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Impacts of recent paraglacial dynamics on plant colonization: A case study on Midtre Lovénbreen foreland, Spitsbergen (79°N)

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Abstract

Climatic changes since the end of the Little Ice Age have considerably disturbed environmental balances of plant colonization in high latitudes. Within one century on Spitsbergen, valley glaciers have retreated up to 1 km from their original terminus as of 1918, affecting several hundred hectares of two types of landscape processes: plant colonization and paraglacial morphogenesis. Since these processes are limited to the chronological position of the old ice front, it is possible to know the rate of plant colonization by both qualitative and quantitative means, as well as speculate on the processes involved, such as the effects of runoff. The present study is limited to the Midtre Lovénbreen forefield (latitude 79°N, longitude 12°E), where geomorphologic and floristic samples were collected in 2003. On stable deposits in this area, the settlement and the evolution of floristic groups have been documented. During this time of period of colonization, the plain areas are reworked by runoff at a kilometric scale and are characterized similar to their surrounding biogeographic landscapes. Thus, a relationship can be observed between the paraglacial process occurring in the proglacial forelands and surrounding stable surfaces in till deposits. These features that occur as spatial discontinuities across the landscape are perceptible through either plant colonization or disturbance to vegetation caused by hydrological processes. Ultimately, however, runoff dynamics maintain pioneer vegetation groups which are superimposed on plant colonization that are driven by temporal periods of deglaciation. Differences in the rates and the nature of plant colonization are biomarkers of paraglacial dynamics.

Keywords: Little Ice Age; Paraglacial landscape; Plant colonization; Glacier forefield; Climate change

1. Introduction

One of the main consequences of climate change in polar environments is the retreat of glaciers and consequently, the increase of glacier forelands that are susceptible to rapid modifications due to two major dynamics: active runoff, which reworks glacial deposits, and the initiation of plant colonization on exposed glacier forelands.

The term paraglacial was introduced by Ryder (1971a,b) to describe alluvial fans in British Columbia and pertains to areas that are no longer directly affected by the scouring action of glaciers. The concept was further defined by Church and Ryder (1972) as "nonglacial processes that are directly conditioned by glaciations". They also identified a "paraglacial period" as the time

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interval over which this process operates. More recently, Ballantyne (2002) proposed a new and more complete definition for the concept of paraglacial as "the nonglacial earth-surface processes, sediment accumulations, landforms, landsystems and landscapes that are directly conditioned by glaciation and deglaciation". This distinguishes it from the term "periglacial" which is defined as "cold, nonglacial" and is applied to environments in which frost-related processes and/or permafrost are either dominant or characteristic (French, 2000).

In the glacier forefields, in general, sediments exposed by glacier retreat are being extensively reworked by runoff, which is the principal and most influential process in the formation of lowlands and slopes (Fitzsimons, 1996; Mercier, 1997; Curry, 1999; Curry and Ballantyne, 1999; Laffly and Mercier, 1999; Etzelmüller, 2000; Güde, 2000; Mercier, 2000, 2001, 2002; Laffly and Mercier, 2002; André, 2003; Mercier et al., 2004; Orwin and Smart, 2004; Mercier and Laffly, 2005). At the same time, plant colonization occurs, occupying the newly exposed areas following glacial retreat in these arctic environments (Kuc, 1964; Brossard, 1985; Minami et al., 1997; Wada, 1999; Nilsen et al., 1999; Moreau, 2003; Hodkinson et al., 2003; Jones and Henry, 2003; Moreau et al., 2004), with species composition of plant communities similar to that found in alpine environments (Palmer and Miller, 1961; Moiroud, 1976; Elven, 1978; Birks, 1980; Matthews and Whittaker, 1987; Matthews, 1992; Timoshok et al., 2003). Some authors have shown that the time of deglaciation is a main factor in the plant colonization; while others have shown that microtopography is also an important factor (Stöcklin and Bäumler, 1996; Jumpponen et al., 1999). These studies, however, do not describe how paraglacial geomorphological dynamics affect the glacier foreland and how plant succession has evolved in relation to stable or unstable deposits as a result of the presence or absence of runoff influences.

The purpose of this study is to analyze the glacier foreland of Midtre Lovénbreen in the northwest region of Spitsbergen and to determine if (1) it can be classified as a "paraglacial landsystem" as defined by Ballantyne (2003); (2) if there is an interaction between the stability of the deposits and the plant colonization; (3) if the paraglacial geomorphological dynamics affect plant succession on the glacial foreland; and (4) does the vegetation cover reveal the differences in morphogenic dynamics that have taken place since the glacial retreat.

2. Study area

This study was conducted on the foreland of the Midtre Lovénbreen glacier, on the Brøggerhalvøya

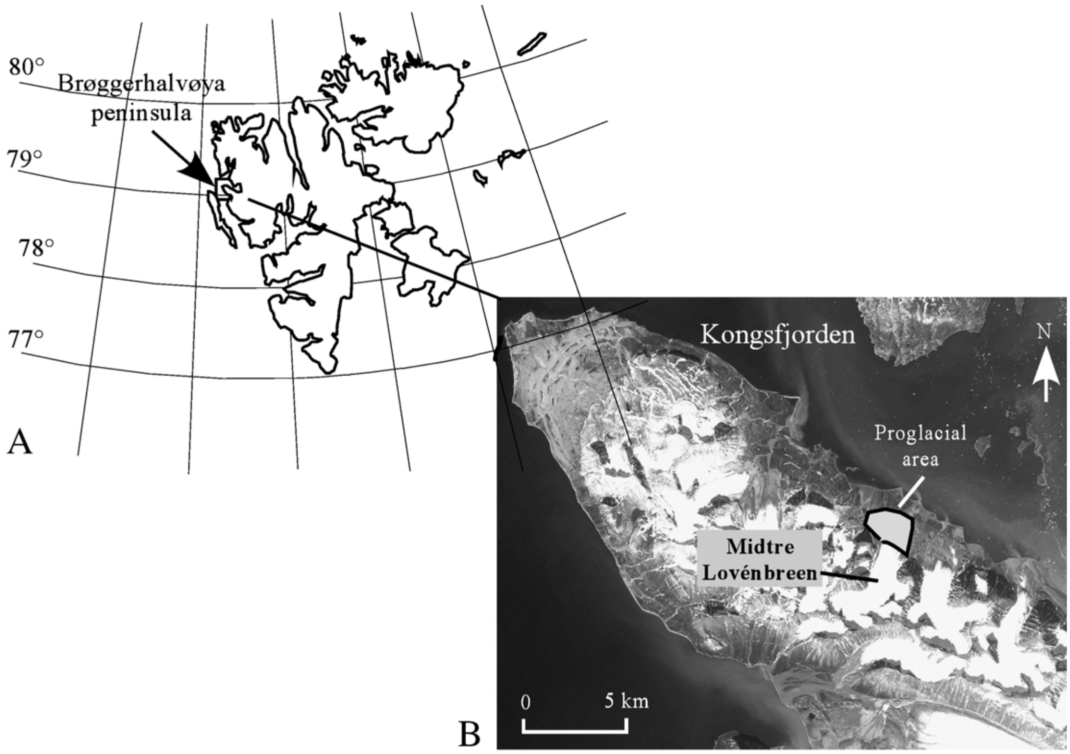

Fig. 1. The Svalbard archipelago (A) and Brøggerhalvøya peninsula (B) in Spitsbergen (SPOT satellite image, 1990).

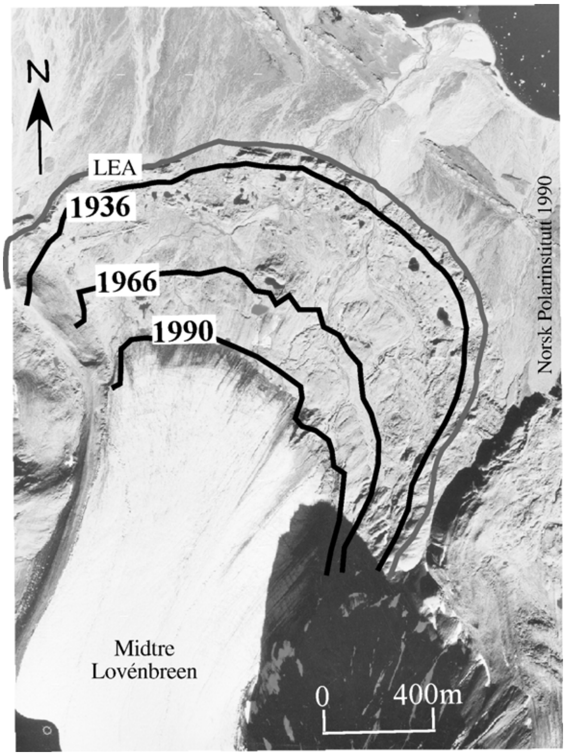

Fig. 2. Map of successive Midtre Lovénbreen glacier fronts from aerial photographs provided by the Norwegian Polar Institute (1–50,000 scale). LEA: Little Ice Age, time of the greatest advance of the glacier.

Peninsula in northwest Spitsbergen (78°55′N, 12°10′E, Fig. 1A). The Brøggerhalvøya Peninsula has a maritime polar climate predominantly influenced by the North Atlantic Current. The Midtre Lovénbreen catchment area is situated 5 km east of the weather station at Ny-Ålesund, where several meteorological parameters have been measured continuously since 1969 (Fig. 1B). The mean annual air temperature was −6.3 °C with measured precipitation averaging 386 mm $year^{-1}$ water equivalent (Førland et al., 1997), with 47% of the precipitation occurring as snow (Mercier, 2001). Local in situ measurements of temperatures in the glacier forelands have shown that the warmest places are located in wind protected areas on the older moraines; the coldest areas are located near the front of the glacier where catabatic winds contribute to continuous air flow (Brossard et al., 2002; Joly et al., 2003; Joly, 2004).

The Midtre Lovénbreen is an alpine-type polythermal valley glacier, which presently covers an area of 5.5 km^2, approximately 6 km long and 1 km wide at the equilibrium line (currently at 395 m above sea level). Its maximum thickness reaches c. 180 m and collects ice from four small cirques (Björnsson et al., 1996; Rippin et al., 2003). Midtre Lovénbreen is likely an example of a glacier that has changed from a surge-type to a non-surge-type during the 20th century due to changes in climate (Hansen, 2003). During this time the Midtre Lovénbreen

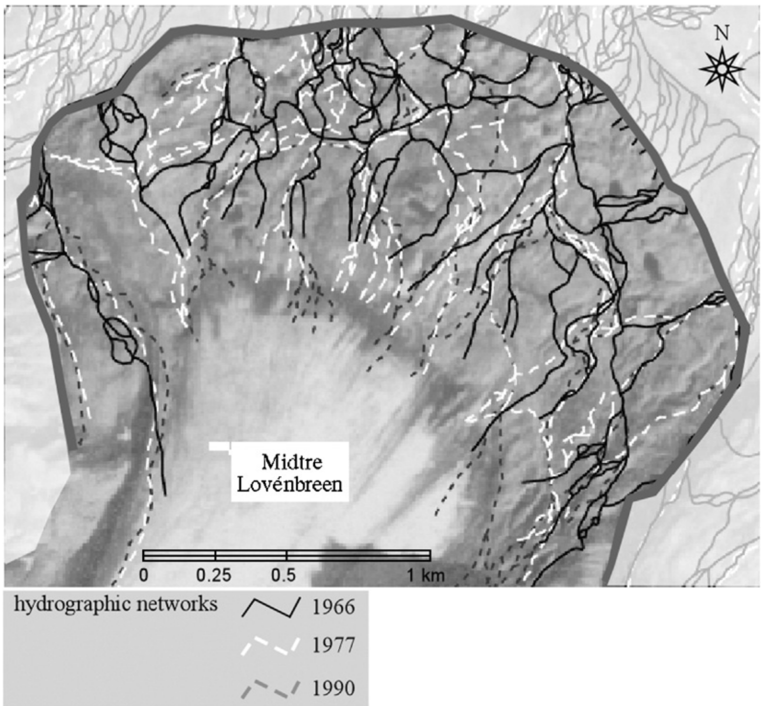

Fig. 3. Map of successive channel networks (1966, 1970 and 1990).

glacier has retreated 1 km, leaving new mineral soil composed mostly of metamorphic rocks dominated by coarse-grained material in the 5- to 20-cm size class and suitable for plant colonization. Mature vegetation communities on the Brøggerhalvøya Peninsula are found on 8000- to 9000-year-old glacio-marine terraces related to isostatic uplift from the Late Weichselian glacial period (Forman, 1990). These exposed areas are dominated by *Dryas octopetala* (Elvebakk, 1997) with other plant communities occurring in associated micro-local habitats (Nimis, 1985; Nilsen et al., 1999).

The Little Ice Age maximum occurred in the 1900s in Svalbard. As with other glaciers in this Arctic zone, Midtre Lovéndreen had a negative mass balance during most of the 20th century. In 1907, Midtre Lovénbreen was at its maximum with domed fronts (Isachsen, 1912). Although most glaciers in these regions were still close to their terminal moraines in 1936, recent studies suggest that the retreat of the Midtre Lovénbreen front occurred closer to 1925 (Hansen, 1999). During 1975–1996 in Ny-Ålesund, 25% of the precipitation was rain, 44% was snow and 31% was mixed rain and snow or as sleet (Førland and Hanssen-Bauer, 2000), with the overall trend negative (less accumulation) for snow and positive (more accumulation) for mixed precipitation. The annual mean temperature at the Svalbard Airport has increased by 0.14 °C per decade since 1912, and the annual precipitation has increased significantly by 2.8% over the same time during the twentieth century (Hanssen-Bauer and Førland, 1998; Hanssen-Bauer, 2002). More regionally, the island of Spitsbergen has undergone a 4–5 °C increase in mean annual temperatures since the end of the Little Ice Age (Fleming et al., 1997).

Statistical relationships between negative mass balance of the glacier and meteorological parameters have been investigated (Lefauconnier and Hagen, 1990; Hansen, 1999; Lefauconnier et al., 1999; Nesje and Dahl, 2000; Hagen et al., 2003) and reflect, in part, a decrease in winter snowfall and a concomitant increase in rainfall. Hansen (1999) calculated the response time of glacial retreat (31 years) of Midtre Lovénbreen front to climate change during the 20th century. It can therefore be an indicator of recent climatic change. One consequence of these changes in climate and glacier mass budget is an increase of seasonal melt water discharge (Hagen and Lefauconnier, 1995). Current summer melt water discharge amounts to about 10^7 m^3, resulting in increased sediment mobilization. Sediment

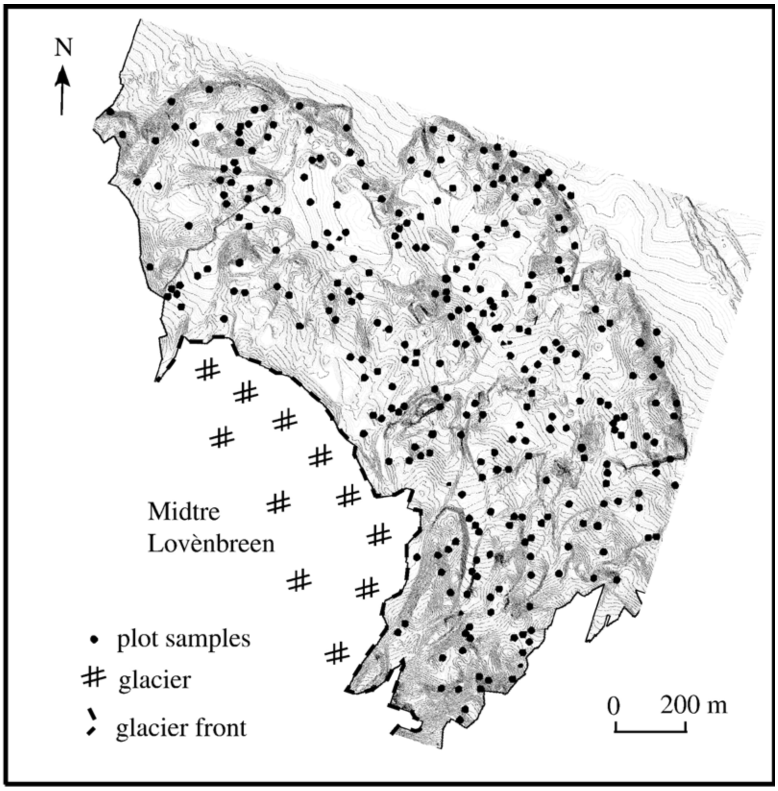

Fig. 4. Digital elevation model (DEM) of the Midtre Lovénbreen forefield with vegetation sampling plot locations.

transport has been estimated to be between 478 and 2,009 t km^{-2} $year^{-1}$ for the Austre Lovénbreen catchment area (Geoffray, 1968; Griselin, 1982) and, similarly, about 940 t km^{-2} $year^{-1}$ for the Vestre Lovénbreen (Etzelmüller, 2000). Paraglacial sediment reworking, particularly by melt water runoff, is therefore of importance for the formation and stabilization of glacial forelands.

Since the end of the Little Ice Age, in particular the period 1900–1920, the Midtre Lovénbreen retreated at a rate of around 18,620 m^2 $year^{-1}$ (Roussel, 2004), causing the catchment (about 13.716 km^2) to shift, with only 40% of its hydrographic basin beneath the Midtre Lovénbreen ice. As a result, the deglaciated till surface increased considerably (Fig. 2). Between 1966 and 1990, the surface retreated 446,213.9 m^2 resulting an exposed area of about 2.3 km^2. The recent deglaciation and associated increase in till surface imply a progression towards increased hydrologic activity in the catchment's upper section.

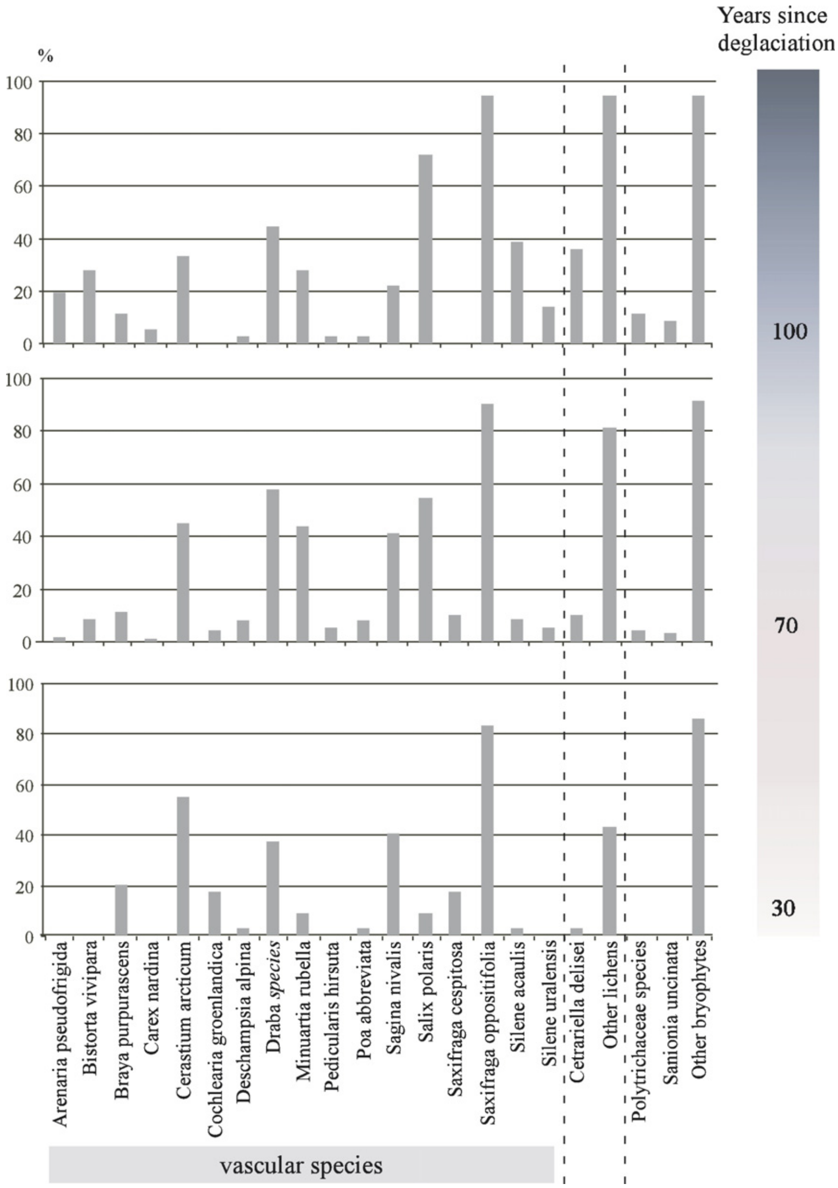

Fig. 5. Plant colonization on Midtre Lovénbreen moraines in relationship to the time of deglaciation. The vascular plant species are organized on the abscissa in alphabetical order and on the right lichens and bryophytes frequency are indicated. The Y-axis gives the frequency of each species inside the three morainic ring-like structures calculated using 217 releves.

3. Methods

3.1. Remote sensing and GIS database

3.1.1. Air photographs

One of the most important factors controlling vegetation distribution over a moraine is the age of the soil substrate that can be inferred by plant community makeup and physical age since glacial retreat. Floristic succession have been organized along the different foreland sectors by the cadence of glacier retreat (Moreau, 2003). High resolution air photo (1:50,000 scale) obtained from the Norwegian Polar Institute were used to visually demarcate successive changes in the glacier frontal terminus from the years 1936, 1966 and 1990. These data were digitized and georeferenced to produce a surface map of successive moraines (Fig. 2) and then added to a geographical information system database.

Although soil substrate age is an important variable for the success of plant colonization, other paraglacial processes are also important, such as the influence of water runoff on the physical relief of the moraine. In addition to mapping the terminal moraines, we also mapped successive changes to the channel networks using aerial photographs from 1966, 1977 and 1990. The networks were then digitized, georeferenced and added to the GIS database. From these data, we calculated several morphologic stream indexes and characteristics, such as length of the stream and width of active channel.

3.1.2. DEM processing from GPS measurements and GIS layers

A DEM with 2-m resolution of the Midtre Lovénbreen foreland was produced using over 40,000 differentially corrected GPS points collected with a TRIMBLE 4000 SE and a LEICA SR 9500 system (Brossard et al., 1998; Fig. 3). Point samples were collected from 1995 to 1997 based on relief characteristics and corrected to a GPS base station established at the French Camp Jean Corbel less than 3 km away. The DEM was calculated by spatial

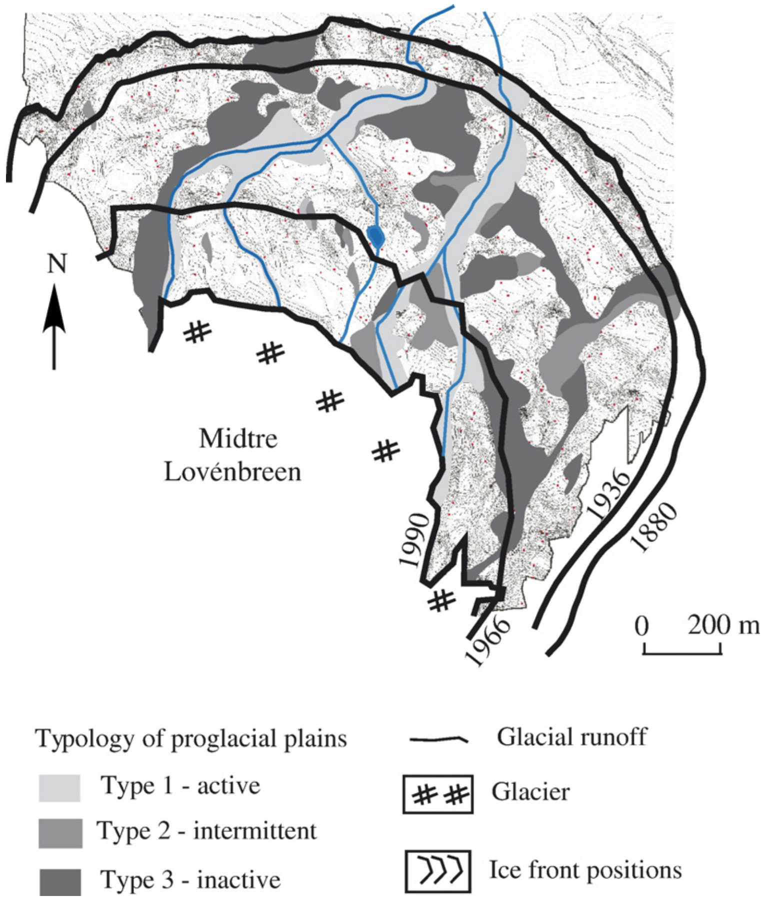

Fig. 6. Map of the proglacial plain of the Midtre Lovénbreen forefield and typology of the plain areas (from the digital elevation model and the aerial photographs provided by the Norwegian Polar Institute).

interpolation between data points following Brossard et al. (1998). Slope and dominant landforms, such as plains, hummocky moraines, thalwegs and crests were derived directly from the DEM.

3.2. Field sampling

Vegetation sampling plots were placed on moraine areas from the terminus to the ice front and within fluvial deposits affected by runoff (Fig. 3). In order to cover the entire geographic foreland area, 300 field sampling points were selected using a non-aligned stratified sample (Keersmaecker, 1987) using the differential GPS to provide a diverse data set that represents the temporal and runoff conditions and associated vegetation types. Releves (2×2 m) were established for vegetation analysis to record number and present or absent of each species categories. The frequency of each species category was the percentage of plots in a part of the moraine of which that species occurred.

Sources used to determine nomenclature of vascular plants follows Rønning (1996) for determination and Elven and Elvebakk (1996) for names.

3.3. Definition of vegetation types

Using the geospatial information obtained for each of our vegetation field plots, we combined the releve data with the data layers of the GIS to identify which geophysical variables (e.g., plain, moraine age and runoff dynamics) correlated best with the plant species present. Statistical analysis of these data determined the presence and the frequency of each plant species on the different areas of the moraine. This data set allowed a synthesis of the different sets of plant species (synonymous to vegetation types) that colonize various portions of the

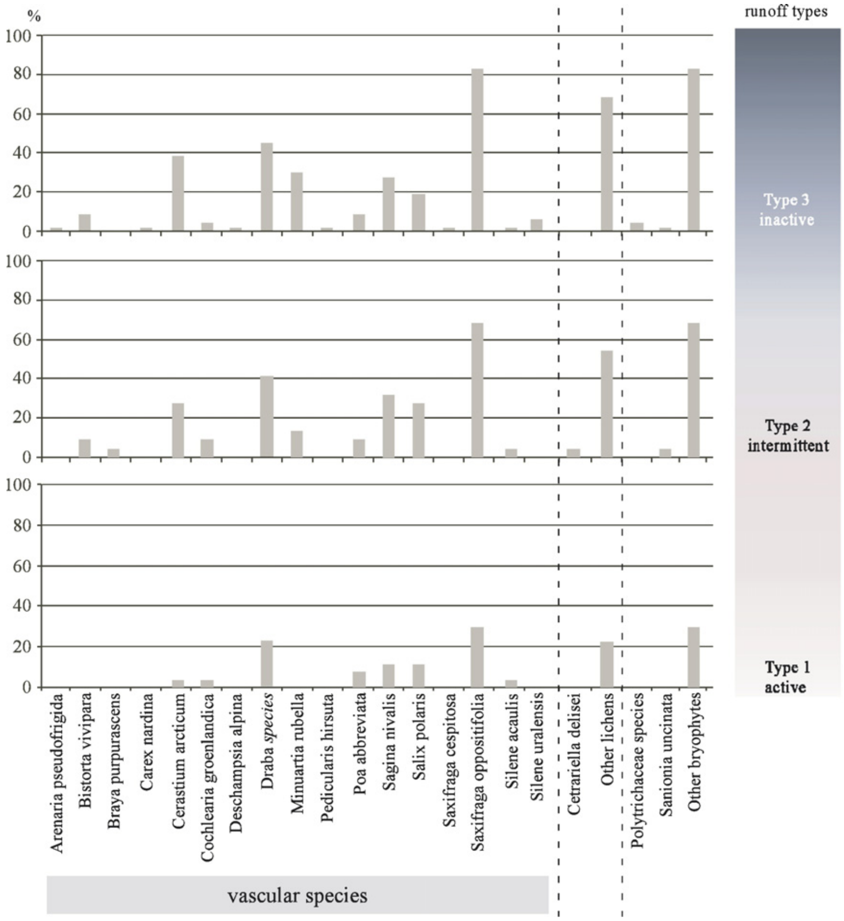

Fig. 7. Plant colonization in relation to runoff dynamics of the proglacial plains. The species are organized on the abscissa in alphabetical order and on the right lichens and bryophytes frequency are indicated. The *Y*-axis gives the frequency of each species inside the three plain types and based on 113 releves.

moraine and allowed correlations to be made with different geomorphologic dynamics, such as the age of soil substrate available for plant colonization and the influence of water runoff and the type of landform feature.

4. Results

In the Midtre Lovénbreen forefield we have distinguished two floristic developments in relation with the stability and instability of the moraine.

4.1. Determination of primary succession on stable soil moraines

Based on interpretation of the aerial photographs, three glacier positions have been located on the Midtre Lovénbreen forefield (Fig. 2). For each terminal moraine a ring-like structure is identified on which a portion of the vegetation plots were located. These plots allowed for the identification of plant groupings or communities that were dated and were correlated to moraine age. For the three moraine rings, a linear relationship was established (Fig. 4), with the following results observed:

- Within young moraines (those deglaciated for less than 30 years) 12 vascular species categories occurred. They are characterized by pioneer species in small frequencies dominated by *Saxifraga oppositifolia*, which was present on more than 80% of the plots.
- On medium aged moraines (areas deglaciated between 30 and 70 years), there is an increase in the number of species categories (23) including *Bistorta vivipara*, *Carex nardina*, *Pedicularis hirsuta* and *Arenaria pseudofrigida*. The increase of *Minuartia rubella* and *Salix polaris* are most striking and as well as an increase of lichens.
- On old moraines (70 to 100 years of deglaciation), the number of species no longer increase and two species actually disappear; however, there is a stronger preponderance of cushion type plants, such as *Silene acaulis* and *A. pseudofrigida*, as well as the prostrate dwarf shrub *S. polaris*. At this stage bryophytes and lichens have the same frequency.

4.2. The impact of runoff dynamics on the Midtre Lovénbreen foreland

The spatial effects of runoff are not constant over space and time (Fig. 5), nor do they impact the entire foreland area in the same manner; it is, however, possible to distinguish the different types of features across the area in relation to the types of hydraulic flow, which in turn can be correlated to the vegetation present as they occur between the terminal and lateral moraines. Using the spatial features of the digital elevation model, field sampling and aerial photographs, three types of plan features were identified (Fig. 6), each distinguished by their flow form and vegetation development (Fig. 7).

Fig. 8. Active channel type (Type I). The retreat of the glacier is accompanied by strong runoff which destroys the moraines. The flat morphology of this channel contrasts with the hummocky moraines (photo by M. Moreau, the 20 of July 2002 (10h20), taken from the proglacial area to the glacier front, towards the south).

Fig. 9. Intermittent channel type (Type II). This weaker runoff allows plant colonization on the banks (photo by M. Moreau, the 19 of July 2003 (11H06), taken from the proglacial area towards the west).

-Type I (active channel)—Stream channels are characterized by strong and steady runoff during the melting season from glacial meltwater (Fig. 8) resulting in minimal plant colonization. The runoff reworks the glacial deposits producing entrenched stream channels, especially on recently deglaciated areas close to the ice front. Frequency of plant categories within this outwash plain type indicate that the dynamics of runoff limits vegetation development to primitive stages of plant succession, and only channel banks are normally colonized. Less than half of the species categories present on the entire forefield area occur in these areas, with the dominating species being *S. oppositifolia* and *Draba* species (Fig. 7).

-Type II (Intermittent Channel)—Stream channels are affected by intermittent runoff resulting from snowmelt. These unsteady flows are fed by the melting of buried ice within the moraines, glacier melt or simply snowmelt and

Fig. 10. Inactive channel type (Type III) colonized by late successional vegetation. In the background, glacial runoff still flows on the proglacial plain and through hummocky moraines which have remained the same since the glacier retreat (photo by M. Moreau, the 11 of July 2002 (14h43), taken from the proglacial area towards the northwest).

rainfall. With fewer disturbances from morphogenic processes, the concurrent development soil and associated of plant colonization can occur (Fig. 9). Thus, vascular species which were absent from the stream channels with active runoff, such as *B. vivipara* and *M. rubella*, are now present and the floristic cover indicates a more stable state (e.g., 11 plant categories; Fig. 7).

-Type III (Inactive Channel)—Finally, a third type that corresponds to areas that are no longer affected by active runoff was identified, characterized by inactive channels and stable plant communities (such as, *A. pseudofrigida*, *P. hirsuta*), but still show the effects of remnant channels (Fig. 10). The species diversity is much higher in these areas, with a total number of vascular species here amounts to 16 (Fig. 7), and is similar to that observed on moraines deglaciated 70 years ago.

5. Discussion

Since the end of the Little Ice Age, it is possible to follow vegetation development on recently deglaciated forelands as it corresponds to primary succession, eventually leading to stable plant colonization (Matthews, 1992). This succession is characterized by progress both in species number and species composition related to the increasing time since moraine deglaciation. Consequently, the duration of deglaciation can be a determining factor leading to the development of vegetation communities. However, this development assumes that deposits have remained immobile since the retreat of the glacier. This is not the case for the entire foreland area near the Midtre Lovénbreen foreland where paraglacial dynamics are active and rework deposits. The drainage network on the foreland of the Midtre Lovénbreen glacier has undergone many changes. Following the retreat of the glacier, the foreland area has been progressively altered by surface runoff dynamics, ultimately culminating in a predominantly stable state after 70 to 100 years. In the identification of the proglacial drainage features, we observed a complex and shifting drainage network (Fig. 5) and described as follows. Initially, numerous active braided streams dominate the glacier foreland; channels rapidly develop on till deposits and evolve rapidly in response to changes in steam discharge and sediment availability. The drainage network, first forming at the front of the glacier as soon as it begins its retreat, forms multiple channels that can grow in length at a rate of 2.4 m year^{-1} (as determined by photo-interpretation of aerial photographs from 1966 to 1990). After 30–70 years (type II, above) a decrease in the number of channels occurs within the forefield (from 320 in 1977 to 230 in 1990 in this study). In addition, active streams may become narrow (from 90 m in 1966 to 60 m in 1990 in this study). Therefore, the effects of active runoff can eventually be concentrated to the major channels, abandoning the braided form of drainage over time due to lateral migration (i.e., shifting to a central channel), vertical down-cutting and continued glacier retreat. In spite of its extreme youth, the drainage pattern rapidly adopts an increasingly stable organization, marked by the reduction of the number of channels and a growing hierarchical organization (e.g., the drainage network becomes simpler with time).

Although these runoff processes affect one third of the Midtre Lovénbreen foreland, they do not adversely affect the terminal and lateral moraines nor does it affect the vegetation cover associated with them. As a result, plant colonization in one third of the foreland area does not follow the same floristic pattern as the primary succession that takes place on more stable soil substrate that occurs on the lateral and terminal moraines. Spatial discontinuities across the foreland due to runoff cause temporal gaps in the development of plant groups colonizing the deposits. While primary succession in relation to the time of deglaciation may take place over many areas within the foreland, other advanced floristic development can be found in relation to the level of runoff within the same moraine ring. We noticed a parallel between the species which populate the runoff-induced disturbed areas and those species which have colonized more recently deglaciated areas. Similarly, in the areas progressively abandoned by runoff dynamics, vegetation development is similar to primary succession.

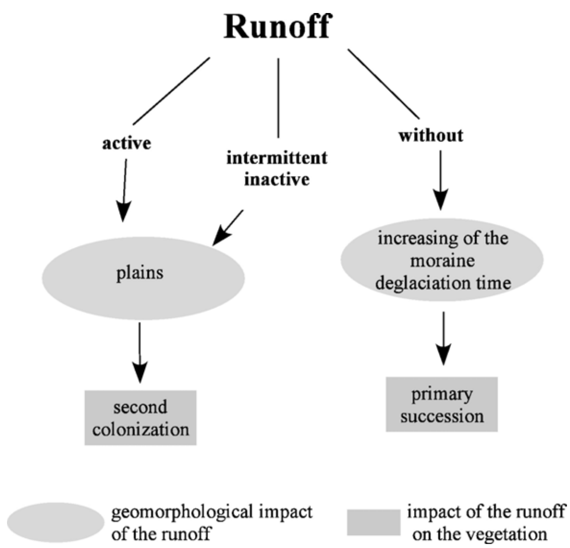

Fig. 11. The central part of runoff in the forefield landscape.

The dynamics of secondary colonization, however, do not correspond to the sequence of floristic groups occurring during primary colonization because the rates at which individual species colonize an area are different for the two successional pathways. Some species, such as *Braya purpurascens*, *Deschampsia alpina*, *Saxifraga cespitosa* and *M. rubella*, colonize quickly on the younger moraines during the primary succession but take longer to colonize on recently exposed surfaces affected by runoff. Whereas certain other species, such as *Cerastium arcticum*, *Draba* species and *Sagina nivalis*, colonize quickly on both the deglaciated areas and the active and intermittent runoff plains. The divergence of species exploitation over new areas is linked to the known changes in environmental conditions during primary succession and secondary colonization. Secondary succession in this region does not begin anew like primary succession immediately following the glacier retreat. The edaphic environment is different and causes a faster progress in colonization for some species due to differences in a number ecologic conditions including moraine stability, soil texture and increases of seed bank and seed availability. These conditions allow the species diversity to increase as the morainal deposits age. With the addition of runoff, a diverse mosaic (patchwork) of landscape patterns has evolved on the moraines of the Midtre Lovénbreen forefield over time and space. The effects of runoff on foreland areas and the resulting effects on vegetation succession may provide future insight on:

(1) how newly exposed arctic environments, like the glacier foreland, experiences geomorphological changes;
(2) how paraglacial dynamics succeed glacial dynamics in time and space and in geomorphological landscape evolution; and
(3) how paraglacial dynamics constitute a hindrance or an opportunity to plant succession in response to global change.

6. Conclusion

Midtre Lovénbreen has retreated more than 1 km from its Little Ice Age limit during the 20th century and glacial melt water has extensively reworked the deposited sediments on the exposed glacier forelands. In such areas, a paraglacial sediment transport regime has become prominent, with runoff as the dominant surface disturbance process. Initial modification is evidenced by a geomorphological transition from a landscape dominated by glacial and periglacial processes to one in which paraglacial landscape response is dominant. According to the general model of paraglacial landscape response proposed by Ballantyne (2002), this situation represents the onset of sediment reworking when sediment availability and thus sediment flux are at their greatest. We propose that runoff is a major contributing major factor for plant colonization in these types of environments that can lead to either secondary colonization or revert to a more primary successional stage, as shown the Fig. 11. Our studies indicate that the runoff dynamics can result in stable moraines or sites that are kept in a more primitive state. For each geomorphologic form there is plant colonization (Fig. 11).

In both moraine environments, it would be interesting to continue the research to observe other environmental conditions that may influence floristic distribution. In a similar area (e.g., Brøggerhalvøya, Minami et al., 1997) on east Brøgger forefield the relationship to topographic forms (landscape position of bottom, slope and crest) controlled the plant distribution. In addition, Nilsen et al. (1999) have shown that on the Midtre Lovénbreen forefield, microclimatic and topographic conditions induce various vegetated landscapes. Also, Elvebakk (1994) reported that in older substrates on Svalbard the ridge-snow bed gradient may result in more dramatic conditions. Elsewhere in the Arctic, Matthews and Whittaker (1987) have shown the role aspect, and Stöcklin and Bäumler (1996) and Jumpponen et al. (1999) have shown the importance of the “safe site” in the seed germination. In the future, this study could be augmented by the incorporation of a slope parameter (derived from the DEM), as well as an analysis of the influence the snow cover on plant distribution.

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