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Dryas aeolian landforms in Arctic deflationary tundra, central Spitsbergen

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Abstract: Aeolian activity is common on ice free areas in regions with permafrost occurrence. Sparse high-Arctic tundra vegetation, modifying surface air flow and sediments transport, influences the generation of individual landforms and their assemblages. Observations were carried in central Spitsbergen (Svalbard), characterized by quasi-continental polar climate conditions with dry summers and common existence of winds velocities above loamy-sandy sediments transportation threshold. *Dryas* aeolian landforms created from aeolian material trapped by *Dryas octopetala* dwarf shrub were diagnosed. Main morphogenetic plants are accompanied by *Saxifraga oppositifolia* and *Bistorta vivipara*, rounded out with biological soil crust. Small size of semi-circular and semi-elliptic forms (0.25–0.85 m^2) is related to low type of *D. octopetala* slowly growing on raised marine terraces. Aeolian sediments are characterised by low level of organic matter content. They exhibit diversified mineralogical composition resulting from variable petrography of source glacial and fluvioglacial covers. Eightpetal mountain avens are a dendroflora species composing phytocoenoses of plant communities related to the end stages of biocoenotic succession. Presented data indicate the reference environmental state for any research on plant cover response in the environment of aeolian activity during climate change.

Keywords: Arctic, Svalbard, biogeomorphology, *Dryas octopetala*, tundra, vegetation pattern.

Introduction

The formation of phytogenic aeolian landforms is one of the morphogenetic impacts of wind on the land covered with vegetation. Such landforms were distinguished mainly in arid and semi-arid regions that are simultaneously warm. It was found that both biotic and abiotic drivers can shape their spatial patterns (Quets *et al.* 2013). They are built of wind-born sediments trapped within and around canopies of burial-tolerant plants (Batanouny 2001; El-Bana *et al.* 2002). Life forms that capture wind-born materials usually are woody plants, shrubs and small- or medium-sized trees (Zhang *et al.* 2011). Variability in the dimension and morphology of phytogenic aeolian landforms depend on the form of plant growth and landscape topography (Mycielska-Dowgiałło *et al.* 2008). Borysiak (2015) reviewed literature on the vegetation of phytogenic aeolian landforms. Relatively little attention has been given to cold climate aeolian processes in polar deserts and their geomorphological effects compared with the research in arid and semi-arid environments. The biological activity of small mounds formed of aeolian sand over colluvium and factors for the soil ecological processes were studied on Baffin Island in the Canadian Arctic (Mueller *et al.* 1999). Speirs *et al.* (2008) investigated cold climate aeolian processes and barchan dune morphology on the hyper-arid polar desert of the McMurdo Dry Valleys in Antarctica.

In Spitsbergen, aeolian processes and/or forms were recorded in different regions of the island (*e.g.*, Czeppe 1968; Riezebos *et al.* 1986; Mizgajski 1989; Karczewski *et al.* 1990; Kostrzewski *et al.* 1989, 2007; Lindner and Chlebowski 2001; Paluszkiewicz 2003; Górska-Zabielska 2007; Zwoliński *et al.* 2007; Haves 2008; Oliva *et al.* 2014; van der Meij *et al.* 2016). Much attention was paid to the deflationary tundra vegetation or vegetated aeolian landforms in the deflation areas. Acock (1940) observed the wind-shaped tussocks of *Carex nardina* within mats of *Dryas octopetala* on the shingle beach terraces on the southern side of Adolfbukta (Bünsow Land). Åkerman (1983) presented the growth pattern with wind-eroded parabolic-shaped *Dryas* tufts on the deflation pavement in the outer part of Isfjorden. Gugnacka-Fiedor and Noryśkiewicz (1982) described the spatial distribution of the deflationary tundra in the Kaffiøyra Plain, and gave the diagnostic species for that formation on the basis Eurola (1968). In turn, Boińska and Gugnacka-Fiedor (1983) listed the bryophytes, lichens and vascular plants found in these communities. Szczypek and Wika (1982) drew attention to the occurrence of sand mini-dunes with *Saxifraga oppositifolia* in the localities of intense deflation in the marine terraces of Gåshamna (Sørkapp Land). The *Dryas*-tundra with *Carex nardina*, growing only on wind-swept ridges, was distinguished by Brossard *et al.* (1984) on the vegetation map of the Ny-Ålesund area. Dubiel (1985) wrote about the crescent shaped biogrups with *S. oppositifolia* in the NW Sørkapp Land, which clearly show the direction of the strongest wind. Rzętkowska (1987) published the map of vegetation of

Calypsostranda (Wedel Jarlsberg Land, Bellsund) with the range of deflation tundra plant communities. Święs (1988, 2013) carried out a study of deflation tundra plant phytocoenoses on the southern coast of Bellsund, and Hanaka *et al.* (2019) investigated there physico-chemical conditions of soil formation and development. Two types of small vegetated aeolian forms occurring on the Tørrflya-Bjørnbeinflya (Sørkapp Land) were characterized by Gębica and Szczęsny (1988), namely aeolian hillocks overgrown by moss or covered by sparse grass. In the phytosociological survey of Spitsbergen by Hadač (1989), *Carici nardinae-Dryadetum* (*Carici rupestris-Kobresietea* class) was included, as an association characteristic for windswept ridges. Lindner and Chlebowski (2001) observed effects of the accumulation activity of winds in form of irregular ridges of aeolian ripplemarks developed from moss growing on the sea terrace in the Kulmstranda, and dune banks in the forefield of Bungebreen (Sørkapp Land).

In general, the majority of above presented elaborations concentrate on properties and distribution of tundra plants, marginally referencing their morphogenetic potential. Patterns of vegetation growth are also closely related to sub-regional environmental conditions, influencing habitats structure as well as meteorological parameters responsible for aeolian activity level. Taking into account tundra types and contemporary geomorphic processes diversity over Spitsbergen, filling the spatial gap and showing biotic-abiotic interdependence in landscape transformations is essential.

In cold and moderately humid areas of Spitsbergen, gelivation predominates among the weathering processes in sedimentary covers (Tricart 1963). In Ebbadalen, at Petuniabukta surrounded by mountains formed from easily-weathered rocks, this process is particularly intensive. As a result, sand and dust are formed, which are transported by valley winds (Zwoliński *et al.* 2013). Aeolian material reaches, amongst other things, the wind-exposed flats of raised marine terraces, where some part of it is trapped by plants. There, they form convex phytogenic landforms, which are extorted with the presence of *D. octopetala*. It was noticed that they are immanent component of the surface morphology of the polar desert landscape, which does not disappear after strong winds. These observations inspired study on this phenomenon. During research in the Arctic biome, a lot of attention has been paid to patterned ground types. Elements of the Arctic tundra, such as circles, frost boils, hummocks and polygons were distinguished and characterized (Kessler *et al.* 2001; Peterson and Krantz 2003; Cannone *et al.* 2004; Walker *et al.* 2004; Kade and Walker 2008; Michaelson *et al.* 2008; Raynolds *et al.* 2008; van Vliet-Lanoë 2014; Ping *et al.* 2015; Szymański *et al.* 2015), however, no works describing the occurrence of phytogenic aeolian landforms in the high Arctic tundra of Spitsbergen were published so far.

The main aims of the undertaken bio-geomorphic studies were to document (i) the structural-functional features of phytogenic aeolian landforms formed by *D. octopetala* on the areas of raised marine terraces at the eastern coast of

Petuniabukta, (ii) the vegetation pattern on exposed deflation surfaces with *Dryas* aeolian landforms, and (iii) the relationship between abiotic conditions and vegetation of these phytogenic aeolian landforms.

Study area

The study area was situated in central part of Spitsbergen, the largest island of the Svalbard Archipelago, in the most north-eastern region of the Isfjorden system, at the eastern coast of Petuniabukta (Fig. 1). Contemporary glaciation around Petuniabukta is reduced to the inner valley parts in the phase of con-

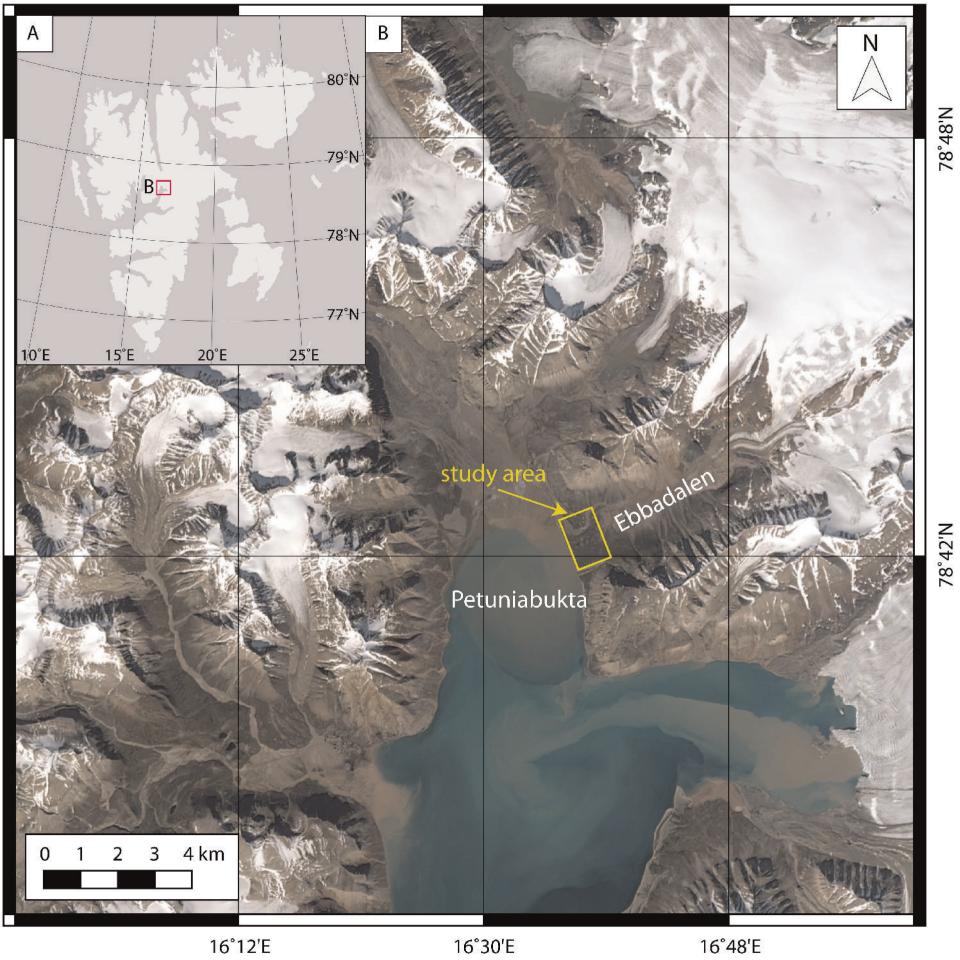

Fig. 1. Location of the study area in Svalbard (**A**) and in Petuniabukta (**B**). Orthophotomap source: https://www.arcgis.com/home/webmap/viewer.html (January 28, 2020)

tinuous retreat from the position of the maximum of Little Ice Age advancement (600–100 BP), marked with distinct frontal moraines (Rachlewicz *et al.* 2007). Most of the rocks around Petuniabukta are from the Late Devonian, through Carboniferous, to Early Permian age and belong to the Billefjorden and Gipsdalen Groups. They consist of several formations, which are represented by clastic rocks (conglomerates, sandstones, and mudstones) with coal seams and the most common carbonate rocks (limestones and dolomites) with anhydrite and gypsum strata (Dallmann *et al.* 1999). The investigated sites were situated in Ebbadalen on the Holocene marine terraces formed during the glacioisostatic uplift. They are developed to the level of ~ 80 m a.s.l. The highest terraces were ^{14}C dated at 37860±1000 yBP. Younger terrace sequences descending from 45 m a.s.l. to the actual coastline are associated with sea level changes since the mid-Holocene period (Rachlewicz 2009a). The system of terraces was cut by Ebba River (Fig. 2A). Rock walls dominating over Ebbadalen undergo intensive weathering processes. Terraces are in the permafrost zone. Maximum active layer thickness at the end of summer may reach up to 1.2 m (Rachlewicz and

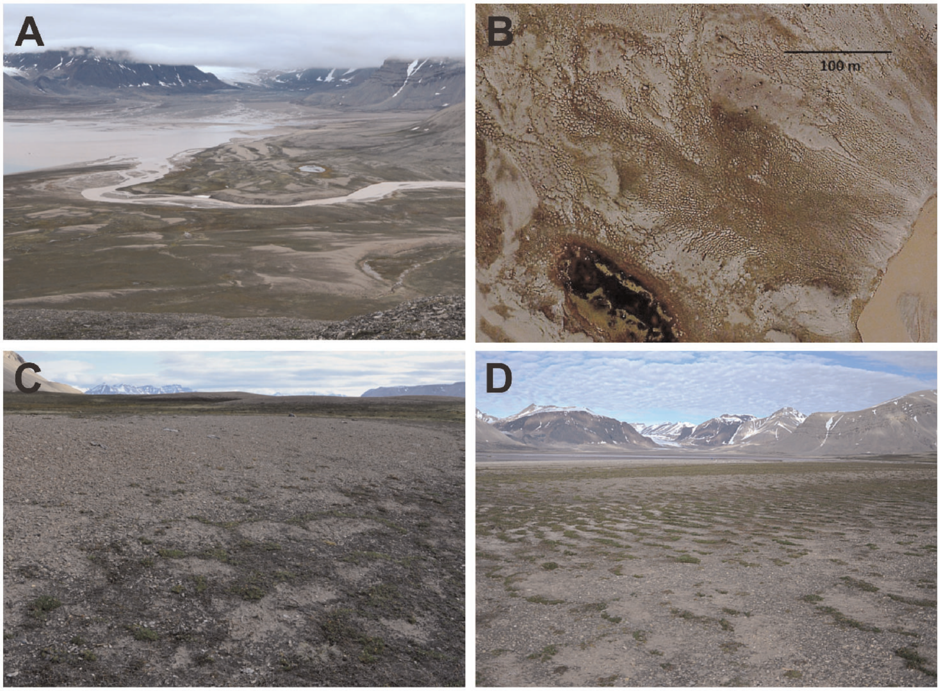

Fig. 2. Distribution pattern of *Dryas* aeolian landforms (DALs) on raised marine terraces in Petuniabukta (Central Spitsbergen): **A** – marine terraces with deflationary tundra (grey color) cut by Ebba River (in central part); **B** – pattern ground with DALs and ripplemarks at the southern side of Ebbadalen (aerial image: Norsk Polarinstitutt 2009); **C** – *Carici nardinae – Dryadetum octopetalae* Rønning 1965 with DALs in sub-flat area of the beach ridge crest; **D** – complex of DALs (foreground photo) and ripplemarks (in shallow depression). Pictures taken in July 2012.

Szczuciński 2008). Analysis of the ground temperature changes between summer 2009 and summer 2012 showed that courses of the temperature during the summers were relatively stable. Extreme values were between +10.8°C and -29.7°C (Rymer and Rachlewicz 2014).

On the basis of data from the years 1995–2000, Przybylak and Araźny (2005) included the climate in Petuniabukta to the sub-oceanic type. Between 1 September 2010 and 31 August 2011, Petuniabukta (Skotehytta, 78°42'N/16°37'E, 5 m a.s.l.) was characterized by the highest values (>43%) of the climate continentality on Svalbard (Przybylak *et al.* 2014). Precipitation in Petuniabukta slightly exceeds 200 mm yr^{-1} (Rachlewicz and Szczuciński 2008). Average monthly temperatures (June–August) are ~5°C, rarely reaching >10°C (Rachlewicz and Styszyńska 2007). Recent warming in Spitsbergen can be observed in growing air temperatures in the winter and summer seasons (Bednorz and Kolendowicz 2013; Nordli *et al.* 2014). Prevailing wind directions observed in the study area in summer seasons 2000–2001 were from south and east and followed the main morphological features, a fjord and valleys (Rachlewicz 2003). In 2000–2003 (July to September), the average daily wind velocities did not exceed 8 m s^{-1}, frequently oscillating ~4 m s^{-1}. Periods of stillness, with the percentage of no-wind conditions reaching 15%, were separated by events of wind gusts with velocities up to 17.7 m s^{-1} (Rachlewicz and Szczuciński 2008). The strongest winds reflected föhn conditions and blew from the north (Rachlewicz 2009b). The growing season lasts no longer than for 3–4 months a year, from June to August-September (Rachlewicz 2003). The raised marine terraces are covered mainly by *Gelic Regosols* and *Geli-Skeletic Regosols* (Stankowski *et al.* 2013). The investigated area belongs to the Arctic bioclimatic subzone B, one of the five subzones of the Arctic (Elvebakk *et al.* 1999).

Methods

***Dryas* aeolian landform measurement and vegetation sampling.** – The fieldwork took place at the eastern coast of Petuniabukta, up to a few hundred metres around central point of coordinates 78°42.5'N and 16°39.5'E, from mid-July to mid-August 2012. The structural features of 30 landforms created from aeolian material trapped by *D. octopetala* were diagnosed. A single landform was a microhabitat consisting of a very shallow basin occurring on the windward side and of a small mound formed on the leeward side, together with *D. octopetala* shoots and captured aeolian deposits**.** They are called *Dryas* aeolian landforms (DALs) throughout in this study. Landforms within homogeneous, in terms of physiognomy and habitat, vegetation units of deflationary tundra, occurring within the raised marine terraces, were selected for detailed description. Investigated forms were located on terraces elevated between 10 and 60 m a.s.l. and extending up to 1 km inland from the bay coast. Morphometric attributes of DALs shape, size and orientation were recorded through their maximal height (H), length (2a), width (2b), radius (r), area (S), and azimuth (A). The area was calculated depending on their circular or elliptic shape, using the formula $S = \pi r^2$ for the circular shape of DAL or $S = \pi ab$ for the elliptic shape.

Vascular plant species present in basins and mounds of DALs were recorded separately. The abundance of each plant was estimated on a five percent step scale. The cover of bryophytes, biological soil crust (algae and lichens), litter and bare ground were also estimated. Additionally, all vascular plants growing in homogeneous patches of deflationary pavement surrounding mounds were listed. The developmental biology of *D. octopetala*, and morphology and adaptation strategy of this species were visually observed. These observations were conducted both on mountain avens specimens building DALs and ones forming phytocoenoses of other types plant communities outside deflationary tundra. The species nomenclature follows Elven and Elvebakk (1996). Syntaxonomic data were taken from Hadač (1989).

Sediments properties measurement and data analysis. – Physical and chemical soil analyses at the 30 DALs were completed. Two sediment samples were collected from each form, one from the surface of the basin and the other one from the sediments captured by the plant. We analysed soil texture, organic matter, $CaCO_3$ content, soil pH, and electrolytic conductivity. The organic matter content was estimated by loss on ignition in 550°C (LOI550), according to the method described by Heiri *et al.* (2001). The pH and electrolytic conductivity (EC) were measured on a mixture of sediment and deionized water using the multifunctional instrument Elmetron CX-401. For the grain size analysis, in turn, dry sieving (fraction >63 μm) and Casagrande−type aerometric (fraction <63 μm) methods have been used. Based on this analysis, three statistical grain size parameters were calculated using GRADISTAT v 8.0 software (Blott and Pye 2001), *i.e.* mean value (M_z), standard deviation (σ), and skewness (S_k). Both calculations of the statistical parameters and sediment classification were based on the Folk and Ward (1957) method.

Results

Distribution and morphology of *Dryas* aeolian landforms. – *Dryas* aeolian landforms were found on deflation surfaces of marine terraces ridges (Fig. 2A and 2B) with patches of *Carici nardinae-Dryadetum octopetalae* Rønning 1965 (Fig. 2C), identified on the basis of the presence of *Carex nardina* - a diagnostic taxa for this association. Their physiognomy was formed by windborne sand that was trapped within dwarf shrubs of *D. octopetala*. They occurred only on flat or very weakly inclined surfaces, relatively often in the vicinity to ripplemarks in subslope and overbank river locations (Fig. 2D). Their largest density was in the area up to

60 m a.s.l. towards Ebbabreen. They usually formed fields of 5–10 independent microforms, *i.e.* not adjacent to each other, and with, although variable, the mean size of the simple field at ~150 m of diameter. Only in a few cases, adjacent DALs were encountered. In one simple field, arches of DALs were oriented in one direction, generally towards north or west. The small sizes of landforms (0.25–0.85 m^2) and their clusters created a small-scale organization pattern in the landscape.

Every single DAL consisted of two elements (Fig. 3A). The first one was a shallow basin, 1–3 cm deep, formed from the windward side. The other element was an elevated surface in the form of a small mound adjacent to the basin, forming a leeward very short slope with a mat consisting of *D. octopetala* shoots with 65–95% density. Sizes and shapes of DALs varied. Shapes were arched, never parabolic. The smallest DALs were semi-circular with 28–34 cm long radii and the surface area of 0.25–0.36 m^2. Larger forms were semi-elliptic (Fig. 3B) and their size was 0.46–0.85 m^2. The length of the semi-major axis of semi-ellipse fell within the range of 59–72 cm, and the semi-minor axis between 24 and 38 cm. The height of the mound at the highest place at the crest-line was 5–14 cm.

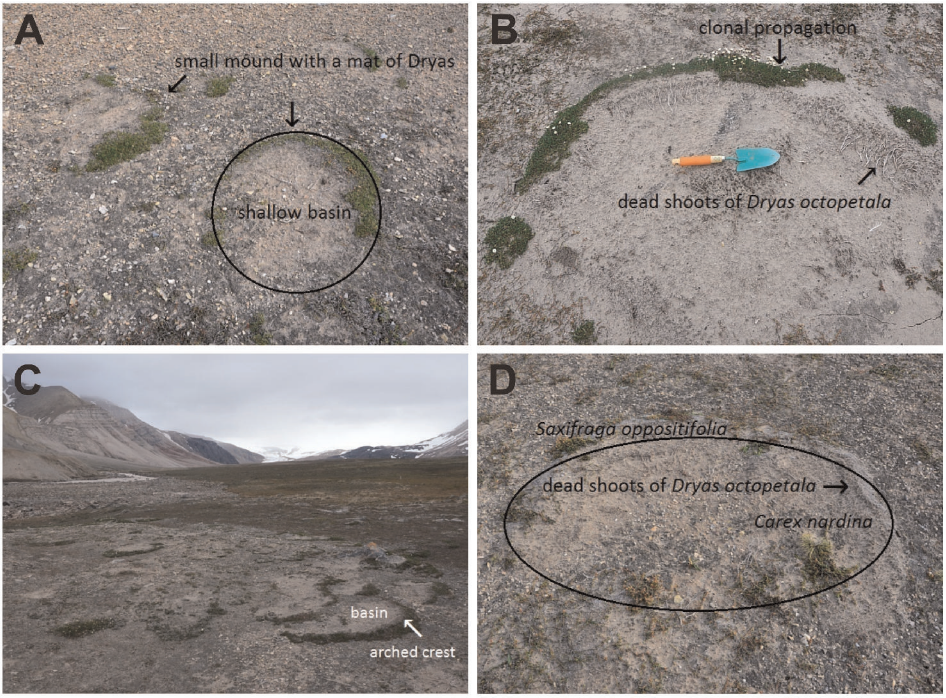

Fig. 3. Morphology of the *Dryas* aeolian landform (DAL): **A** – semi-circular shaped microform 0.25 m^2; **B** – semi-elliptic shaped microform 0.67 m^2; **C** – phytogenic *Dryas* microforms at the river bank of Ebba river, in place of abundant supply of wind-born sand, on outwash; **D** – degradation of DAL morphology due to desiccating and abrasive effects of strong wind. Pictures taken in July 2012.

Smaller DALs occurred, predominantly, on weakly inclined sub-flat areas of the crests of the raised beach ridges. Phytogenic aeolian landforms were also observed on outwash (Fig. 3C). These were not in the scope of this study. Two, sometimes three, internal strips of dead shoots were occasionally observed, when covered with sediments forming successive micro ramparts around eroded basins. In many DALs, flatly-arranged dead shoots, coming from one main stem, could be observed on the surface of the basin. Degradation of the DAL morphology due to desiccating and abrasive effects of strong wind were often recorded (Fig. 3D).

Due to relations between deflation and aeolian accumulation in the vicinity of vegetation mats, attention was paid to examples of relevant micro landforms and their development stages (Fig. 4). Active sediments trapping resulted in formation of mounds (Fig. 4A) or coverage of previously eroded surfaces with loose sandy deposits (Figs. 4D, 4G and 4H). Effective, unidirectional power of wind gusts was causing destruction of proximal sides of plant clusters, deforming patterns of their growth (Fig. 4B). In the most exposed sites, fine grains were blown away, to leave stony-gravel pavement, bared root system and dead shoots (Fig. 4C). Aeolian processes decline was stabilizing mineral-organic sediment covers within DALs, leading to their preservation at earlier stages of development (Figs. 4E and 4F).

Physical and chemical sediments features of *Dryas* aeolian landforms. – All investigated forms were characterized by the uniform, low organic matter content as indicated by the mean LOI550 values that reached 3.66% with a standard deviation equalling 1.32%. The within-form comparison between the windward shallow basin and mound showed that samples taken from the mounds were slightly enriched in organic compounds in majority of forms (Fig. 5). Sediment pH varied also depending on the location within the form, although, the reaction data in all samples indicated neutral or slightly alkaline conditions, the leeward samples had a tendency to show slightly lower values.

The average electrolytic conductivity, in turn, amounted to 461.92 μS/cm with a significant variability of the values between sites ($\sigma = 205.92$ μS/cm). However, these values did not show any clear relation between the sediment characteristic and the sampled side of the form. This was also the case for statistical grain size distribution parameters. The mean grain size allowed to classify most of sampled sediments as fine sands, with the exception of a few samples which sediments were slightly coarser, *i.e.* medium sand, or slightly finer, *i.e.* very fine sand. Based on the σ of grain size distribution results, sediments sorting could be defined as poor, again with the exception of few samples which sediments were slightly better (*i.e.* moderately) or slightly less (*i.e.* very poorly) sorted. As to S_k, there was no clear trend among investigated samples of which part was symmetrical, part fine skewed and part coarse skewed.

Vegetation structure of *Dryas* aeolian landforms. – The flora of the thirty examined DALs included 12 vascular species (Table 1). Landforms were similar

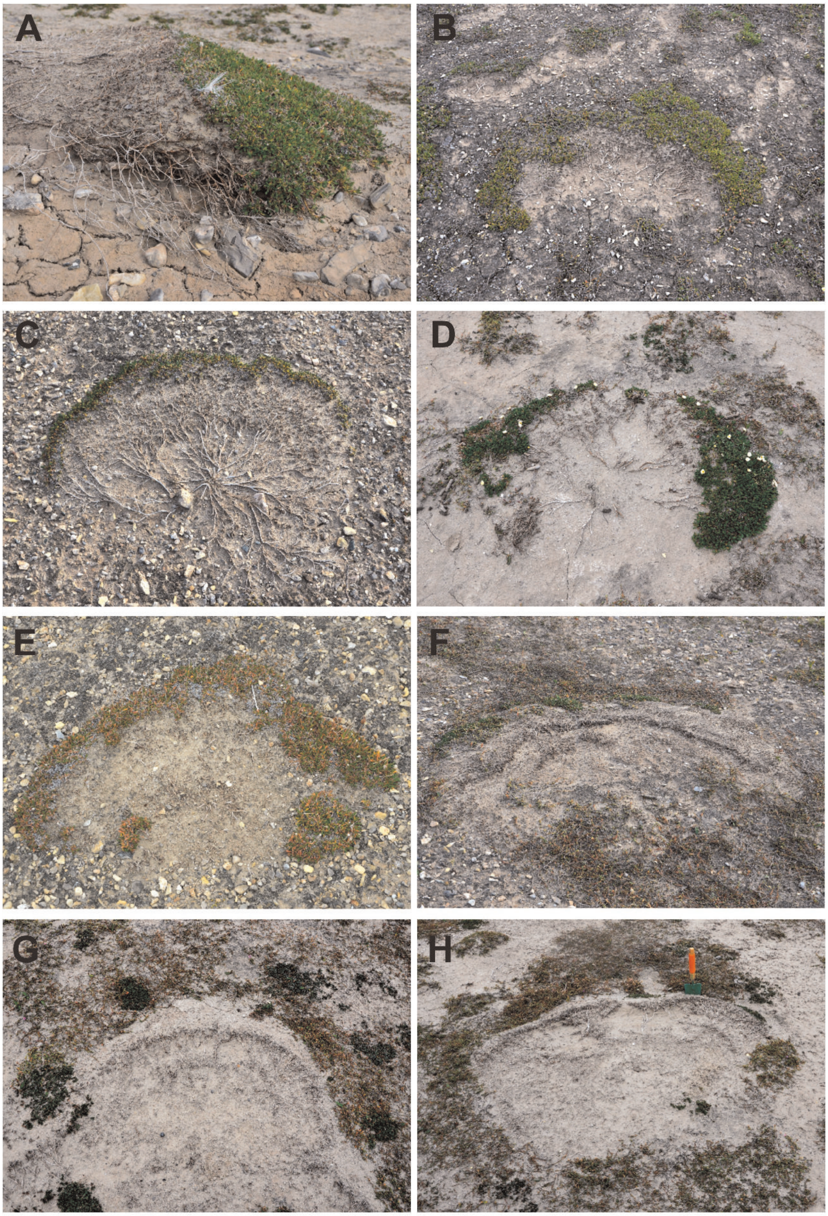

Fig. 4. *Dryas* aeolian landforms (DAL) development stages and variants: **A** – well developed mound of sediments accumulated within *Dryas octopetala* mat; **B** – wind eroded mat on the surface covered with mineral-organic crust; **C** – heavily eroded form on a deflationary surface; **D** – secondary accumulation of loose sandy deposits within eroded roots and dead shoots of *Dryas octopetala*; **E** – stabilized mineral-organic sediments cover of DAL's eroded basin on the deflationary surface; **F** – same as 'E' with three successive outer micro ramparts; **G** – ellipsoidal DAL with two outer ramparts covered with fresh sandy deposits; **H** – distinct circular DAL basin refilled with fresh sandy deposits. Pictures taken in July 2012.

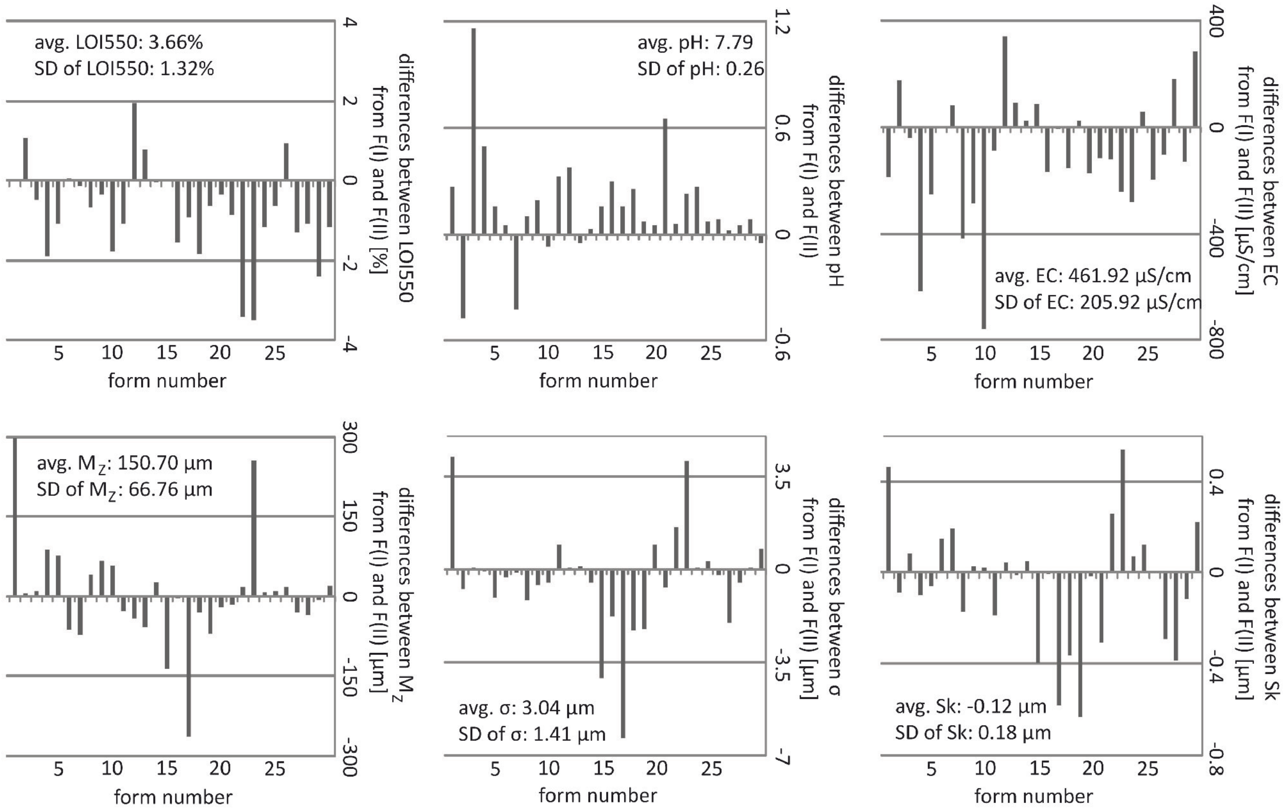

Fig. 5. Geochemical and granulometric parameters of *Dryas* aeolian landforms sediments shown as the difference between material sampled from basins and mounds (F(I) and F(II) respectively) with the average (avg.) values and their standard deviation (SD) indicated on the charts: LOI550 - loss on ignition in 550°C; pH – reaction; EC – electrolytic conductivity; M_z – grain size distribution mean value; σ – grain size distribution standard deviation; S_k – grain size distribution skewness.

Table 1.

Morphology and floristic structure of *Dryas* aeolian landforms on raised marine terraces in Petuniabukta (Spitsbergen).

Number of Dryas aeolian landform	1	2	3	4	5	6	7	8	9	10	11
Shape [sC - semi-circular, sE - semi-elliptic]	sC	sC	sC	sC	sC	sC	sC	sC	sC	sC	sC
Hight of mound [*h]*	6	12	9	13	9	14	9	9	8	10	11
Radius of circular mound [*R*]	32	31	28	28	32	33	29	33	32	29	32
Lenght of semi-major axis of elliptic mound [*a*]	.	.	.	.	.	.	.	.	.	.	.
Lenght of semi-minor axis of elliptic mound [*b*]	.	.	.	.	.	.	.	.	.	.	.
Area [m-1]	0.32	0.3	0.25	0.25	0.32	0.34	0.26	0.34	0.32	0.26	0.32
Number of vascular plants	3	3	3	4	2	3	2	3	2	5	5
Species of mound [%]											
Dryas octopetala	75	70	70	80	90	75	90	80	80	90	95
Saxifraga oppositifolia	20	20	5	5	.	.	.	.	.	.	.
Bistorta vivipara	<5	<5	.	.	.	<5	.	.	.	<5	<5
Salix polaris	.	.	<5	.	10	10	.	.	.	.	.
Carex nardina ssp. *hepburnii*	.	.	.	.	.	.	.	<5	.	.	<5
Poa arctica	.	.	.	<5	.	.	.	.	.	.	.
Potentilla pulchella ssp. *pulchella*	.	.	.	<5	.	.	.	.	.	.	.
Draba arctica ssp. *arctica*	.	.	.	.	.	.	.	.	<5	.	<5
Carex rupestris	.	.	.	.	.	.	.	.	.	<5	.
Pedicularis hirsuta	.	.	.	.	.	.	.	.	.	.	.
Arenaria pseudofrygida	.	.	.	.	.	.	.	<5	.	.	.
Papaver dahlianum	.	.	.	.	.	.	.	.	.	<5	.
Biological soil crust (algae < 5lichens)	.	.	5	5	<5	10	5	10	10	.	.
Bryophyte cover	.	.	.	.	.	.	.	.	.	.	.
Species of basin [%]											
Saxifraga oppositifolia	.	.	.	.	.	.	.	.	.	<5	<5
Bistorta vivipara	.	.	.	.	.	.	.	.	.	.	<5
Potentilla pulchella ssp. *pulchella*	.	.	.	<5	.	.	.	.	.	.	.
Carex nardina ssp. *hepburnii*	.	.	.	.	.	.	<5	.	.	.	.
Biological soil crust	.	10	.	.	.	.	.	10	.	5	5

Table 1 continued

12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
sC	sC	sC	sE	sE	sE	sE	sE	sE	sE	sE	sE	sE	sE	sE	sE	sE	sE	sE
10	9	8	7	12	6	5	8	8	7	9	7	9	10	8	8	7	8	6
33	34	33	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	68	72	71	66	69	70	65	68	66	66	59	65	69	68	68	66
.	.	.	28	34	38	24	29	32	33	29	32	33	25	30	34	36	35	26
0.34	0.36	0.34	0.6	0.77	0.85	0.5	0.63	0.7	0.67	0.62	0.66	0.68	0.46	0.61	0.74	0.77	0.75	0.54
3	3	2	5	2	3	3	4	4	3	2	3	3	2	2	3	2	2	2
90	90	95	80	80	75	75	65	75	75	70	80	75	85	75	80	95	80	85
.	<5	.	<5	10	10	5	10	5	.	.	<5	<5	<5	.	.	.	<5	.
<5	.	<5	.	.	.	.	.	<5	<5	.	<5	<5		.	<5	.		<5
.	.	.	.	.	5	5	5	.	.	.	.	.	.	.	.	.	.	.
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in terms of floristic composition. Apart from the ever-present *D. octopetala*, forming a mat from shoots making up 65–95% of the cover, *S. oppositifolia* was often present (in 50% of the samples) and *Bistorta vivipara* (43%), as well as biological soil crust (67%). Both plants grew in the mat on the leeward side of the mound. Mosses were observed sporadically. Only single specimens of four vascular plant species were observed in the basins. The leaves of *D. octopetala* were leathery, shiny on the topside and tomentose on the bottom with the edges bent under. They were directed vertically upwards and oblique in relation to the shoots. Their edges were bent under. There was aeolian deposits between leaves. The density of the shoots was very high. They formed a compact mat of tangled shoots. It could be seen in the cross sections of mounds that, depending on DAL, captured deflated sediments composed 20–40% of their volume. They were completely and evenly overgrown by shoots. Live parts of plants and poorly decomposed organic matter formed the rest (60–80%) and were intertwined. The vegetative shoots of *D. octopetala* were never grazed, despite the fact that reindeer were present in the area of Petuniabukta. On the other hand, in several DALs, grazed flower buds were observed. In the direct vicinity of DALs, deflation pavement was present as dominated by biological soil crust, with sparse vegetation cover, scattered mosses and very small forbs. Only five vascular plant species were observed there. There were, at most, several specimens of each species grown into the dark-coloured biological (cryptogamic) soil crust. These were *B. vivipara, Carex nardina* ssp. *hepburnii*, *Potentilla pulchella* ssp. *pulchella*, *D. octopetala*, and *S. oppositifolia.*

Discussion

In the deflated surfaces of the marine terraces system cut by Ebba River, phytogenic landforms were found built from aeolian sands captured by the *D. octopetala* prostrate dwarf-shrub. They created a relatively homogeneous formation, which had characteristic patterned-ground features expressed, among other things, by spatial distribution and the morphology of these specific microhabitats. The structure of plant formations creating patterned-ground tundra landscapes in high Arctic had been researched on numerous occasions and for a long time. Walker *et al.* (2008) discussed the variability of patterned-ground forms along a 1800 km trans-Arctic temperature gradient. Among the forms they examined in all five Arctic bioclimatic subzones, they did not distinguish any type of phytogenic aeolian mounds. It is possible that DALs are present at the forefield of the Midre Lovénbreen and Austre Lovénbreen in Svalbard. Moreau *et al.* (2009) distinguished seven vegetation types over there, including the dry mature stage of succession found on marine terraces. Species characteristic for this stage include, among other things, *C. nardina* and *D. octopetala*. The former was regarded by Rønning (1965) as diagnostic for the

Carici nardini-Dryadetum association, which phytocoenoses are associated with deflationary tundra.

DAL formation and sediment composition. – In samples of aeolian sediments collected from 30 DALs, a low level of organic matter content was found. This is the effect of both scarce vegetation cover and the wind-induced movement of the forms. The former causes the low supply of the plant remains that are additionally readily decomposed in the arid and well-oxygenated environment (Nichols 2009). The latter, in turn, make the accumulation of the organic matter inefficient since the older organic material is not covered by the younger; but the younger is deposited, depending on the rate of mound movement, slightly further leeward. The movement of the forms also seems to be the reason for lower organic content in samples from the windward side. This is because these sediments, as being slightly older, are characterized by the more completed organic remains from decomposition. Moreover, the movement-related, less completed decomposition on the leeward side, expressed in slightly higher LOI550 values, possibly affects the pH, since the degradation of organic matter provides additional acids to the sediments (Sollins *et al.* 1996). However, generally low organic matter content is not sufficient to significantly acidify the sands from which the mounds are formed, therefore their pH is nearly neutral.

The aforementioned autochthonous organic matter from dead plants forming DALs was not the only source of humic substances. The observed C_{org} value and electrolytic conductivity in the analysed samples of aeolian material collected from DALs was undoubtedly influenced by the bedding transported together with aeolian material. Fahnestock *et al.* (2000) described the physical and chemical consequences on the abiotic conditions of plant litter redistribution by wind and snow in Arctic landscapes. Annual carbon input from allochtonous litter was 143 g C m^{-2} in heavy deposition areas. *Gelic Regosols* (as occur in DAL fields) tested by Melke and Chodorowski (2006) in Chamberlindalen (SW Spitsbergen) contained 0.99 % $C_{org.}$ and 1.89% (at pH_{KCl}=7.85 and 7.06). For comparison, alkaline *Gelic Lithosols* formed on slopes (30–50°) of mountain ridges in Wedel Jarlsberg Land, at the belt of 100–500 m a.s.l., *i.e.* in source points of litter redistribution by wind and snow, contained 0.2–8.0% (on average 1.4%) $C_{org.}$ at pH_{KCl}=7.85–8.6 (on average 7.5). *Dryas octopetala* is also listed among woody perennials species, showing high values of soil components bioconcentration and translocation indexes (Hanaka *et al.* 2019). The amount and distribution of organic matter were limited by exposure, altitude and distance from the sea. Mycielska-Dowgiałło *et al.* (2008) emphasized that organic matter in soils of extorted aeolian accumulation form affects cohesion of trapped deposits and inhibits degradation by aeolian erosion.

The great variability of electrolytic conductivity values, as opposed to relatively uniform LOI550 and pH values, is probably derived from variable mineralogical composition of sediments forming DALs. This assumption is based on the studies of soil properties conducted on Spitsbergen by Klimowicz and Uziak (1996), who found that concentrations of inorganic chemicals, here indicated by electrolytic conductivity values varying significantly between particular sites, depend mainly just on the variable mineralogical composition. Such a finding is supported by the fact that the silt and sand particles transported by the wind in the vicinity of Petuniabukta are sourced mainly from the glacier forelands (Paluszkiewicz 2003) that are known to be diversified in terms of petrographic composition (Rachlewicz 2009a; Pleskot 2015). As the particle transport is short, even less resistant minerals like micas could survive; hence, the inferred variable mineralogical composition of DALs seem to correspond to the variable mineralogical composition of the source material.

The aeolian transport of these particles also influenced sediment grain size. It is primarily exhibited by the domination of fine sand fraction, since this fraction is known to be the most common in the forms built from wind-transported material (Nickling 1994). In contrast to the classical aeolian forms, however, sediments of investigated mounds are poorly sorted and have variable skewness. This is probably caused by the branches and the leaves of plants that grow within the mounds and also act as a trap for sediments. As the result, both finer and coarser material than fine sand could be immobilized, making the grain size distribution less uniform.

Generally, DALs were of a small size, despite the potential abundance of the aeolian material. Karczewski *et al.* (1990) reported that an extensive source of sand reaching the levels of raised marine terraces in the lower section of the Ebbadalen includes alluvial fans, tallus and proluvial cones, frontal and lateral moraines, and wide outwash plains. According to more recent research by Paluszkiewicz (2003), in the Petuniabukta region, wind transports material, which is mostly blown away from the foreland of glaciers. It can be supposed that with such possibilities of delivery of aeolian deposits, small sizes of DALs are related to the slow and low type of *D. octopetala* growth, which is referred to by Elkington (1971), as well as to the generally slow growth of all Arctic tundra plants (Pirożnikow 1996).

The size of DALs seems to be a function of the wind regime and sediment availability. On flat and windward sub-flat areas of flat surfaces in the marine terraces, which are strongly exposed to the wind, confirmed by the presence of deflation pavement, DALs of small sizes occurred more often than in the other regions of their occurrence. The possibility of keeping the aeolian material is limited in areas exposed to strong winds, which was found by Mycielska-Dowgiałło *et al.* (2008) who examined the morphogenesis of the plant extorted landforms in Sahara desert. Bednorz and Kolendowicz (2010) characterized the anemometric and thermal conditions between 11 and 25 of July 2009. Assuming that it is the period of full-blown vegetative season, they are expected to reflect the conditions of DAL development. According to Bednorz and Kolendowicz (2010), during the days with the non-radiation weather, the mean wind speed reached up 5 m s^{-1}, with gusts up to 8 m s^{-1}, mainly from the NE quadrant. The daily mean air temperature in the areas of marine terrace, 50 m from the shore of the bay, was about 5°C. On days with radiation weather, wind speed was 2.1 m s^{-1} on average. The absolute highest values of wind speed were not much higher than 10 m s^{-1}. Małecki (2015) reported from Ebba valley, in July and August 2008–2010, average wind speed 3.2 m s^{-1}. It should be mentioned here that bioclimatic zonation in the Arctic was prepared. One of the five distinguished units is subzone B. It is characterized by the mean July temperature of 3–5°C and the occurrence of the *Dryas* prostrate dwarf-shrub (Walker *et al.* 2005). The values of meteorological parameters provided by Bednorz and Kolendowicz (2010) and Małecki (2015) assign the area under analysis in this zone.

Morphogenetic potential of *D. octopetala*. – The size of DALs most likely depended on the age of *D. octopetala.* No dendrochronological studies were performed for mountain avens, as it was done by Buchwał *et al.* (2013) for *Salix polaris* from the Petuniabukta region. Such studies would have made it possible to determine the age of individual forms. Wookey *et al.* (1995) documented that in the high Arctic polar semi-desert of Svalbard, individual clones of *D. octopetala* commonly live more than 100 years. Thanks to such a long-lived clonal dwarf shrub, sand is captured by live shoots of the mat for a long period of time. Productive and destructive processes occur in the mat, which is indicated by the participation (60–80% of the DAL volume) of live parts of plants mixed with dead, yet still poorly decomposed parts. Thus, the plant forms and keeps favourable conditions for its development and for several other plant species. At the same time, it protects the aeolian accumulation form against degradation. Decomposing dead leaves of *D. octopetala* and other plants enrich sand deposits by adding biogenic compounds and humus that contribute to water retention. Such retention function of the parabolic shaped wind-eroded tufts of *D. octopetala* on the deflation surfaces in the outer part of Isfjorden were noted by Åkerman (1983).

The DAL structure depends of the developmental biology and morphology of *D. octopetala* and the related adaptation strategy for specific conditions of deflationary tundra, strong mechanical pressure of the wind and its drying impact. The following features are characterizing mountain avens after Elkington (1971): the plant is a prostrate branched dwarf shrub, mat-forming, sometimes evergreen, with stems up to 0.5 m; colonisation of unvegetated ground may take place by the lateral spread of vegetative ramets; the upper surfaces of leaves are glabrous or with simple hairs, rugose with impressed veins, and often with the margins revolute, especially on plants from exposed sites; lower surfaces have densely white tomentose with simple hairs. Kojima and Wada (1999) categorized some vascular plants growing in Ny-Ålesund (Spitsbergen) in relation to the soil moisture index. *Dryas octopetala* was classified as stenohygrotopic xerophyte, which optimum of occurrence is related to well-drained xeric habitats. Many traits are characteristic of stress resistance syndrome. They make it possible to understand why this plant is capable of growing on the surfaces under the influence of wind shear stress and the stream of wind saturated with sand. Within the live mat, the wind slides on the smooth surface of hard leathery leaves, mostly diagonally arranged on the shoots. At the same time, upon encountering the obstacle in the form of *Dryas* specimens building the mat, the sand falls, is trapped between shoots and builds the superstructure. This is promoted by the morphology of mountain avens, *i.e.* the tomentose surface on the bottom, revolute margins of leaf blades, hollow spaces occurring on the top side of the leaf related to the nerves as well as the delicate folding of the leaf blade in half.

From the windward side of DALs, the strongest winds damage the leaves mechanically, however, the leathery leaves of *D. octopetala* are especially resistant. Otherwise, they would not be the only plant building mats. On many occasions, dead leafless shoots and their whole systems are observed on the basin side. Wind causes vertical reduction of the life sphere. This can account for the low height (5–14 cm) of compact mats. Owing to the ability of *D. octopetala* to clonal proliferation at a high Arctic polar semi-desert, documented by Wookey *et al.* (1995) and Klimešová *et al.* (2012) and the related ability to colonize bare ground, a new mat of live shoots with the potential to store windborne sands is being continually formed on the leeward side. Therefore, predilection to clonal propagation makes *D. octopetala* a plant effective in capturing and retaining wind-laden sediments. The prostrate-branched dwarf shrub is a crucially influencing factor of the morphological shape of the DAL. As mentioned above, vegetative shoots of mountain avens, which build forms, have never been under grazing pressure. Most likely, they are too hard and unpalatable. However, flower buds damaged by browsing were recorded. Wada (1999) presented the grazing pattern of reindeer on *D. octopetala* flowers near Brøggerbreen (Ny-Ålesund, Spitsbergen). From among three hundred shoots randomly tagged in July 1996, as many as 33% flowers and flower buds were grazed by reindeer. It can be supposed that grazing reduces the natural accumulative capacity of DALs. Trampling by reindeer accompanies damage by browsing. Perhaps the ability of mountain avens to clonal proliferation is related to the resistance of phytocoenoses built on *D. octopetala* to tramping. Monz (2002) documented the consequences of human tramping on *Dryas* tundra in the Alaskan Arctic. Plots where low and moderate levels of trampling were applied returned to predisturbance conditions by four years after trampling.

In Petuniabukta, an evergreen pattern of leaf development of *D. octopetala* was observed and Bell and Bliss (1977), who wrote that evergreen leaves, like *Dryas*, are active for longer than two growing season. Such phenological strategy is an adaptation to a short and cold summer. Plants are ready to start photosynthesis in the spring, with minimal time spent in leaf expansion. So, the shoots of mountain avens with permanent leaves are able to fulfil the function of a trap for aeolian material from the very beginning of the vegetative season.

In the tested DALs of deflationary tundra, *D. octopetala* used two types of adaptation strategy, among the four types distinguished by Mazurenko (1986) for polar deserts. Those were miniaturization and geophytization. The study does not provide evidence for miniaturization from biometric tests. It can be only generally stated, on the basis of observations, that mountain avens specimens building DAL mats had smaller shoots than those occurred outside deflationary tundra. Mat formation testified to geophytization. Prostrate scrubby shrubs had very dense shoots, staying alive in sand burial conditions. Apart from the examined DALs, uncovered root systems of *D. octopetala* were also observed on several occasions. Those were taproots with a relatively dense network of side ones. Thus, one can suppose that such morphology ensures stability and durability to these forms in the landscape. Bliss (1971) reported that the rhizome systems of tundra plants are often very extensive in relation to the ground parts of plants, even though they may be growing in a cool, shallow, active layer above the permafrost. Łukasiewicz (1992) concluded that plants occurring in dune environments are adapted to both being covered by sand and to the substrate being blown away. He included the ability to produce root suckers and to regulate the optimal immersion in the substrate to the most important adaptations to living in such dynamic sedimentation conditions.

Such an adaptation mechanism was also documented by Qong *et al.* (2002), and Mycielska-Dowgiałło *et al.* (2008) as a result of research on *Tamarix* aeolian cones. In the case of the *Tamarix* shrub burial, its trunk grows up and the buried parts convert into roots, which increased the height of the cones. The observations of structures of mats of the tested DALs showed analogy to these processes as described for the arid desert. *Dryas octopetala* forms ramets rooted in the retained aeolian inputs that branch, forming an ever-broader mat with simultaneous dying shoots on the basin side. The shape of DALs change, from semi-circular to semi-elliptic. Evidence for the dynamics with this direction included semi-elliptic mounds with retained strips of the strongly-compact dead shoots of *D. octopetala*, in which the most internal strip had a semi-circular shape. Two build-up phases probably are associated with the rate of *D. octopetala* growth adjusted to the aeolian accumulation intensity. The quantity of trapped sands was so large that the plant had enough time to grow through deposits. This rate of growth and moderate sand burial were confirmed by the absence of layers, which consisted only of sand distinguished on the mat surface. Chernov and Matveyeva (1997) reported that the main role in stabilizing the loose, dispersible sands in the Eurasian tundra zone play dwarf shrubs that form a compact, pressed mat.

Another factor affecting DAL morphology, as well as the physiochemical features of their sand deposits, is probably low rainfall in the Petuniabukta region, which, according to Rachlewicz and Szczuciński (2008) slightly exceed

200 mm yr^{-1}. Rainfall is normal, *i.e.* < 5 mm h^{-1}, never torrential. Infiltration predominates over the runoff. Under such conditions, the retained aeolian sediments are poorly washed from among the shoots of plants that form the mat of *D. octopetala*. According to Pękala and Wojtanowicz (1987), high moisture from the ground at the beginning of the polar summer and the cementation of sediments by ice in winter are factors that limit aeolian processes. Therefore, the DAL superstructure is formed during the full-blown vegetative season, generated by the growth of DAL-shaping plants. Due to the constant evolutionary modelling of the microforms, the deflationary tundra should be regarded as biogeomorphologically active zone.

Geoecological significance of deflationary tundra. – Chernov and Matveyeva (1997) characterized four main types of horizontal structures of plant communities in the Russian Arctic. Deflationary tundra in Petuniabukta with isolated DAL microhabitats may be defined as the spotted type. According to the cited authors, the horizontal structure of such a type is characteristic of the initial stages of succession. This occurs in regions of dry fell-fields of polar deserts with plants, which have the potential biotic ability to form compact individuals and isolated mats. In succession, such plant communities are permanent pioneers, because in the case of the deflationary tundra, the wind is the factor that significantly limits the transition to more advanced stages of succession. Kostrzewski *et al.* (2007) distinguished morphogenetic domains in Ebbadalen (Petuniabukta). They paid attention to an increase in the proportion of high winds, which reinforce the deflation and aeolian accumulation processes. They called the domain in which such geomorphologic processes occur an aeolian-subsystem, and they quoted the places of geosuccession in the valley as an example, such as raised marine terraces and alluvial fans modified by ‘desertification’. According to these authors, a process similar to desertification is the result of the morphogenetic sequence of the thawing of the active layer, permafrost melt-out, drainage of meltwater, and the drying of land through evaporation and deflation, which is a result of the climate warming in the Arctic.

The warming of the Arctic near-surface air temperatures has been almost twice as large as the global average over recent decades, which is known as 'Arctic amplification' (Graversen *et al.* 2008). Kasse (1997) wrote, that the disappearance of permafrost leads to an increase in infiltration and enhanced water storage capacity of the unconsolidated sandy soil, which induces drier land surface conditions and an increase in aeolian processes. If climate warming progresses, and accompanying aeolian processes will become more intense, structural and functional changes can be observed within DALs. Miller and Smith (2012) reported that the Arctic land area has warmed by >1°C in the last 30 years. As a result of Arctic warming, they forecast an increasing representation of dendroflora species in vegetation. Therefore, it is not excluded that, in the future, other shrubs species (even small-sized trees) will take part in the evolution of phytogenic aeolian landforms rather than *D. octopetala*.

The flora of 30 investigated DALs consisted of 12 vascular species, which constituted 7% of Spitsbergen's flora listed by Elven and Elvebakk (1996), which includes only 173 species. This number of species can be regarded as low. It was mentioned in the result chapter that in the direct surroundings of DALs*, i.e.* hard deflation pavement, only five vascular plant species were recorded, *i.e. B. vivipara, Carex nardina* ssp. *hepburnii*, *Potentilla pulchella* ssp. *pulchella*, *D. octopetala* and *S. oppositifolia.* Single specimens were present over there sporadically. They were grown into dark-coloured biological (cryptogamic) soil crust. The first three of the plants listed above were able to survive in strong wind, thanks to a thick tunic with dead leaves enveloping the stem, which protected them against mechanical damage and drying by the wind. *Carex nardina* ssp. *hepburnii* and *Potentilla pulchella* ssp. *pulchella* can be regarded as bioindicators of wind erosion.

An overview of floras from various regions of Spitsbergen (author's recognition) made it possible to conclude that optimum conditions in the ecological scale of *C. nardina* ssp. *hepburnii* is situated in the deflationary tundra. Probably, such a type of deflationary tundra with *D. octopetala* and the occasional wind-shaped tussocks of *C. nardina* were observed by Acock (1940) on the beach ridges of Adolfbukta near Petuniabukta. *Carici nardina* was recognized as diagnostic taxa for *Carici nardinae-Dryadetum* Rønning 1965 association from *Caricion nardinae* Nordhagen 1935 alliance, *Kobresio-Dryadetalia* Ohba 1974 order and *Carici rupestris-Kobresietea* Ohba 1974 class (Hadač 1989). This research confirms the rightness of such a syntaxonomic approach. Elvebakk (1994) wrote that it is a plant community on the most exposed ridges and at the same time alkaline and circumneutral substrates.

Carbonate rocks, *i.e.* limestones and dolomites with anhydrite and gypsum strata, surround the marine terraces with deflationary tundra (Dallmann *et al.* 1999) and supply alkaline aeolian sediments. *Saxifraga oppositifolia* was present in a half of DALs tested. In margin environments of the stone deflationary pavement, this plant had a prostrate growth form. If formed creeping with multi-branched shoots, closely adhered to the pavement, it is protected against mechanical damage and being, dried by the wind. It could be a tetraploid since as many as 30 samples out of 60 of *S. oppositifolia* shoots collected by Eidesen *et al.* (2013) from the Skottehytta in Petuniabukta in *D. octopetala* tundra represented tetraploids.

Dryas octopetala was also observed between DALs, on surfaces that are the stone deflationary pavement. Those were single individual at the juvenile or early mature development from seed propagation. Germinability for Svalbard native angiosperms is assumed to be low. When tested in greenhouse conditions for *D. octopetala* after one winter of storage (seeds collected in 2008) in the Svalbard Global Seed Vault, it was at the level of 26.2% (intermediate), which was regarded as an average value (Alsos *et al.* 2013). Germination percentages were not similar to reported in 1998 by Hagen (2002) at <10% (very low). It can be assumed that recent climate warming improved the reproductive capacity of mountain avens in Spitsbergen. The observed juvenile individual closely adhered to the substrate covered by flatly-distributed rock fragments and biological soil crust. In the morphology of mountain avens, the influence of wind was already visible. It was manifested by the arrangements of shoots generally in one direction. This allows one to forecast the formation of subsequent DALs, as long as abiotic conditions similar to the current ones will continue. Most likely, an important role in this geosuccession will be played by biological soil crust, which, according to Belnap and Lange (2001), can be the dominant source of nitrogen, element essential for plant development, in some desert ecosystems. Generally, it can be concluded that microhabitats of DALs create landscape patches that can have a strong effect on the spatial distribution of plant resources. They seem to be an important factor promoting species recruitment. Such role of aeolian landforms was previously underlain by Hedding *et al.* (2015).

Conclusion

It has been reported from Spitsbergen, Petuniabukta region in central part of the island, that deflationary tundra with specific plant cover and/or small aeolian forms occurred on raised marine terraces. Life form which trapped aeolian material was a prostrate branched dwarf shrub *Dryas octopetala* and therefore the form was named *Dryas* aeolian landform (DAL). Spatial distribution of these landforms was characterized together with their geophysical conditions, morphology, floristic structure and vegetation pattern as follows:

- sediments taking part in the formation of aeolian mounds are delivered from neighboring glacial, outwash and slope environments; they are enriched in dead leaves and other plant fragments, contributing to water retention and increasing cohesiveness;
- structure of DALs is related to the developmental biology, age and shape of *D. octopetala*, forming mats on unvegetated ground; in conditions of morphologically effective winds, Aeolian covers accumulation and formation of soils is initiated;
- observed plant community is able to survive in strong winds on exposed surfaces in margin environments, giving rise to geomorphological and ecological changes.

Under current climatic conditions of Spitsbergen, *D. octopetala* is a dendroflora species composing phytocoenoses of plant communities related to the end stages of biocoenotic succession. In the future, it will also be possible to assess structural-functional changes in DALs over space and time by using the data presented in this paper. This data indicates the reference environmental state for any research on plant cover response in the environment of aeolian activity during climate change.

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