

# Vegetation re-establishment in polar “lichen-kill” landscapes: a case study of the Little Ice Age impact

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It has been accepted that the extremely sparse vegetation currently observed in Canadian polar deserts is due to prevailing unfavourable climatic conditions, inhibiting plant establishment, growth and survival. Less considered in the literature is the additional antagonistic factor of episodic adverse climatic anomalies. Such was the most recent Little Ice Age (LIA) cooling which caused a setback to, or even large-scale extinction of, high Arctic plant communities that had taken centuries to develop. The LIA brought about new glacial advances, expansion of permanent snow banks and formation of ice crusts over entire landscapes. The newly formed ice (and snow) killed the underlying vegetation, thus creating what is in the geological literature referred to as “lichen-kill zones.” In these zones the current plant diversity and abundance are exceedingly low and the plants are all relatively young and even-aged, factors which all point to their recent origin. Here we maintain that this vegetation has not yet reached equilibrium with the present prevailing climate and that it is still in an initial stage of succession. We present results of eight upland sites sampled in the vicinity of Alexandra Fiord Lowland, Ellesmere Island, Canada, to demonstrate the slow recolonization process that has been occurring within the last 100–150 years after the LIA termination. The widespread presence of the “lichen-kill” zones throughout the Canadian polar regions reflects the extent and destructive nature of even minor climatic cooling on vulnerable polar ecosystems.

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## Introduction

Central Ellesmere Island is mountainous and still partially glaciated (Fig. 1). Until 8 to 6 Kya, a continental ice sheet covered most of the island (Bradley 1990). Following the large-scale ice retreat, the primary tundra vegetation advanced from the south and established locally from propagules imported from the nearby ice-free refugia. In coastal regions it also returned from vegetated coastal shelves exposed during the ice age due to the lower sea level (Murray 1995).

This post-glacial (early Holocene) vegetation was probably quite abundant, especially during the warm hypsithermal period (4–6 Kya). However, it suffered repeated setbacks during the later cold climatic periods. Present Canadian polar deserts are ecologically marginal habitats for the estab-

lishment of higher plants. These polar deserts have minimal lichen and bryophyte abundance, and, on average, less than 5% vascular plant cover. They are also low in species richness (Bliss & Matveyeva 1992).

During the most recent climatic cooling called the Little Ice Age (LIA), ca. 1430–1850 AD (Gribbin & Lamb 1978), neoglaciation took place over the entire high Arctic and many high mountain regions. Extensive snow patches and ice crusts developed or expanded on high Arctic uplands causing large segments of the vegetation to perish. These areas, now snow- and ice-free once more, are clearly visible as pale stretches of land (Fig. 2). Though all vegetation perished under the persisting blanket of snow and ice, since crustose lichens dominate old rock surfaces and give them a distinctly dark colour, landscapes

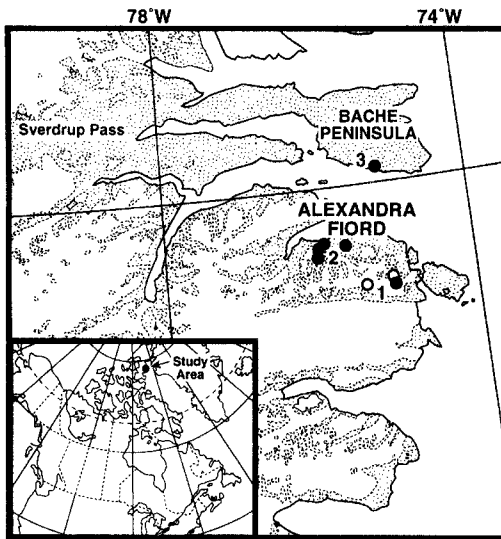


Fig. 1. Map of central Ellesmere Island, Canada, indicating the major sampling area near Alexandra Fiord and sites with (filled circles) and without (empty circles) higher plants.

which now appear bleached on photographs have been referred to in the literature as mere “lichen-kill zones” (Dyke 1978).

After the ice retreat, remnants of the killed plants weather away and disappear without a trace within a few years. In some areas entire ancient plant communities are currently being released along the margins of a melting ice. For example, Bergsma et al. (1984) documented emergence of

well-preserved but dead plants at the melting front of an outlet glacier at Alexandra Fiord (see below) which during the LIA period had advanced several hundred metres below its present position. Interestingly, the released ancient plant community had a higher representation of *Dryas integrifolia* while the extant re-invading community is richer in *Cassiope tetragona*, indicating drier habitat conditions during the pre-LIA period compared to those at present. Havström et al. (1995) analysed preserved pre-LIA shoots of *C. tetragona* from the same locality and found that shoot growth and flowering were significantly lower in comparison to the plants alive today. Havström et al. also calculated that the summer temperature during the period preceding these plants being entombed was 0.7°C lower than that at present. These plant communities may have been growing for many decades during the colder and drier LIA climate before the outlet glacier reached and buried them.

This paper presents information on the impact of LIA on vegetation and the limited progress of plant re-establishment following the end of this minor climatic cooling period. Eight upland sites in the vicinity of Alexandra Fiord, Ellesmere Island, Canada, were studied.

## Methods

To demonstrate the impact of the LIA on polar desert plant communities, an extensive four-year



Fig. 2. Granitic upland and mountain slopes showing the extensive light-coloured “lichen-kill” zones contrasting with the darker pre-LIA lichen-covered landscape at 79°N, Ellesmere Island, Canada.

Table 1. The general (date of sampling, longitude, latitude, altitude and substrate type) and vegetation characteristics (vascular species diversity, cover [%] and density [plants/m<sup>2</sup>]; ground covering bryophyte and lichen cover [%]) of eight upland sites in the proximity of Alexandra Fiord Lowland, Ellesmere Island, Canada. Lichen cover was dominated by black lichen mixed with other cryptogams in a cryptogamic crust; N/A = not available; p = present on the site but exact cover not determined; tr = trace, rare on the site.

Site	N2	N3	N5	E1	S1	AG	AD	B1
<b>General characteristics</b>								
Date	28/07/93	28/07/93	28/07/93	21/07/90	22/07/90	04/07/92	04/07/92	16/07/90
Latitude (N)	78°46'14	78°44'55	78°44'55	78°51'	78°48'	78°50'	78°51'	79°03'
Longitude (W)	75°17'47	75°06'00	75°06'00	75°38'	75°58'	76°01'	76°00'	75°00'
Altitude (m asl)	962	812	1003	818	786	540	540	608
Substrate type	Granitic	Granitic	Granitic	Granitic	Granitic	Granitic	Carbonate	Carbonate
<b>Vegetation</b>								
Vascular species richness	0	9	0	11	8	12	8	8
Vascular plant cover (%)	0	0.5	0	1.9	0.5	11.2	5.2	0.5
Vascular plant density (plants/m <sup>2</sup> )	0	6.6	0	N/A	9.1	66.4	27.2	16.5
Bryophyte cover (%)	0.9	0.2	p	14.4	0.1	3.5	0.1	tr
Lichen cover (%)	2.2	2.6	0	33.0	0.2	50.3	3.3	0.2

research programme was conducted in central Ellesmere Island, Canada, during which over 80 upland and mountain localities were visited and systematically surveyed. Of these, eight sites surrounding the Alexandra Fiord lowland (78°53'N, 75°55'W) were selected for this case study. In contrast with the partially glaciated and mostly barren uplands, some reaching elevations over 1000 m, the lowland supports a relatively rich and diverse flora. The 8 km<sup>2</sup> locality represents an oasis within an ice-covered and bare ground desert (Svoboda & Freedman 1994).

Three of the eight selected sites were located on rugged, hard rock nunataks, protruding through the ice of glaciers that descended into the lowland (Fig. 1). The N2 site (962 m asl) and, a little further east, sites N3 (812 m asl) and N5 (1003 m asl), were situated to the south-east of the Alexandra Fiord Lowland, near the Saate glacier. The fourth site, E1 at 812 m asl, was located near the margin of an ice cap remnant, topping a high plateau at the eastern side of the lowland. This small ice cap, captured on a 1959 airphoto, and still present during the 1990 survey, has now almost completely disappeared. Three of the remaining sites were selected on the upland surrounding the western side of the lowland. Two of these, both at ca. 540 m asl, were close to each other but had different substrates. Site AG was on granite while AD was on carbonate rock overtopping the granite. The third one, S1 at 786 m asl, was on the same upland slope but much higher and closer to the ice

margin of a wide descending glacier. Finally, the eighth site, B1 at 608 m asl, was a carbonate rock plateau at Bache Peninsula, at the north side across the fiord (Fig. 1). General site characteristics are presented in Table 1.

All these sites showed signs of having been covered by ice during the LIA. The nunatak sites (N2, N3 and N5) and sites E1 and S1 were in close proximity to ice margins and no macro-lichens were yet visible on the exposed rocks, suggesting their having been released from ice during the last two or three decades. The three other sites (AG, AD and B1) were probably released earlier since some lichens were growing on the rocks (though fewer than in the lowland) and larger long-lived plants were growing on the sites (e.g. *Salix arctica* and *Saxifraga oppositifolia*).

In 1990–93, vegetation and soil of all studied polar desert sites were thoroughly surveyed. In particular, at each site the vascular plant cover and density were measured with randomly laid quadrats (50 cm × 50 cm) using a modified abundance scale specifically designed to accurately assess sparse vegetation (Lévesque 1996). Total lichen and bryophyte cover and ground area with fine material were also determined. At some sites the ground surface was coated by a cryptogamic crust described by Gold & Bliss (1995) from similar polar desert sites at Devon Island. The cover of this crust was included in the total lichen cover. The number of quadrats sampled per site ranged from 15 to 129 depending on the site heterogeneity and

Table 2. The site specific vascular plant cover (%) of six upland sites studied near Alexandra Fiord, Ellesmere Island. Data are presented as percentage of total number of quadrats sampled during the 5 to 8 hours survey sampling; tr = represents species found on site but not in sampled quadrats; Occ. = occurrence of species out of the six sites. Nomenclature follows Porsild & Cody (1980).

Species	Site						Occ.
	N3	E1	S1	AG	AD	B1	
<i>Braya purpurascens</i>						0.05	1
<i>Cardamine bellidifolia</i>	<0.01	0.08	0.02				3
<i>Cassiope tetragona</i>			tr				1
<i>Cerastium cf arcticum</i>			tr	0.02		0.03	3
<i>Draba corymbosa</i>		0.01	0.02			0.12	3
<i>Draba lactea</i>		tr					1
<i>Draba nivalis</i>		0.01					1
<i>Draba subcapitata</i>	0.04			0.03	0.08	0.14	4
<i>Dryas integrifolia</i>				0.02	0.65		2
<i>Luzula arctica</i>		0.43		0.20			2
<i>Luzula confusa</i>	tr		0.13	0.69	0.01		4
<i>Minuartia rubella</i>	0.01					0.02	2
<i>Oxyria digyna</i>				0.04			1
<i>Papaver radicum</i>	0.07	0.75	tr	0.04	0.01	0.02	6
<i>Pedicularis cf arctica</i>				0.01	tr		2
<i>Phippsia algida</i>	tr			0.47			2
<i>Poa arctica</i>		0.08		0.30			2
<i>Puccinellia bruggemannii</i>						0.08	1
<i>Salix arctica</i>		0.01		8.49	3.03		3
<i>Saxifraga caespitosa</i>					tr		1
<i>Saxifraga cernua</i>	<0.01	0.31					2
<i>Saxifraga nivalis</i>	tr		tr				2
<i>Saxifraga oppositifolia</i>	0.40	0.26	0.28	0.87	1.40	0.04	6
<i>Saxifraga tricuspidata</i>		tr					1
Number of quadrats sampled:	129	93	15	25	25	30	

the time available (Table 2). In addition, a complete vascular species list was established. Nomenclature follows Porsild & Cody (1980).

Soil samples (top 10 cm; n = 3) were collected and pre-sifted on site (4 mm). In the laboratory the soils were dried to constant weight (60°C) and the fine fraction (<2 mm) analysed. Total organic carbon (OC; n = 2) was determined by wet combustion method (Nelson & Sommers 1996), and extractable phosphorus (P; n = 3) by a weak hydrochloric acid method (Bray & Kurtz 1945). Results are presented as percent or ppm of the small soil fraction (<2 mm).

## Results and discussion

As expected by nature of their arcto-alpine position, the studied localities supported very little vegetation (Table 1). In fact, the two highest sites, at 962 m and 1003 m asl, had no vascular plants at all. These sites were either released from ice quite

recently or they were situated above the present altitudinal limit for vascular vegetation at this high latitude.

Vascular plant cover ranged from 0.5% to 11% and decreased with increasing altitude, with a break point at ca. 600 m asl (Fig. 3). Bryophyte cover was scanty (except at the E1 site, with 14%). The lichen cover, present mostly as a component of the cryptogamic crust, showed correlation with moisture availability. Vascular species richness of mere 8–10 species was low and did not vary greatly among sites (Table 1). Only two vascular species, *Saxifraga oppositifolia* and *Papaver radicum* were common to all six vegetated sites, followed by *Draba subcapitata* and *Luzula confusa*, present at four of the sites (Table 2).

The marked difference in the vascular plant cover between the low altitude sites AD and AG (cover >5%) and the higher altitude sites (cover <2%) was not associated with an increase in species richness. The difference depended on the relatively high cover of *Salix arctica* at sites AG

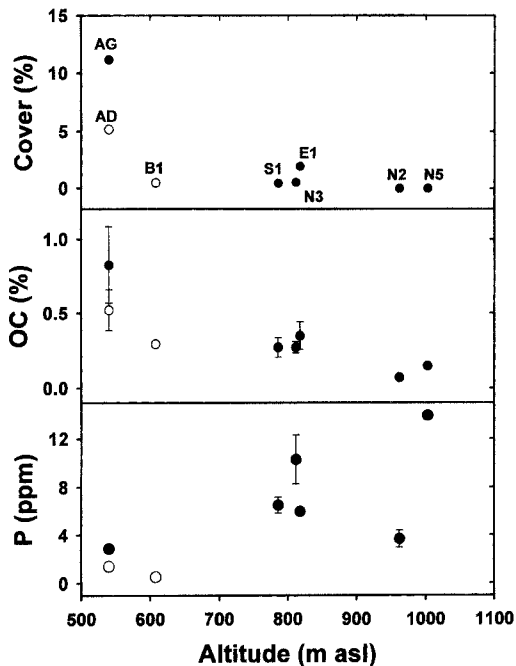


Fig. 3. Total vascular plant cover (%), soil organic carbon (%;  $n = 2$ ) and extractable phosphorus (ppm;  $n = 3$ ) of eight sites sampled in the vicinity of Alexandra Fiord Lowland. Mean  $\pm$  SE: full circles represent granitic sites and the empty circles carbonate rocks sites. Soil parameters were calculated for the fine fraction of the soil (<2 mm) which represents ca. 5% of the soil volume.

and AD and the slightly larger size of *Saxifraga oppositifolia* plants, especially at site AD (Table 2). As described in previous studies on Ellesmere Island, we also noted a difference in plant abundance associated with the substrate, the vegetation on carbonate rocks being generally more sparse (Batten & Svoboda 1994; Lévesque 1997).

Plant density varied greatly and was inversely correlated with the altitude (Table 1). The two lower sites, again, had the highest values (66 and 27 plants/m<sup>2</sup> for AG and AD, respectively). This suggests that plant establishment was more successful at the lower sites. This could be associated with generally more favourable conditions for plant growth for sites AG and AD. However, site B1, which was only slightly higher than sites AD and AG, had only 0.5% cover but 16.5 plants/m<sup>2</sup>. This plant density would suggest either a higher recruitment rate on site B1 than on sites N3 and S1 or a longer time since ice retreat, allowing greater plant recruitment. Since plants

remain small and total cover remains <1% on this dolomitic plateau, environmental conditions are considered particularly limiting to plant growth and an earlier ice retreat would explain the higher density observed.

Bergsma et al. (1984) present a photo of the ice front of the glacier releasing the entombed plants at Alexandra Fiord. The ground moraine shows two distinct retreat zones. The first, adjacent to the ice front, has been expanding since about 1948. The second, more distant, zone marks the glacier's maximum LIA advance and could be dated to 80–100 years earlier, i.e. to the mid-1800s. There is a distinct time hiatus between the two zones suggesting that the glacier stopped retreating for several decades prior to 1948. Consequently, the lower stands on the plateau must also have become free from ice prior to the upper slope stands, thus allowing their communities more time to develop.

The coarse, very poorly developed soils contained a large proportion of angular boulders and pebbles. They all fit the category of lithic regosolic cryosols, following Muc et al. (1994). Organic carbon generally decreased with altitude, paralleling the diminishing plant cover and biomass. The phosphorus availability in the fine soil fraction was lowest on sites with the highest plant cover at low altitude (Fig. 3). Our values are comparable to those published by Muc et al. (1994) for the Alexandra Fiord area. These authors linked the low phosphorus availability in the lowland (1–7 ppm for various plant communities) with the high organic content of these soils, whereas they obtained higher values of available phosphorus in the soils of the sparsely vegetated polar deserts (up to 64 ppm). Nutrients tend to form organic complexes and are unavailable to plants at the more productive sites. This process keeps draining the available nutrients from the soil into the sink of the slowly accumulating standing crop and litter, especially since mineralization processes are extremely slow at these latitudes (Nadelhoffer et al. 1992).

Two other plant community studies were conducted on Alexandra Fiord uplands prior to our survey of the polar plateaux. Batten & Svoboda (1994) gathered data on plant cover and frequency from 26 sites, of which about 10 were situated above the 600 m contour line and could have been, therefore, altitudinally comparable with our sites. By using Principal Component Analysis (PCA) Batten & Svoboda recognize seven community types. However, these commu-



Fig. 4. General features of site N3 (812m asl), with a large flowering *Luzula confusa* plant, near Alexandra Fiord, Ellesmere Island, Canada. Note that the rocks are free of macro-lichens.

nity types widely range in elevation. Thus, a *Saxifraga oppositifolia-Luzula* based community was found at elevations 520–920 m; *Cassiope*-dominated community occurred at elevations 630–870 m, etc. Since the objectives of their study were different from ours, all collected data were pooled to generate a matrix for the PCA in order to obtain the desired community types. As a result, information on individual sites for a meaningful comparison with our sites is not available.

More relevant with respect to our study is the work of Bliss, Henry et al. (1994) at the western plateau. Eleven stands of vegetation were surveyed for plant diversity and cover down the long slope (ca. 750–500 m) along the West Arm Glacier. The total vascular plant cover ranged from 0% (the highest four stands) to 12.6% at the granitic rim circumscribing the dolomitic “dome” on the east end of the plateau; this last stand is comparable to our site AG (11.2%). Although Bliss, Henry et al. make no attempt to correlate the community data with the time the surveyed sites were released from ice or snow, two conclusions can be made in retrospect, both supporting our findings: 1) the lower sites were released earlier than the uppermost sites where more areas are being still open to plant colonization; 2) the environmental conditions (especially the microclimate) of the higher elevated sites are less favourable (cf. Svoboda & Henry 1987) than those at the altitudinally lower stands, hindering plant establishment, successional progress and standing crop accumulation (Bliss, Henry et al. 1994).

There are many factors which hamper vegetation development in marginal polar environments: shorter and colder growing season (even in comparison with the latitudinal normals), extremely low nutrient availability and drought (e.g. Bliss, Svoboda et al. 1984; Gold & Bliss 1995; Lévesque et al. 1997), inadequate supply of viable propagules (Svoboda & Henry 1987), and consequently meagre viable seed bank with less than 100 seeds/m<sup>2</sup> (Lévesque & Svoboda 1995). Also natural disturbance such as needle ice, cryoturbation, grazing, trampling and erosion often uproot and eliminate the already established plants (Forbes 1996; Anderson & Bliss 1998).

The inhospitable polar desert environment at the Alexandra Fiord uplands acts as a barrier for many species, which flourish in the lowland below. Out of 91 vascular species listed for Alexandra Fiord lowland by Ball & Hill (1994), Batten & Svoboda (1994) list 34 species and Bliss, Henry et al. (1994) 19 vascular species (in quadrats only) in their respective upland sites. A total of 24 vascular species was identified in our eight sites.

Yet, surprisingly, we observed that some plant individuals growing on high nunataks and plateaux (sites N2, N3, N5, E1 and S1) formed vigorous healthy clusters with prolific blooms while the surrounding rocks were still free from crustose macro-lichens. These plants had few leaf scars on their short shoots, revealing their young age, which corroborated the notion about their recent establishment (Fig. 4). Closeness to the water source (melting ice) and flush of nutrients

available in the freshly exposed soil have temporarily compensated for the cold microclimate. In time, after the glacier retreats further up the slope, the soil dries out and the nutrients become depleted, these plants will slowly lose their vigour and a significant portion of standing dead will appear in their clumps. The plant assemblage will eventually become indistinguishable from typical polar desert vegetation.

Colonization success is a function of seed availability, supporting environment and the time period since the site has become available to plant reinvasion (Svoboda & Henry 1987). Even at 80°N, productive meadows developed in protected irrigated valleys (e.g. Svoboda & Freedman 1994). However, these more lush vegetation such as the Alexandra Fiord Lowland or the 80 km long Sverdrup Pass at central Ellesmere Island (Bergeron & Svoboda 1989) were deglaciated 5–7 Kya and were spared the LIA neoglaciation (Muc et al. 1994). These richly vegetated areas with more developed soils and higher organic carbon content in the soil represent less than 10% of the island's ice-free area. Polar deserts and semi-deserts cover the majority of the island (Bliss & Matveyeva 1992). Since the retreat of the continental ice sheet (not yet fully completed at Ellesmere Island), vegetation that had developed at ice-free uplands was decimated by several neoglaciations of which the most recent was the LIA period (Svoboda 1982).

We found no dead pre-LIA plants at the studied upland sites. If there were any, they have weathered away over the decades after their release from ice. Thus, no direct evidence of the pre-LIA vegetation on these uplands is available so far. The only indication of ancient vegetation may come from soil organic carbon. Although the values were very low, in view of the extremely low extant plant productivity and biomass, accumulation of the detected soil organic carbon must have taken a very long time. Hence, we conclude that the carbon extracted from these soils must, in part, have been incorporated in the pre-LIA period.

Even though we know not what vegetation grew on Alexandra Fiord uplands prior the LIA, it seems evident that the recovering vegetation has not reached an equilibrium with the climate of today. While some areas with persistently adverse conditions (dry, wind-swept ridges such as site B1) may resist the development of a more significant plant cover, many other areas have a potential of supporting a more diverse and abundant vegetation – providing enough time is

allowed to elapse before another major disturbance occurs. What could be the impact of the ongoing global warming on these vast deglaciated and still deglaciating landscapes? Biological processes (e.g. plant growth, nutrient mineralization) take place more rapidly in a more favourable environment, resulting in a much faster successional progress within the same time frame. The active layer would deepen, making new nutrients and moisture available to expanding established plants and to new invaders. Polar deserts may upgrade to semi-deserts and semi-deserts may develop into a more fully vegetated tundra. However, such climatic changes may be associated with more severe surface drought, which could hinder vegetation succession. They may, in contrast, bring about more abundant winter snowfall, which could further delay the short growing season. Clearly, even a minor climatic anomaly may have an extensive and lasting impact on marginal polar ecosystems.

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