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Analysis of plant colonization on an arctic moraine since the end of the Little Ice Age using remotely sensed data and a Bayesian approach

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Abstract

Young moraines less than 100 years old are considered as key areas for monitoring the effects of climate change since the end of the Little Ice Age. One way of documenting this change is by recognizing and characterizing the different plant colonization stages and trends that occur on these relatively new environments. Previous studies have shown that remotely sensed data alone are not sufficient to map the vegetation over these types of landscapes because the most significant part of the radiometric information is related to mineral landscape components. Therefore, the authors used an indirect approach which consisted in the following steps.

1. An optimized sampling procedure was used to collect georeferenced vegetation plot data. A multivariate analysis was then used to define vegetation types that could be related to different colonization stages and environmental contexts.
2. Color infrared aerial photographs were then used to produce a baseline vegetation map. This map was then integrated into a data base along with other environment factors known to control plant colonization processes, such as climate (wind, temperature), physical landscape components (habitat characteristics) and morphodynamic processes (runoff).
3. A Bayesian model using conditional probabilities was used to identify the primary environmental habitats corresponding to the different vegetation types.

This protocol was tested on the fore field of the Midre Lovénbreen (Svalbard) glacier where several vegetation belts correspond to well defined stages of deglaciation and corresponding local conditions such as microtopography, microclimate and runoff dynamics.

Keywords: Little Ice Age; Bayesian approach; Midre Lovénbreen fore field; Plant colonization

1. Introduction

Since the end of the Little Ice Age (LIA), a significant decrease of the glaciated areas has been observed in the circumpolar region, especially during the second half of the 19th and early part of the 20th century (Serreze et al., 2000; Watson et al., 1997). These recent deglaciated areas are of a great interest for studying plant colonization because they provide a unique and quantifiable time reference when vegetation begins to colonize the newly exposed mineral soils. Because the retreat of the glaciers often occur in distinct segments of time it is possible to examine how the vegetation dynamics are controlled both by time and local environmental conditions. Plant colonization on the recently exposed moraines have been studied in many polar and boreal areas (Chapin et al., 1994; Frenot et al., 1998; Helm & Allen, 1995; Hodkinson et al., 2002; Moreau, 2003; Nilsen et al., 1999; Stöcklin & Bäumler, 1996; Vetaas, 1997). Most of these studies focused on observing plant distribution along transects that extended from the recent glacier front (the present) to the terminal

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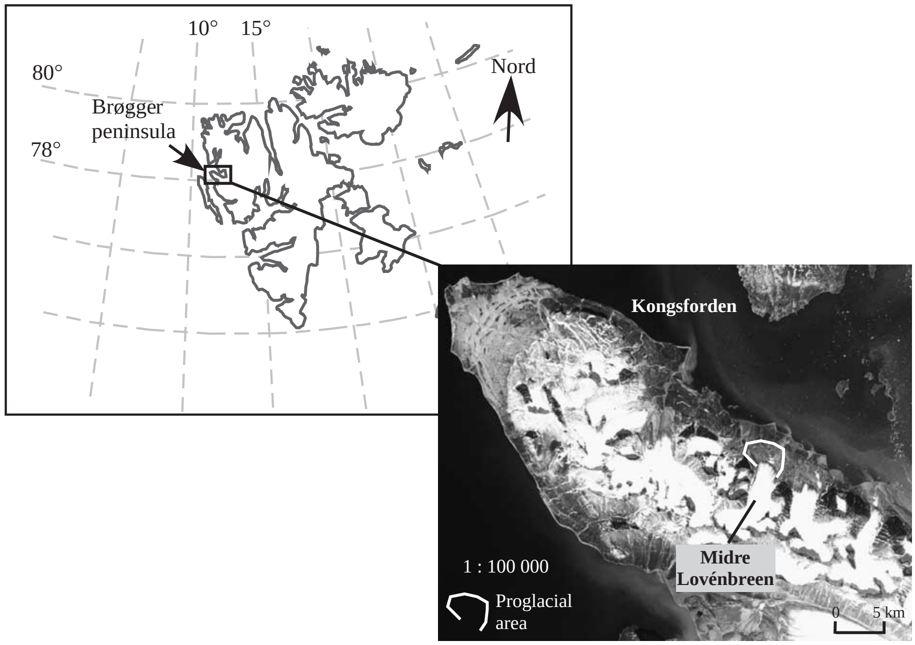

Fig. 1. Svalbard map and Brøgger peninsula location.

ridge indicating the maximum glacial advance (historical glacial front). The botanical data acquired along the transect were then used to establish a time–space correspondence between the position of each vegetation serial stage to a corresponding stage of glacier retreat. This linear type of sampling offers a satisfactory means to document the different states of vegetation development through time; however, it assumes that plant colonization of the moraine through time is a linear and homogenous process in terms of potential evolution which is not normally the case. Therefore, we propose a method of combining field observations, remote sensed data and GIS that take into account the spatial and temporal diversity of the moraine field. In addition, field data collections are based on observed vegetation serial state zonation along the moraine, instead of a continuous transect. The relationship between the in situ observed features and associated environmental data layers are stored in a GIS and then analyzed through modelling using Bayesian conditional probabilities. The resulting from the field observation is considered as variables to be explained (i.e. botanical evolution features) and the data taken from the GIS as explaining variables (i.e. environment factors). The resulting models are then applied to the environmental variables to produce a vegetation map.

2. Study area and database development

2.1. Study area

The study area is located on the foreland of the Midre Lovénbreen, Brøgger Peninsula, Svalbard (79°N, 12°W; Fig. 1). The basin of this glacier covers approximately 10 km^2. Lefauconnier (1987) reported 1880 as the date of the terminal ridge of the moraine corresponding to the Little Ice Age maximum. From then until the present the glacier has retreated 1 km leaving new mineral soil for plant colonization. Mature vegetation communities on the Brøgger Peninsula, are found on 8000- to 9000-year-old glacio-marine terraces and are related to isostatic uplift from the Late Weichselian glacial period (Forman, 1990). These areas are dominated by *Dryas octopetala* (Elvebakk, 1997), with

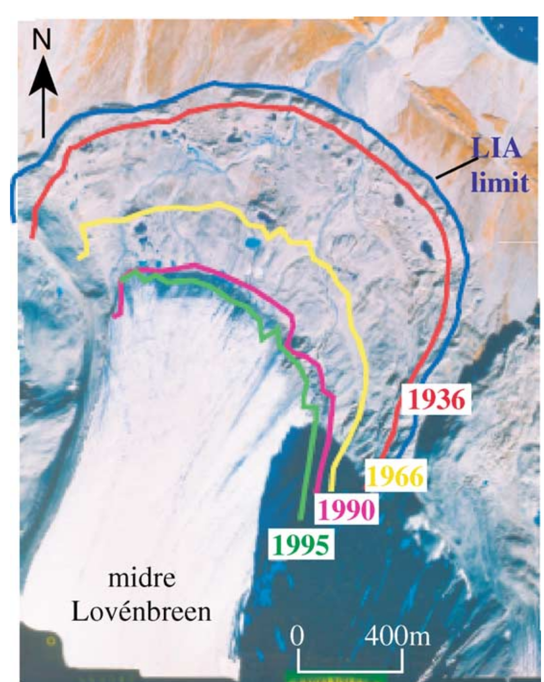

Fig. 2. Map of successive Midre Lovénbreen glacier terminus obtained from 1/50,000-scale aerial photographs.

plant distribution dependent on micro-local habitat conditions (Nilsen et al., 1999; Nimis, 1985). Plant physiognomy and composition of the vegetation reflect the characteristics of the local environment and can by considered as an evolution marker. This aspect of mature tundra provides the starting point for our research on the plant colonization process on young moraines.

2.2. Remote sensed and GIS data base

2.2.1. Air photos and satellites images

One of the most important factors of vegetation distribution over a moraine is the age of the soil substrate. Floristic successions can be used as surrogates to soil age and are organised along the different parts of the proglacial sectors by the cadence of glacier retreat (Moreau, 2003). High resolution air photos (1/50 000) from Norwegian Polar Institute were used to visually demarcate successive changes in the glacier front terminus in 1936, 1966 and 1990. These data were digitized, georeferenced, and combined to produce surface map of the moraines retreat (Fig. 2).

In addition to the age of soil substrate available for colonization, paraglacial processes such as the influence, water runoff is also an important factor on plant colonization. Three kinds of plain features were identified on the moraine using air photos and a satellite image (1/25 000 aerial air photos from Norwegian Polar Institute and Spot Pan 10-m resolution) in relation to runoff: 1) channels affected by dynamic glacier runoff; 2) areas affected by an intermittent runoff caused by rain and snow melt; and 3) areas with minimal runoff (Fig. 3).

2.2.2. DEM processed from GPS measurements

A 2-m DEM of the Midre Lovénbreen moraine foreland was produced using over 40,000 differentially corrected GPS points collected with a TRIMBLE 4000 SE and a LEICA SR 9500 system. Point samples were collected from 1995 to 1998 based on relief characteristics and corrected to a GPS base station established at the French science camp J. Corbel less than 3 km

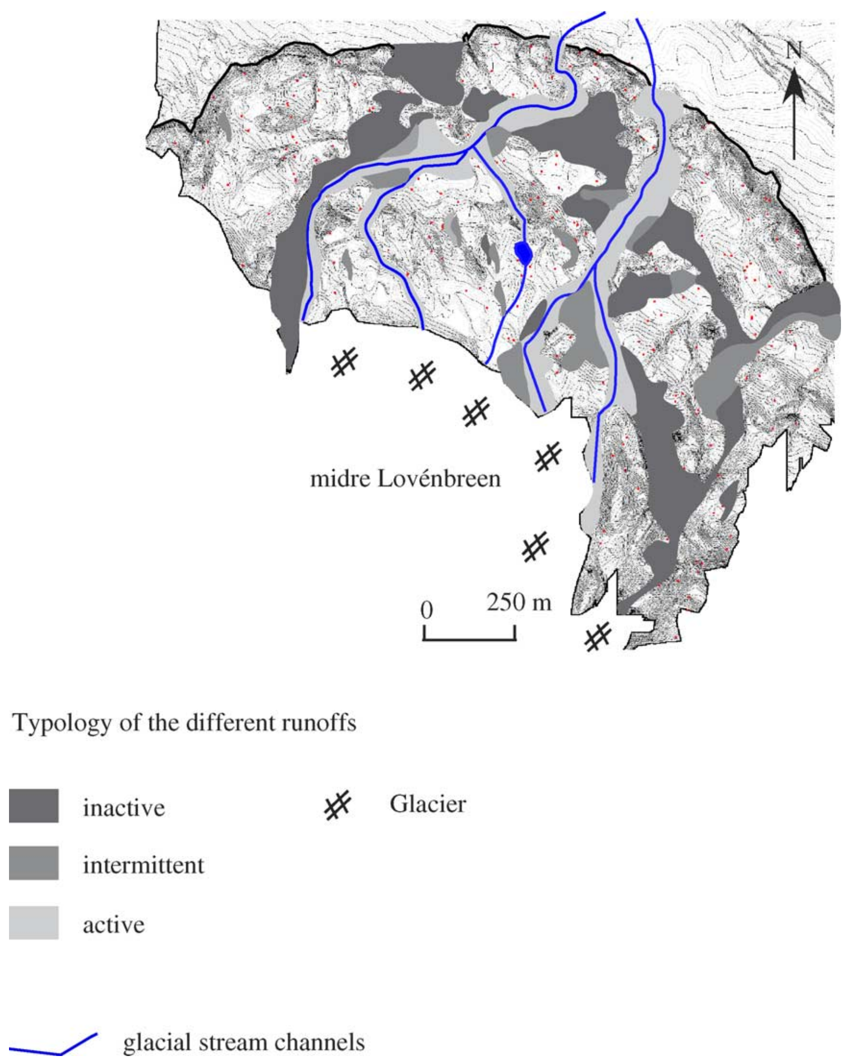

Fig. 3. Map of the Midre Lovénbreen fore field and typology of the three different kinds of runoffs relief.

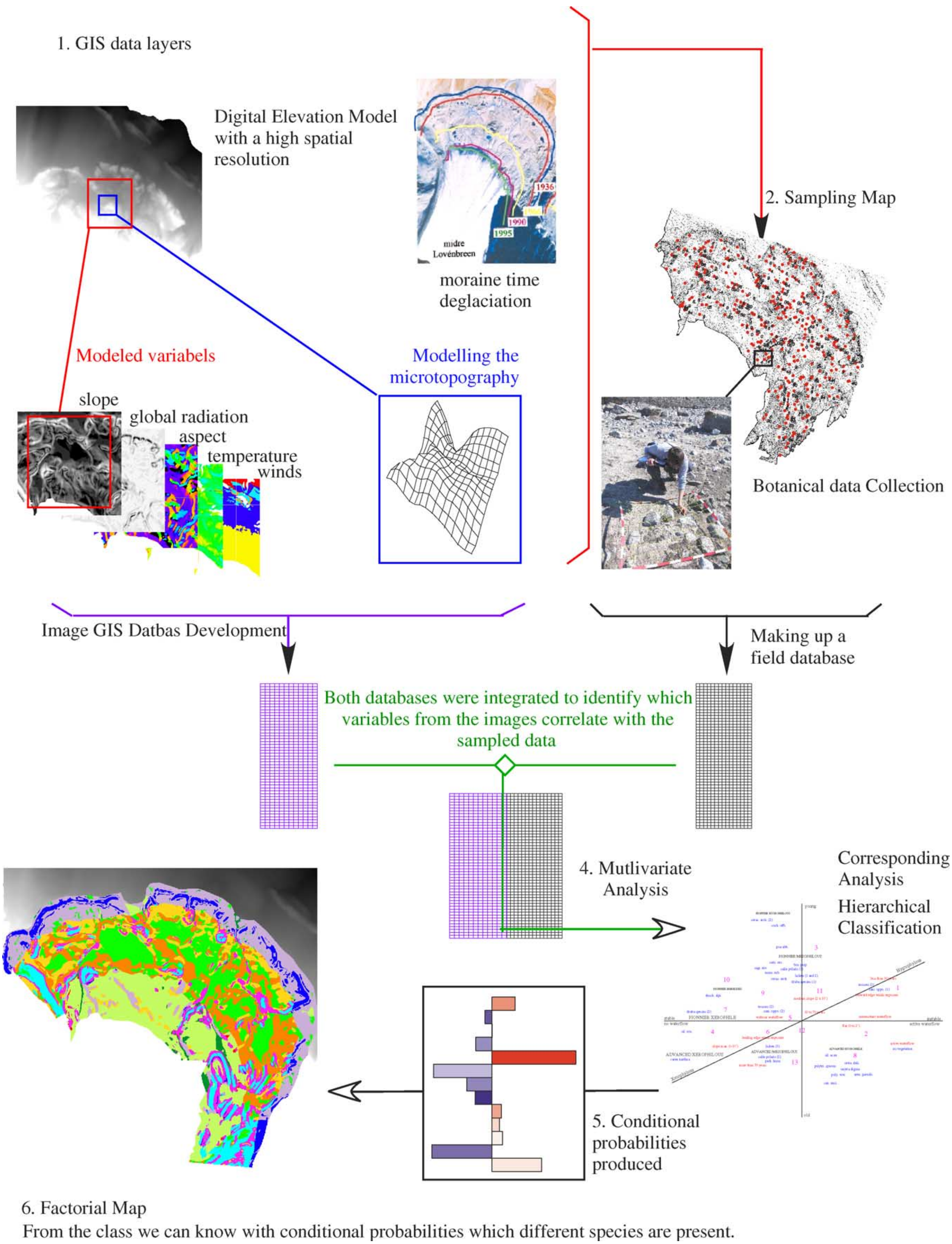

Fig. 4. Flow diagram showing methods used to form the GIS database and map the vegetation on the foreland of the Midre Lovénbreen glacier.

away. The DEM was calculated by spatial interpolation between data points following Nilsen et al. (1996) and Brossard et al. (1998).

2.2.3. Other GIS layers

Micro-topographic relief and wind exposure conditions were also identified as secondary influence variables for plant colonization. Slope, aspect and dominant landform were derived directly from the DEM. A solar radiation layer was produced using a model that estimates direct and diffuse solar radiation of an area based on the Sun's elevation and ephemeral data. Dominate local winds and ground temperature were modelled by a combination of local and global ground surface relief analysis and in situ temperature measurements collected in the field (Brossard et al., 2003; Fury & Joly, 2003). Because wind impact influences a number of factors important to plant colonization (e.g., snow distribution, ground temperature and moisture), wind exposure was mapped into two types: the four most dominating leading edge winds and the four most dominating leeward edge winds.

These data, along with the runoff maps and soil age maps were integrated as geographical information layers to map glacier retreat (Fig. 4, part 1).

2.3. Field sampling

2.3.1. Sampling protocol

Field sampling points was selected using a non-aligned stratified sample (Keersmaecker, 1987; Laffly, 1995) based on dominate relief forms, elevation, slope, aspect and global radiation from the GIS database (Fig. 5). Six micro-topographic relief forms were identified as being suitable to characterize the structure of the biogeographical landscape: plane surface; peaks and thalwegs; and three slopes identified as important to geomorphological process in cold-climate conditions (French, 1996; Van Vliet-Lanoë, 1988), 0° to 2°, 2° to 10°, and more than 10°. For each sampling stratification, 50 points are sampled using the differential GPS to provide a diverse data set that described the temporal and micro-topographic conditions and associated vegetation types.

2.3.2. Botanical data collection

Field vegetation plots were obtained randomly by selecting 3000 pixels within the DEM grid over the study area. Each pixel was located and subdivided into four 1-m^2 quadrants and further divided into 10 cm^2 cells. A random sample of 24 10-cm^2 cells was then selected to obtain plant species, and counts of each species (Fig. 6). These counts were then used to

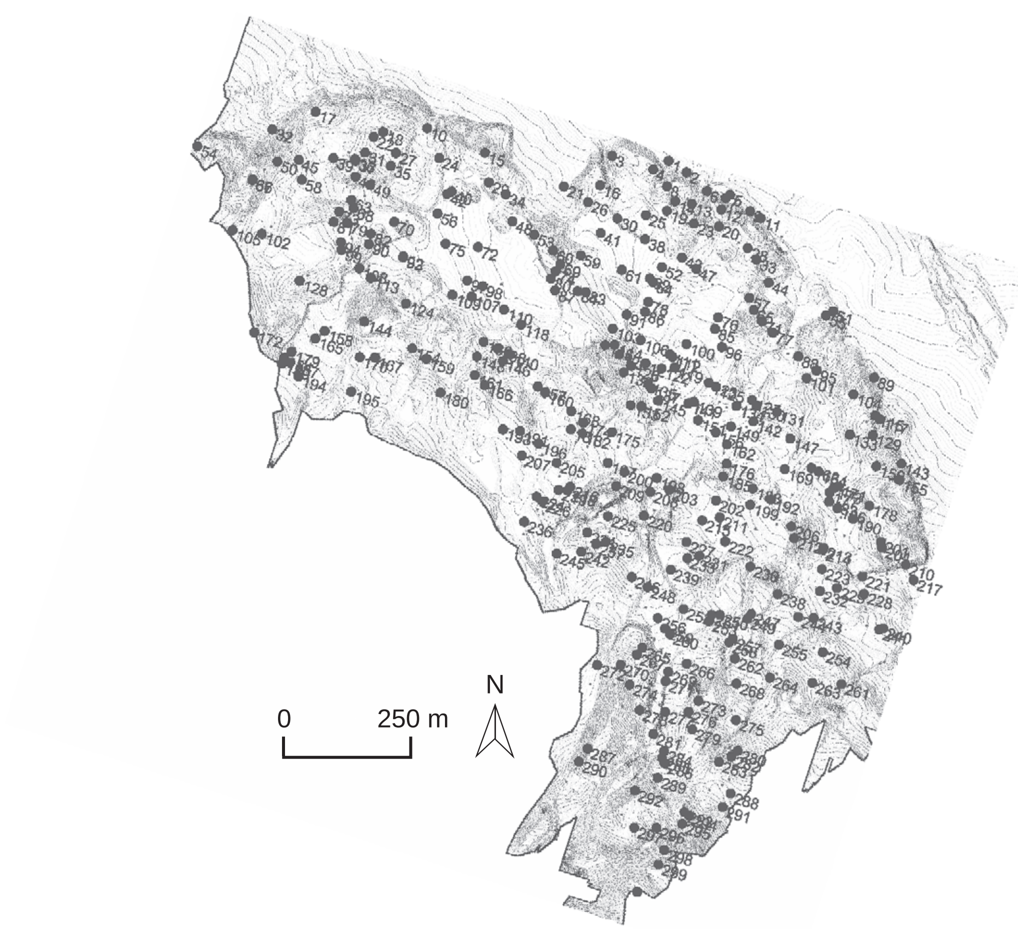

Fig. 5. Sample point locations plotted over the derived DEM.

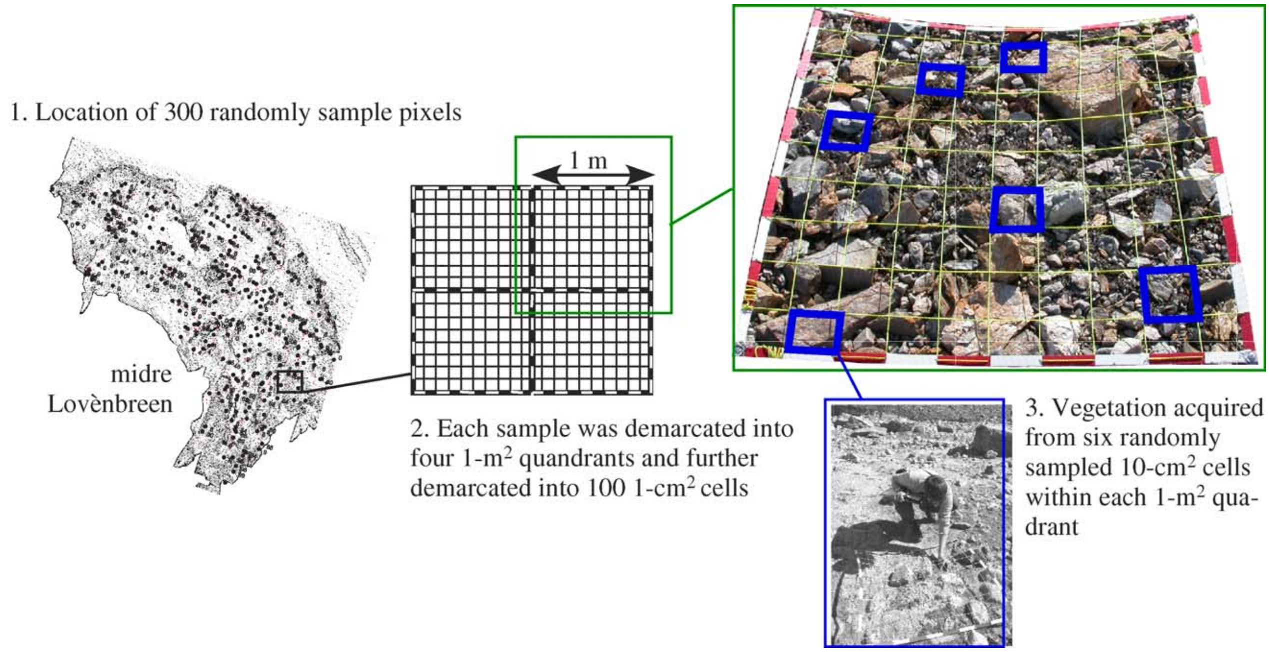

Fig. 6. Method used to randomly select sites for the botanical field data collection.

determine vegetation abundance and frequency (Whittaker, 1991).

3. Method

3.1. Defining the vegetation types by coupling multivariate analysis and classification

The resulting database contained both qualitative (presence and absence) and quantitative (frequency and measurement) data. We used Correspondences Factors Analysis (CFA) to simultaneously analyse all the variables. Because CFA requires homogeneous data for processing, the quantitative variables were made into 'discrete items'. Then, the variables – micro-topographic, runoff, age of surface, and wind exposure data – are added into the factorial space as additional variables. The resulting first three axes were able to explain the structure of data organisation and relationships between species with runoff types along the first axes; moraine ages along the second axis; and edaphic condition along the third axis (Fig. 7).

Finally, a hierarchical classification (Ward distance) was then applied to the results of CFA analysis. The result of the classification was a dendrogram that could be partitioned into 13 classes, with each class being defined by its location in the factorial space (Fig. 7) based on the measure of importance associated with the independent variables (vegetation) and dependent variables (geomorphological and climate parameters).

3.2. Bayesian modelling for establishing the relationship between vegetation types and environment factors

The frequency histogram of each variable from the CFA is considered as an empirical probability, or a priori knowledge. Consequently, according to the Bayesian theorem (1) knowing the profile of different variables for an observation makes it possible to determinate the conditional probability that belongs to each class. It can be calculated as shown in Eq. (1).

$$P(B_i/A) = \frac{P(B_i).P(A/B_i)}{\sum_{j=1}^{n} P(B_j).P(A/B_j)} \quad (1)$$

Where $P(B_i/A)$: conditional probability of event B_i knowing that event A is realised (for example, probability of *intermittent runoff* to be in class 1); $P(B_i)$: conditional probability of event B_i (frequency of *intermittent runoff*, for example); $P(A/B_i)$: conditional probability of event A knowing that event B_i is realised (for example, frequency of *intermittent runoff* in class 1); $P(B_j)$: conditional probability of event B_j (for example, frequency of all variables); $P(A/B_j)$: conditional probability of event A knowing that event B_i is realised (frequency of all variables in class 1, for example); n: number of possible events (number of variables).

Two probabilities tables are obtained. The first table gives the conditional probability of each class knowing a priori the frequency of all variables (Table 1). The second table gives the conditional probability of each variable knowing a priori the frequency of all classes (Table 2). This Bayesian probability model is similar to a maximum likelihood classification except that it can use qualitative variables.

Therefore, the Bayesian model can be used as a cartographic tool for restoring the spatial distribution of the vegetation types (Laffy & Moreau, 2004).

Additional environmental variables incorporated in the statistical model also included digital aerial data. These data allowed a pixel by pixel description of the study area. Each pixel was described using a frequency histogram to

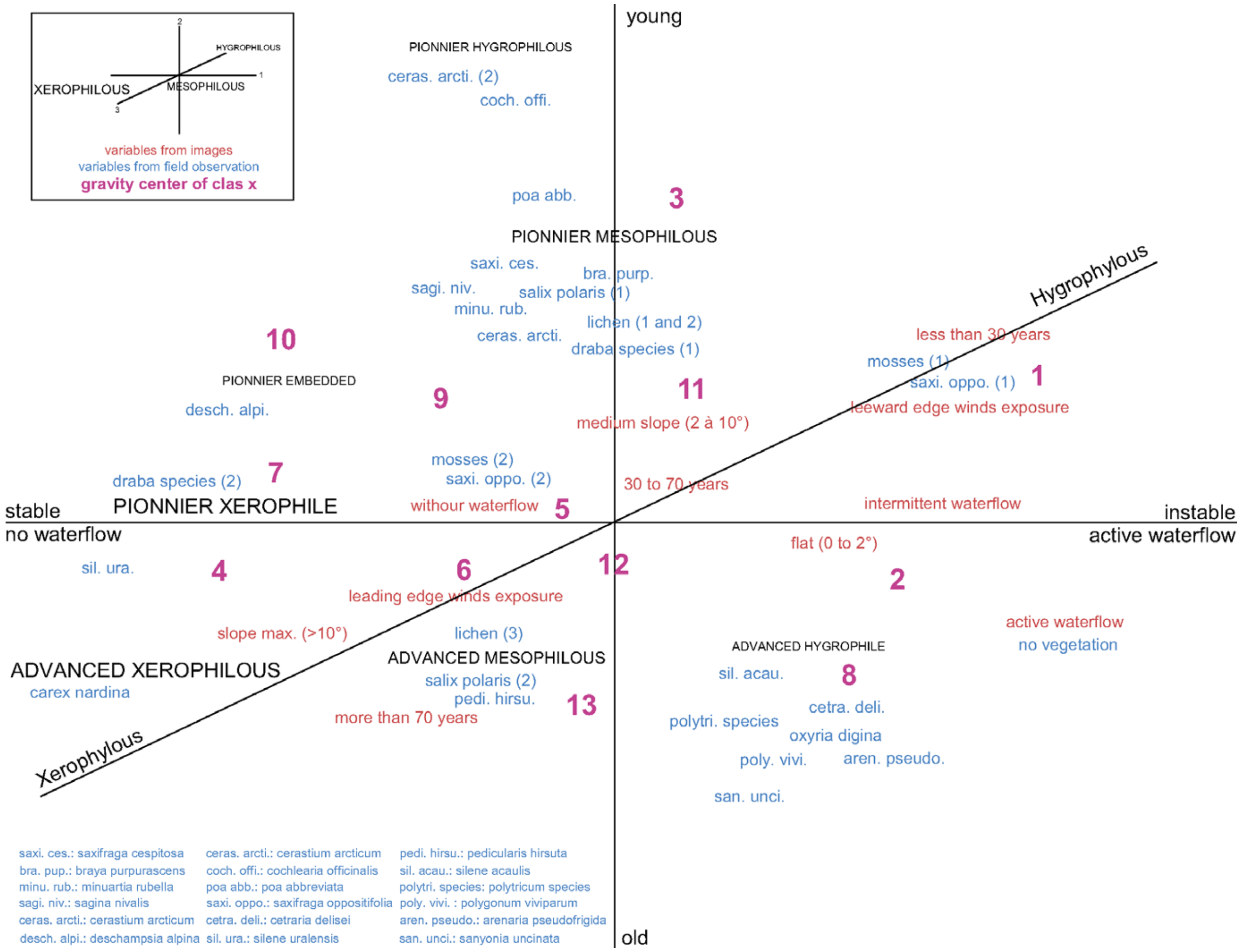

Fig. 7. Factorial space and class identification of the hierarchical classification (in purple).

calculate conditional probability of each class. The resulting probabilities were then used to generate a numerical image of each class based on the higher probability score producing a probability map of vegetation variables for all classes (Fig. 8).

4. Results and discussion

In this study, the number of data variables and associated data points appeared to be robust enough to produce a usable CFA and vegetation map. The results presented here were

Table 1
Conditional probabilities of each class knowing the frequency of each of the different variables

Class	Without runoff	Active runoff	Intermittent runoff	No runoff	Age 3	Age 2	Age 1	Flat	2° to 10°	More than 10°	Wind no data	Back wind	Front wind
1	5.438	11.81	13.03	17.23		7.049	21.78	11.02	8.544			12.24	6.225
2	3.012	17.01	62.53	10.63	1.172	7.579	18.18	15.86	5.566	0.837	3.767	10.82	5.378
3	7.868	11.49	4.225	6.386		10.24	11.06	10	9.104			12.95	4.845
4	9.202			4.922		13.54		13.22	7.323			9.019	12.45
5	8.108		6.012	9.087	11.27	3.123	17.48	1.017	8.45	16.09	15.7	4.163	6.895
6	7.301	12.88		10.74	13.32	7.383		8.412	8.655	3.804	2.854	5.622	16.3
7	9.322			4.219	16.75	5.801			2.092	35.86	26.91		4.268
8	9.126		14.21	0	29.31	0		4.807	9.32	7.607	8.562		21.73
9	9.035			5.907	1.466	12.18	2.273	5.288	11.72		3.139	10.82	5.976
10	7.808			13.13	3.257	9.775	7.576		13.83	2.324	13.95	3.436	9.96
11	6.214	20.24		14.06		7.09	21.65	13.85	6.974			15.46	
12	7.529	26.57		3.692		13.54		16.52	5.492			15.46	
13	10.04				23.45	2.707			2.929	33.47	25.12		5.976
Total	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 2
Conditional probabilities of each variable knowing the probability of each of the different classes

Class	Without runoff	Active runoff	Intermittent runoff	No runoff	Age 3	Age 2	Age 1	Flat	2° to 10°	More than 10°	Wind no data	Back wind	Front wind	Total
1	3.63	4.99	3.63	4.12		13.50	7.94	5.40	13.75			14.92	1.23	100
2	16.84	7.18	17.31	2.53	1.22	14.49	6.55	7.72	8.89	0.42	2.95	13.99	1.53	100
3	39.67	4.28	1.54	1.37		17.56	3.59	4.39	13.19			14.14	0.86	100
4	46.85			1.65		23.43		5.86	1.65			9.94	2.22	100
5	39.83		1.46	1.90	1.27	5.22	5.53	0.44	11.85	7.11	1.79	4.43	1.19	100
6	37.59	4.90		2.35	12.73	12.92		3.77	12.73	1.76	2.56	6.27	2.94	100
7	41.77			0.83	13.92	8.84			2.68	14.46	16.87		0.67	100
8	43.48		3.35		25.96			1.99	12.68	3.26	5.77		3.62	100
9	43.77			1.22	1.32	2.61	0.79	2.23	16.21		2.13	11.35	1.13	100
10	39.70			2.79	3.23	16.63	2.44		19.77	1.47	9.77	3.72	1.74	100
11	33.32	8.90		3.23		12.92	7.48	6.46	1.68			17.94		100
12	36.55	9.52		0.76		22.34		6.98	7.61			16.24		100
13	43.88				19.13	4.22			3.66	13.16	15.36		0.91	100

limited in that only three types of surfaces ages were delineated and they were not enhanced with the addition of information from the aerial photographs.

The main contribution of our research lies in the production of maps of the vegetation in the moraine. Most authors (Chapin et al., 1994; Helm & Allen, 1995; Jumpponen et al., 1999; Kaufmann et al., 2002; Vetaas, 1994, 1997) study samples to describe the characteristics of plant colonization and succession in the moraines cautiously. For those authors, the age of soil surfaces is the main factor but they stress the second role played by the local geographical conditions. Nilsen et al. (1996, 1999) propose a model using conditional probabilities to map plant communities on the Brøgger area (Spitsbergen). They combine field observations with topographic data and infrared aerial photo in a similar way to ours. Their model is applied to all the landscapes of the peninsula but it can not be accurate in the moraines of the LIA because it is necessary to integrate the time factor in the analysis. In the moraine, plant colonization has rhythms and levels of development which are not the same as those in the old stable areas.

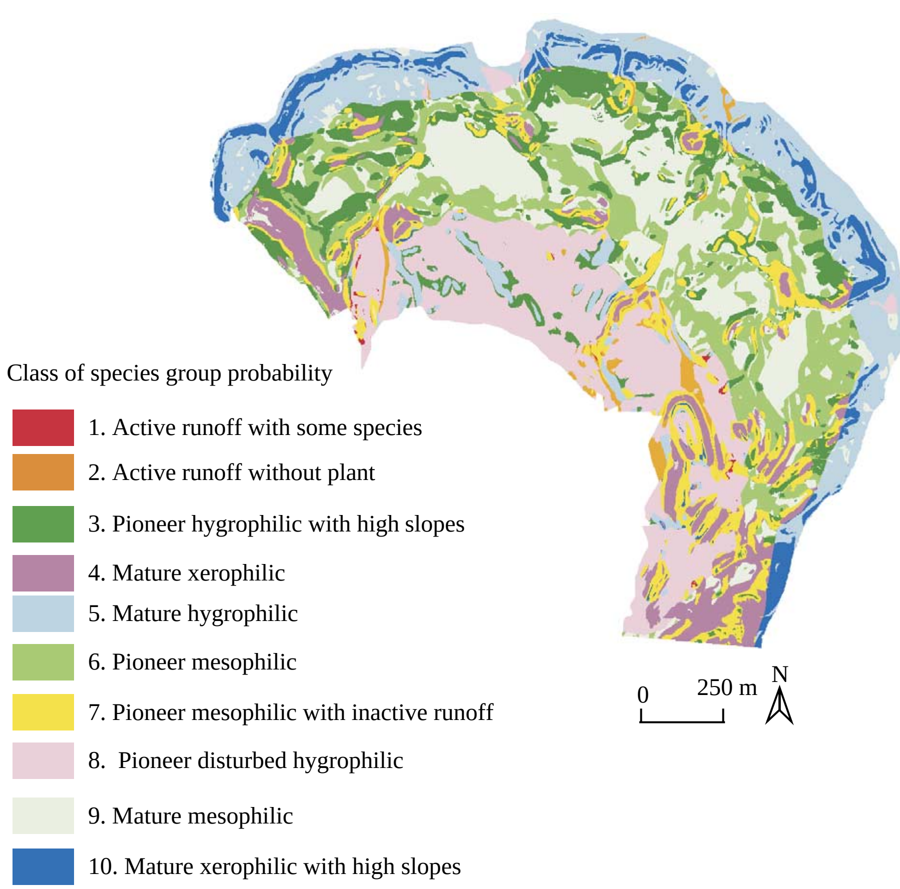

Fig. 8. Vegetation map of the Midre Lovénbreen fore field showing the 10 final classes.

4.1. The vegetation types

Old tundra outside of moraine is considered as equilibrium vegetation type on that part of Spitsbergen. A systematic approach of plant distribution might reveal how the vegetation adjustment to environment has worked during this last century. The result of the CFA are shown in Fig. 7 and indicates that runoff has the most influence in species occurrence, and hence community development (first axis) and that time since deglaciation had the second most influence on community development. Between the limits of each axis, the different levels of community development can be seen. Along the first axis, runoff can be demarcated into three intensities: active, intermittent and inactive. Landscapes dominated by stony ground, are typically devoid of plants but gradually increases in abundance as runoff becomes less of an influence. On the more stable moraines mature species groups with *Carex nardina*, *Polygonum viviparum* occur. Along the second axis, the age of the moraines can be distinguished into three temporal periods: deglaciated for less than 30 years, deglaciated for 30 to 70 years, and those areas deglaciated for more the 70 years.

The young moraines, deglaciated for less than 30 years, are characterized by pioneer species in small abundance and include *Salix polaris*. On the older, more stable moraines, similar species as those occurring on areas of no runoff are found, such as *Polygonum viviparum*.

The third axis of the graph shows species patterns in relationship to wet or dry environmental conditions which modify some of the species groups such as the inclusion of hygrophilic species (*Cochlearia officinalis*), mesophilic species (*Saxifraga cespitosa*) and xerophilic species (*Arenaria pseudofrigida*). Other variables relating to topography, wind exposure and slope were also importance, but to a lesser degree.

Thematic interpretation of the factorial space provides a better understanding of the primary variables contributing to community development in this proglacial environment. The length of deglaciation and runoff dynamics appear to be the most important variables, but wind exposure, slope and edaphic condition also have an influence on the landscape dynamics. Slopes of 0° to 2° are associated with more moist conditions, while those greater than 10° are associated with xerophilic conditions. In addition, windward sites are associated generally with dry conditions and conversely the leeward slope with the moist conditions.

4.2. The vegetation map

Thirteen vegetation classes were mapped for the foreland of Midre Lovénbreen, which were combined into 10 final classes, which clearly show three concentric rings relating to the three temporal periods of moraine age identified in the factorial analysis.

Moraine age appears to be the fundamental parameter affecting topography and vegetation (Fig. 8). On moraines more than 70 years old, two floristic groups can be distinguished, each occurring on different slopes. On the highest slopes (>10°), we have a high probability of finding xeric species, such as *Arenaria pseudofrigida*, occurring in dry environment (class 10). On lower slopes characterized by flat ground or with slopes of less than 10° there is a high probability of observing plant communities containing mesic species (such as *Carex nardina* or *Cetraria delisei*) representing most edaphic conditions (class 5).

Similar types of floristic groups can be seen on moraines 30 to 70 years of age. Areas characterized by low leeward slopes have a high probability of being colonized by pioneer species such as *Salix polaris* and *Saxifraga oppositifolia* (class 6). Class 9 is similar to class 6, but is less affected by runoff and characterized by *Cetraria delisei* and *Polygonum viviparum*. For moraines less than 30 years of age, pioneering hygrophilous species such as *Cochlearia officinalis* and *Poa abbreviata* are found (class 8). It is interesting to note that class 8, which is typical of pioneer stages, is also present in the highest moraines (Fig. 8). The probability of finding this class in an older aged area is due to the runoff dynamics that move deposits resulting in pioneer stage vegetation. Class 7, shown in the different concentric rings is also affected by runoff with the resulting vegetation remaining at a juvenile stage with a high probability of finding pioneer species such as *Sagina nivalis* or *Braya purpurascens*.

5. Conclusion

Air photos and satellite images are not well adapted to describe in detail partially vegetated landscapes dominated by mineral surface such as those found in sparsely vegetated moraines recently exposed since the end of the LIA. To adequately map these types of environments, it is necessary to add other environmental variables to obtain a proper model of plant colonization.

In this study, we found that it was important to combine a number of different variables, environmental and radiometric, complimented by a high resolution DEM and accurate field data points. The use of a GPS also offered the ability to measure in detail, the geospatial location of micro-topographic parameters such as wind exposure and ground temperature. These variables along with Bayesian analysis provided an interesting solution to show significant links between in situ field observations (for example, botanical descriptions of existing plant communities) and high resolution image data and other environmental variables. In addition, this probability approach offers the potential to produce thematic maps that show the dynamics of existing vegetation in relationship to the geomorphic features of the area.

It should be noted however, that there are two shortcomings to this method. First, if there is not a significant amount of environmental data points (either as grided thematic data or randomly sampled point data), the outcome may be limited. The incorporation of high-resolution radar images, however, may offer very interesting possibilities, especially in the production of high spatial and resolution DEM's and magnitude images, and the additional possibility of mapping ground water and ice lenses. Secondly, the sampling methods used to define the number and location of the field observations may not be robust enough to obtain a sufficiently sized sample of all the potential variability that existed in the study area. Although the methodology was statistically valid, it was, as is the case in most studies, based on an a priori knowledge in hindsight, and is perhaps the underlying foundation of statistical theory in general because of its commonality to all projects.

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