, the largest aboveground phytomass was found for *Empetrum hermaphroditum*

(13%), followed by *Betula nana* (7%), *Loiseleuria procumbens* (5%), *Vaccinium uliginosum* (4%). The dominant moss species accounted for *Pleurozium schreberi* (2%), *Racomitrium lanuginosum* (2%).

Assimilating organs dominated the structure of the aboveground phytomass, accounting for 65–87%. The annual increase averaged 59 g m^{-2} (ranging from 48 to 68 g m^{-2} across sample plots) per year, representing 4% of the total reserve and 9% of the aboveground phytomass stocks. The stocks of underground organs in the lichen community averaged 969 g m^{-2}, with their share of the total phytomass across sample plots varying between 41% and 68%. The ratio of aboveground to underground phytomass was 1:1.6, indicating the predominance of underground organs.

Compared to the shrub community, the lichen community showed a narrower range of variation in annual growth, aboveground, and total phytomass (CV – no more than 14%). The highest coefficient of variation (CV – 34.6%) for the aboveground phytomass was observed for stem biomass, reflecting the variable contribution of vascular plants to the vegetation cover.

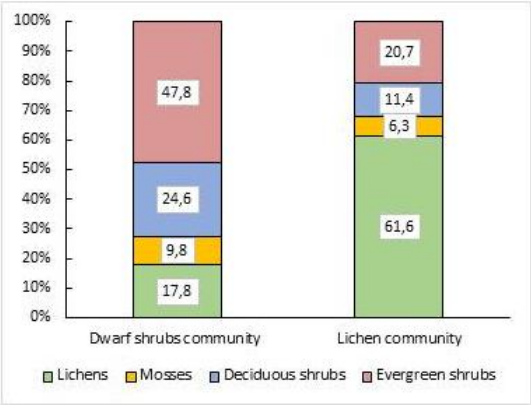


Fig. 6. The structure of aboveground phytomass in mountain tundra communities of the Khibiny Mts., 2023.

Comparative characteristics of aboveground phytomass reserves and structure in different monitoring years

Table 2 presents data on the reserves and structure of phytomass in the communities of the Khibiny mountain tundra obtained in 2000. Using non-metric multidimensional scaling (NMDS), the positions of sample plots from dwarf shrub and lichen communities were analyzed for both monitoring years (Fig. 7). It is evident that, in the ordination space, the plots form three well-differentiated clusters: (1) dwarf shrub community of 2000; (2) dwarf shrub community of 2023; and (3) lichen community of both 2000 and 2023. A divergence in the feature space between dwarf shrub plots from different monitoring years is clearly observed, whereas no such divergence was noted for lichen plots.

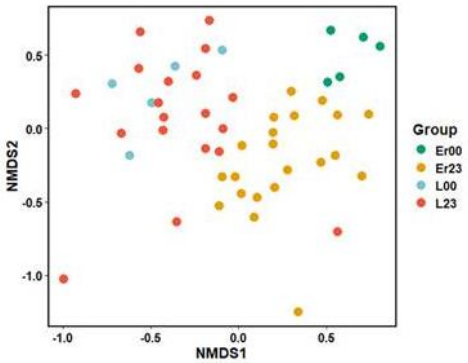


Fig. 7. Ordination of sample plots from the Khibiny mountain tundra communities using NMDS.

To assess the significance of these differences, the stress value was considered. In this case, the stress level was 15%, which is within an acceptable range for reliable interpretation, although some objects may still be randomly positioned (Clarke 1993). Thus, the obtained results can be considered reliable. This conclusion was further supported by an analysis of group similarities using ANOSIM (Analysis of Similarities): for shrub plots, $p = 0.008$ between 2000 and 2023, while for lichen plots, $p = 0.594$.

A comparative analysis of the structure of aboveground phytomass in different years of monitoring (Fig. 8) was conducted on sample plots with the same coordinates. The differences in the size of aboveground phytomass between years were minimal, although a slight decrease was observed in 2023 (18% in the shrub community and 6% in the lichen community).

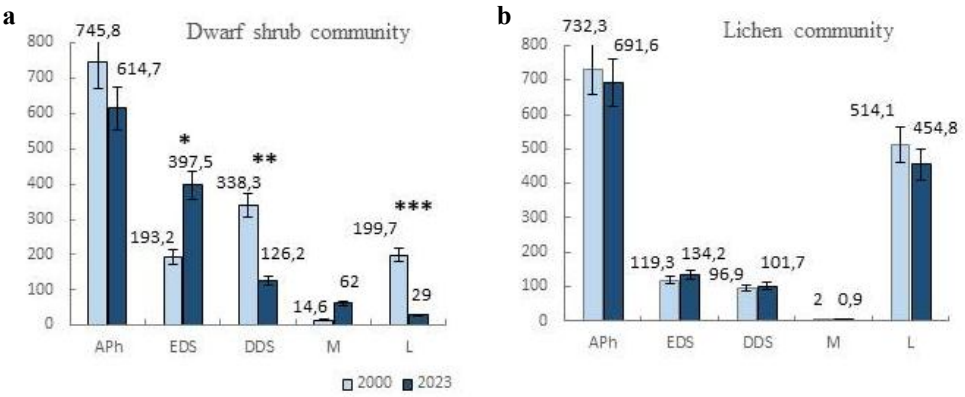


Fig. 8. The structure of the aboveground phytomass (g m^{-2}) in the communities of the Khibiny mountain tundra in different years of monitoring on the same sample plots: (**a**) dwarf shrubs community; (**b**) lichen community. *Significance of differences*: * – $p \leq 0.1$; ** – $p \leq 0.01$; *** – $p \leq 0.001$. *Note*: APh – aboveground phytomass; EDS – evergreen dwarf shrubs; DDS – deciduous dwarf shrubs; M – mosses; L – lichens.

Regarding the structure of aboveground phytomass, no significant differences were found between plant groups in the lichen community; however, there was a visible tendency for an increase in the proportion of dwarf shrubs (evergreen – 11%, deciduous – 5%) and a decrease in the contribution of mosses and lichens by 55% and 12%, respectively. Significant changes were observed only in the dwarf shrub community, where, in 2023, the mass of evergreen shrubs was 51% higher than in 2000, and the mass of deciduous shrubs and lichens was 63% and 85% lower, respectively. Although the moss mass in the aboveground phytomass was 76% higher in 2023, the differences between years are not statistically significant.

A comparative analysis of annual production revealed lower values in 2023: by 25% in the lichen community (differences are not significant) and by 41% in the dwarf shrub community ($p < 0.1$). Based on the characteristics of the growing season (Fig. 4), it would be expected that annual production in 2023 would exceed that of 2000, given that 2000 was colder and drier. While temperature and precipitation are the main driving factors, the shorter growing season in 2023 – by 7 days – may also have contributed to the observed decline. An analysis of the contribution of plants of different life forms (Fig. 9) to annual production showed that in 2023, compared to 2000, the mass of deciduous shrubs significantly decreased, but only in the dwarf shrub community (by 4.8 times).

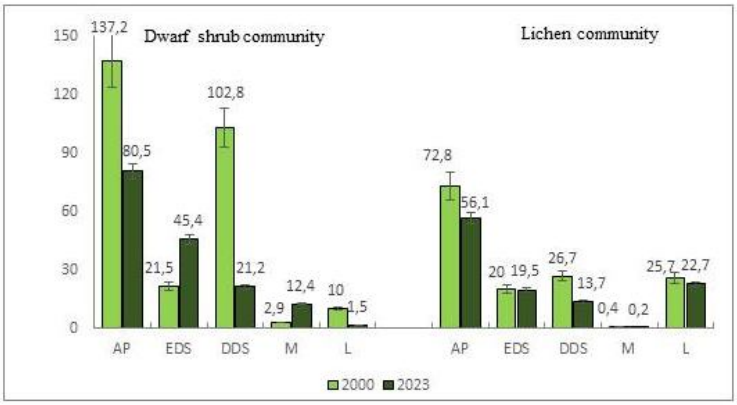


Fig. 9. The structure of annual production (g m^{-2}) in the communities of the Khibiny Mountain tundra in different years of monitoring on the same sample plots *Note*: AP – annual production; EDS – evergreen dwarf shrubs; DDS – deciduous dwarf shrubs; M – mosses; L – lichens.

In the dwarf shrub community, the reduction in mass was primarily associated with a decline in the contribution of the dominant species *Vaccinium myrtillus*, whose share of the aboveground phytomass decreased from 42% in 2000 to 14% in 2023 (Fig. 10). At the same time, an increase in the share of other dominants – *Empetrum hermaphroditum*, *Betula nana*, and *Pleurozium schreberi* and a decrease in the share of *Cladonia islandica* were observed.

In the lichen community, no significant changes were found among the dominants (Fig. 10), although a decrease in the share of *Vaccinium uliginosum* and an increase in *Betula nana* were noted in the vegetation cover. The dominant species remained the lichens *Flavocetraria nivalis*, *Cladonia islandica*, and *Alectoria ochroleuca*.

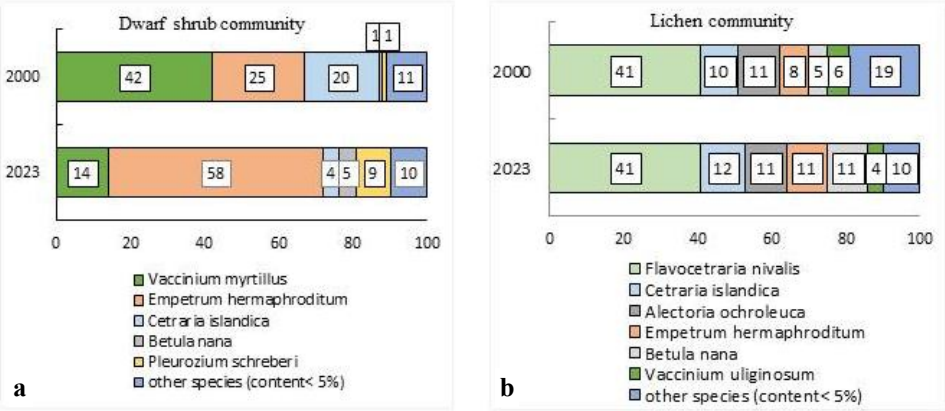


Fig. 10. Species distribution of dominants (%) in plant communities of the Khibiny Mountain tundra in different years of monitoring on the same sample plots: (**a**) dwarf shrubs community; (**b**) lichen community.

Carbon content and reserves in the aboveground phytomass of mountain tundra communities in the Khibiny Mountains

The carbon content determined in the aboveground parts of 22 plant and lichen species ranged from 41% to 56% of the absolutely dry mass, forming the following sequence: evergreen dwarf shrubs (47 – 56%), deciduous dwarf shrubs (47 – 53%), herbaceous perennials (44 – 45%), mosses (44–50%), and lichens (41–47%). The carbon content in the underground organs was 51–52%. Differences in the carbon content of the same species between different communities were statistically insignificant. The carbon content depends on the structure of the aboveground phytomass (Table 4) and on the species dominating the vegetation cover (Table 3).

The carbon content in annual growth is higher than in perennial parts. In the aboveground phytomass of evergreen dwarf shrubs, assimilating organs generally contain more carbon than stems, whereas in deciduous dwarf shrubs, the opposite pattern is observed. The highest carbon contents in both communities were found in evergreen dwarf shrubs, particularly in the dominant species *Empetrum hermaphroditum*. The lowest values were recorded for lichens, especially the dominant species *Cladonia islandica* and *Flavocetraria nivalis* (41 – 43%).

As shown in Table 4, the phytomass of the dwarf shrub community accumulates 440 g C m^{-2} of which 51% is stored in evergreen dwarf shrubs, 25% in deciduous shrubs, 9% in mosses and 15% in lichens. The lichen community accumulates 1.5 times less carbon than the dwarf shrub community (287 g C m^{-2}), with most carbon concentrated in lichens (58%), followed by evergreen shrubs (23%), deciduous shrubs (12%), and mosses (6%).

Species[1]	Dwarf shrub community	Lichen community
Empetrum hermaphroditum	54.78±0.35	51.38±0.41
Vaccinium vitis-idaea	48.00±0.47	49.79±1.02
Loiseleuria procumbens	51.40±0.25	51.38±0.58
Phyllodoce coerulea	51.36±0.35	–
Betula nana	51.50±0.96	49.21±0.41
V. uliginosum	50.43±0.36	49.74±0.86
V. myrtillus	49.51±0.16	–
Pleurozium schreberii	44.92±0.28	49.56±0.50
Cetraria islandica	41.09±0.36	43.23±1.96
Alectoria ochroleuca	–	44.99±3.98
Flavocetraria nivalis	–	41.78± 0.64

Table 3. Carbon content (%) in dominant plant species of the Khibiny Mountain tundra belt. *Note*: [1] Species whose contribution to the aboveground phytomass is ≥ 5%; "–" — species absent from the community or with a contribution ≤ 2%.

Life forms	Aboveground phytomass (g m^{-2})	Carbon content (%)	Carbon stock (g C m^{-2})
Dwarf shrub community			
Evergreen dwarf shrubs	434.0 ± 46.6	51.59 ± 0.64	223.9 ± 20.91
Deciduous dwarf shrubs	223.3 ± 74.5	49.47 ± 0.66	110.47 ± 20.13
Mosses	88.7 ± 34.8	44.53 ± 0.21	39.5 ± 10.18
Lichens	161.8 ± 53.3	40.87 ± 0.22	66.14 ± 15.77
Total	**907.8 ± 119.1**	–	**440.01 ± 61.83**
Lichen community			
Evergreen dwarf shrubs	128.8 ± 23.3	51.22 ± 0.40	66.0 ± 12.01
Deciduous dwarf shrubs	70.9 ± 10.9	49.29 ± 0.44	34.95 ± 5.24
Mosses	38.9 ± 20.7	47.57 ± 0.67	18.5 ± 9.51
Lichens	383.2 ± 33.7	43.81 ± 0.69	167.9 ± 14.48
Total	**621.8 ± 32.8**	–	**287.35 ± 10.74**

Table 4. Organic matter and carbon stocks in plant groups of the Khibiny Mountain tundra communities. *Note*: [1] Species whose contribution to the aboveground phytomass is ≥ 5%; "–" — species absent from the community or with a contribution ≤ 2%.

Discussion

A clear trend toward climate warming, with an increase of 2.2°C in between 1991 and 2020 was found. Recent warming is most pronounced during the spring months (April and May) and in the autumn, particularly November, while summer warming is less marked. During an earlier observation period (1991–2010), pronounced warming across the Kola Peninsula was primarily observed in winter, mainly in December and January. when temperatures increased by up to 2°C (Demin 2012).

Correlation analysis revealed a strong positive relationship (r = 0.90) between the average annual temperature and air temperatures during the cold period (October

– May), although no significant warming trend was recorded specifically during the winter months. In recent literature, two scenarios leading to extended growing seasons are apparent. The first one related to greening, *i.e.* increased plant productivity in significant parts of high-latitude regions (Walker et al. 2005, Hudson and Henry 2009, Speed et al. 2010, Walker et al. 2012, Xu et al. 2013, Vickers et al. 2016). However, contrasting scenario emphasize that most Arctic regions exhibit stable productivity in recent years or decreased productivity (browning). The scenario is attributed to summer drought. as described in the second variant (Verbyla 2015, Miles and Esau 2016, Raynolds and Walker 2016, Bjerke et al. 2017).

The most favorable ecological conditions for phytomass growth are associated with communities located on transeluvial and accumulative-eluvial landscape elements, resulting in greater productivity. In these areas, thick snow cover protects vegetation during the winter from drying winds. The thickness of winter snow cover and soil moisture levels during the growing season are critical factors determining species composition and, consequently, community productivity.

In communities located on autonomous landscape elements, phytomass stocks and annual production were significantly lower. These habitats experience strong and frequent winter–spring winds and uneven snow cover distribution, resulting in a sparse presence of vascular plants and dominance by a single lichen species.

Although tundra plant communities are generally polydominant, the values of aboveground phytomass and annual growth in all communities are primarily determined by two or three dominant species. The aboveground phytomass of the dwarf shrub community averaged 908 g m^{-2}, which is 1.5 times larger than that of the lichen community (622 g m^{-2}). Due to the high mosaic structure of the plant cover within sample plots, aboveground phytomass distribution in the dwarf shrub community is highly uneven, with differences reaching up to twofold. In contrast, aboveground phytomass in the lichen community is more uniform (coefficient of variation: 11.8% for lichens versus 29.3% for dwarf shrubs).

Differences in aboveground phytomass stocks are primarily associated with the proportion of perennial woody plant organs (72% dwarf shrubs in the shrub community versus 32% in the lichen community). The persistence of aboveground structures over several years contributes significantly to phytomass accumulation (Maslov et al. 2016).

Primary production also varied considerably between communities, being 2.2 times higher in the dwarf shrub community than in the lichen community (128 and 59 g m^{-2}, respectively). However, the relative growth (the ratio of primary production to total biomass stocks) was similar: 5% in the dwarf shrub community and 4% in the lichen community.

Underground biomass in the shrub community was 1.4 times greater than in the lichen community (1383 and 969 g m^{-2}, respectively). The ratio of aboveground to underground phytomass (1:1.5) highlights the predominance of underground organs in mountain tundra communities, where underground biomass accounts for an average of 60% of total phytomass. Despite differences in the absolute sizes of aboveground, underground, and total phytomass between the two community types, their relative distributions were consistent (aboveground phytomass making up 39 – 40% and underground phytomass comprising 60 – 61% of total phytomass).

The total phytomass stocks values for communities on the northeastern slope of Mount Vudjavrchorr were higher compared to those from the southwestern slope of Mount Rasvumchorr, where more severe microclimatic conditions were observed. In shrub communities, total phytomass stocks ranged from 1454 to 1547 gm^{-2},

while in lichen communities, stocks ranged from 920 to 1331 g m^{-2} (Shmakova et al. 2008). In the Tuliyok River valley (Khibiny), aboveground phytomass in lichen communities amounted to 940 – 1230 g m^{-2} according to gravimetric measurements and 860 – 100 g m^{-2} according to NDVI data (Golubeva et al. 2010).

The total biomass stocks of the studied Khibiny communities correspond well to those of similar communities in northern Fennoscandia, such as Abisko (2400 g m^{-2}) (Sorensen et al. 2008), but differ from values reported for other regions: 1800 g m^{-2} in the forest-tundra of the Eastern Urals, 800–2000 g m^{-2} in the mountain tundra of the Polar Urals (Andreyashkina and Peshkova 2003), and 757 – 903 g m^{-2} in the Eastern European tundra (Uvarov et al. 2021). Primary production in the Polar Urals communities ranges from 40 to 356 g m^{-2} (Andreyashkina and Peshkova 2003).

In the work of Berner et al. (2024), a dataset of aboveground biomass measurements across Arctic and subarctic ecosystems was presented, covering 2327 sample plots in 636 field locations across seven countries. In this dataset, the mean aboveground phytomass for subarctic tundra is 1128 g m^{-2}. As aboveground biomass is a key source of soil organic matter, studying biomass accumulation processes in tundra communities is critical for understanding carbon sequestration. Our data fall within the range of aboveground biomass and plant functional type biomass values reported by Berner et al. (2024). According to our previous research (Shmakova et al. 2008), the total biomass in six dwarf shrub community types of the Khibiny mountain tundra ranges from 1300 to 2400 g m^{-2} (of which the aboveground component accounts for 550–1150 g m^{-2}). In three lichen-dominated community types, the total aboveground biomass ranges from 1150 to 1340 g m^{-2} (with the aboveground part being 730–960 g m^{-2}).

The carbon content in plants of the Khibiny Mountain-tundra communities exhibited a wide range (41–56% of absolute dry weight) and varied according to the following order: evergreen dwarf shrubs > deciduous dwarf shrubs > herbaceous perennials > mosses > lichens. For identical species growing in different communities, carbon content was similar. Most researchers of forest and tundra communities estimate plant carbon content at 45 – 50% of dry mass (Bobkova and Tuzhilkina 2001). In tundra plants of northern Fennoscandia, carbon content ranges from 35 – 54%, following the order: dwarf shrubs > mosses > lichens > sedges > grasses > forbs (Maslov et al. 2016). In dwarf shrubs of Kola Peninsula forest ground cover, carbon content varies from 35 – 66%; in moss green shoots from 45 – 73%; and in *Cladonia* lichen thalli from 45 – 48% (Sukhareva et al. 2023). The carbon content in mosses is a stable parameter. In 2000, it ranged from 41.2% to 45.5%. In 2023, the mean moss carbon content was 44.5% in the dwarf shrub community and 47.1% in the lichen community. For individual species: *Pleurozium schreberi* – 44.3% in 2000 *vs*. 47.2% in 2023; *Dicranum majus* – 45.5% in 2000 *vs*. 45.6% in 2023. We conclude that no significant interannual differences were detected.

According to our data, the aboveground phytomass of dwarf shrub communities accumulated 1.5 times more carbon than that of lichen communities (440 and 287 g C m^{-2}, respectively), largely due to differences in biomass size. Carbon stocks in the studied Khibiny communities align with those reported for tundra ecosystems in northern Fennoscandia: 311 g C m^{-2} in Flavocetraria-crowberry communities and 294 g C m^{-2} in moss-dwarf shrub tundra communities. In most tundra ecosystems, carbon is predominantly stored in underground phytomass, a distribution that reflects the ratio between aboveground and underground plant parts (Maslov et al. 2016).

In light of observed climate warming in the Khibiny mountain-tundra belt, a comparative analysis of vegetation and phytomass stocks was conducted on the same test plots after a 23-year interval. The analysis revealed no significant differences in aboveground phytomass size in either community type. However, in the dwarf shrub community, shifts at the species and functional group levels were recorded. A substantial decrease in the mass of deciduous dwarf shrubs and lichens, accompanied by an increase in evergreen dwarf shrub mass, was observed. Despite similar dominant species compositions between monitoring years, their proportions shifted by 2023, with *Vaccinium myrtillus* decreasing from 42% to 14%, and *Empetrum hermaphroditum* increasing from 25% to 58%. This likely contributed to the decrease in annual production observed in 2023, as the photosynthetic productivity of evergreen dwarf shrubs (3.5 mg CO_2 g^{-1} DW h^{-1}) is substantially lower than that of deciduous dwarf shrubs (12.7 mg CO_2 g^{-1} DW h^{-1}) in the Khibiny (Shmakova et al. 1996).

The weighted average carbon content in leaves – a proxy for dominant species changes – also significantly ($p < 0.05$) increased in 2023. In the lichen community, no significant structural or compositional changes in aboveground phytomass were observed.

It is widely believed that the recent warming trend will lead to increases in productivity, biomass, and dwarf shrub cover across significant areas of high-latitude tundra, along with shifts in species composition and the possible emergence of new species (Walker et al. 2005, Hudson and Henry 2009, Speed et al. 2010, Zamolodchikov 2011, Walker et al. 2012, Xu et al. 2013, Titkova and Vinogradova 2015, Belonovskaya et al. 2016, Vickers et al. 2016, Berner et al. 2018, Grigoriev et al. 2021). A recent 27-year study from the Alexandra Fjord region of Ellesmere Island was the first plot-based study to document long-term tundra biomass increases in the Arctic (Hudson and Henry 2009). The study linked increases in bryophyte and evergreen shrub biomass to regional warming during the past 30 – 50 years (Bhatt et al. 2010).

Moreover, with rising surface air temperatures, increasing snow cover thickness, and lengthening growing seasons in the Arctic, lichen tundra is increasingly vulnerable to replacement by grass, shrub, and shrub-dominated communities (Belonovskaya et al. 2016). Nonetheless, our findings indicate the stability of the Khibiny mountain tundra ecosystem. In the dwarf shrub community during the past two decades (2000–2023), the contribution of dwarf shrubs to the aboveground phytomass remained unchanged. However, a compositional change occurred: the proportion of evergreen dwarf shrubs nearly doubled. The share of deciduous shrubs in the biomass of the shrub community (2023) has decreased by almost two times.

Similar results have been reported for tundra vegetation in Alaska (Andreyashkina and Peshkova 2003, Sambyla 2010, Jorgenson et al. 2015), even as Khibiny experiences the encroachment of the forest-tundra into tundra zones and a rise in the upper forest line (Demin 2012).

In recent decades, the global scientific community has increasingly focused on assessing the impacts of climate change and human activities on land and forest use. This trend is reinforced by international agreements aimed at combating climate change, reducing greenhouse gas emissions, and preserving biodiversity (Kurbanov et al. 2015). Satellite data, ground-based monitoring, and aerial photography contribute to the mapping of environmental conditions, even in remote regions. However, the relatively low spatial resolution of satellite imagery complicates the detection of plant community changes, especially when mosses and lichens predominate (Hudson and Henry 2009). Therefore, ground-based studies remain essen-

tial even in the era of advanced remote sensing technologies (Sumina 2017).

Warming in the Arctic is faster than on the planet as a whole. During the past 40 years, mainly due to deforestation, widespread combustion of fossil fuels, and steadily increasing industrial emissions, the atmospheric carbon dioxide (CO_2) concentration has risen from 0.027% to 0.036%. This increase has contributed to a documented increase in the mean annual temperature of 0.6°C (Bratkov and Voronin 2015). According to Rosgidromet, the average annual temperature in the Arctic increased by 2.43°C between 1990–2019.

Our study contributes to assessing the current state of tundra ecosystems by providing a critical baseline for future comparative analyses. These analyses will be essential for identifying key trends in vegetation dynamics under ongoing environmental change. The research demonstrates measurable transformations within the plant cover of mountain tundra communities in the Khibiny Mountains of the Kola Subarctic, driven by global climate warming. These changes manifest themselves at the level of shifting community components; however, in its current developmental stage, the ecosystem retains a functional capacity for self-regulation, maintaining its overall structural integrity.

The findings underscore the importance of establishing long-term monitoring programmes along environmental gradients in other vegetation belts of the Vudyavrchorr Mountain. As part of the Khibiny protected area, this site offers a unique opportunity to track ecosystem responses to climate change in multiple altitudinal zones.

The results of our study contribute to the assessment of the current state of tundra ecosystems, providing a baseline for future comparative analyses to determine key trends under changing environmental conditions.

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