



## Succession of vascular plants in front of retreating glaciers in central Spitsbergen

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**Abstract:** Vegetation succession in front of five retreating glaciers was studied using phytosociological relevés (60) located at different distances between the Little Ice Age (LIA) moraines and the present glacier fronts around Petunia Bay. Approximate dating of succession stages was based on a study of the changing position of glacier fronts in the past approximately 100 years. The described succession corresponds to the uni-directional, non-replacement model of succession. All constituent species, except one, present in the nearby old tundra have colonized the glacier forelands since the end of the LIA. The first species appeared about 5 years after deglaciation. The latest succession stages closely resemble the old tundra.

Key words: Arctic, Svalbard, climate warming, glacier forelands, vegetation succession.

### Introduction

Vegetation succession in front of retreating glaciers has been rather frequently studied in the case of both alpine and arctic glaciers (Matthews 2008). Any new case study can contribute to deepening our knowledge about the responses of both glaciers themselves and vegetation to ongoing climate change (Parmesan 2006; Thuiller *et al.* 2008). Many detailed mechanisms and processes of plant succession and relations to environmental factors are not yet known (Walker and del Moral 2003).

Succession in glacier forelands is a typical primary succession where we cannot expect any relevant biotic legacy just after melting of the ice (Walker and del Moral 2003). Thus, the newly exposed terrain is available for colonization from

outside. The rate of colonization varies greatly and can be generally expected to be slower with increasing extremity of a site in terms of the character of the exposed substratum and the external environment, especially climate (Matthews 2008). Distance to and the character of the surrounding vegetation also play important roles; see, for example Bullock *et al.* (2002) and Jones and del Moral (2009) for glaciers; del Moral and Erin (2004) and Řehounková and Prach (2006) in general.

Classical studies on vegetation succession in front of retreating glaciers were especially intense in Alaska (*e.g.* Cooper 1939; Boggs *et al.* 2010), the Alps (*e.g.* Burga *et al.* 2010; Erschbamer *et al.* 2008) and the Scandinavian Mountains (*e.g.* Matthews and Whittaker 1987). In Svalbard, several studies were performed in the northwestern part near Ny-Ålesund (*e.g.* Hodkinson *et al.* 2003; Moreau *et al.* 2009; Nakatsubo *et al.* 2011), the central-western near Longyearbyen (Ziaja and Dubiel 1996), the southwestern part (Olech *et al.* 2011) and in southeastern Svalbard (Ziaja *et al.* 2009). Around Petunia Bay, where our study was performed, detailed data exist on the rate of glaciers retreat (Rachlewicz *et al.* 2007). That study served as the basis for dating the respective succession stages described here. The retreat of these glaciers started with the end of the LIA about the beginning of the 20<sup>th</sup> century (Rachlewicz *et al.* 2007).

In the recent study, we addressed the following questions: How fast is the newly exposed terrain colonized by plants? Which species of the local flora participate and which not? Is any species turnover obvious? How do the late succession stages differ in species composition from that of permanent (old) tundra which existed in front of foreland moraines in the time of the LIA?

## Material and methods

**Site description and data collection.** — Vegetation was sampled in front of five main glaciers terminating on land around Petunia Bay (central Spitsbergen, Svalbard): Ferdinand, Sven, Hørbye, Ragnar and Ebba (Fig. 1). The particular glaciers and their marginal zones were described by Rachlewicz *et al.* (2007). Vegetation samples (phytosociological relevés) were located at different distances between the LIA moraines and the present glacier fronts, avoiding sites obviously additionally eroded, flooded or buried with sediments from streams or landslides, being homogenous in their substratum and geomorphology and nearly flat (up to a slope of 20°). The coordinates of the central point of phytosociological relevés (5×5 m) were recorded by GPS with an accuracy up to 3 m. The cover of each presented vascular plant species was estimated visually (Kent and Coker 1992). Five phytosociological relevés were taken in the nearby old tundra. Altogether, 60 phytosociological relevés were studied. Nomenclature of vascular plants follows Rønning (1996).

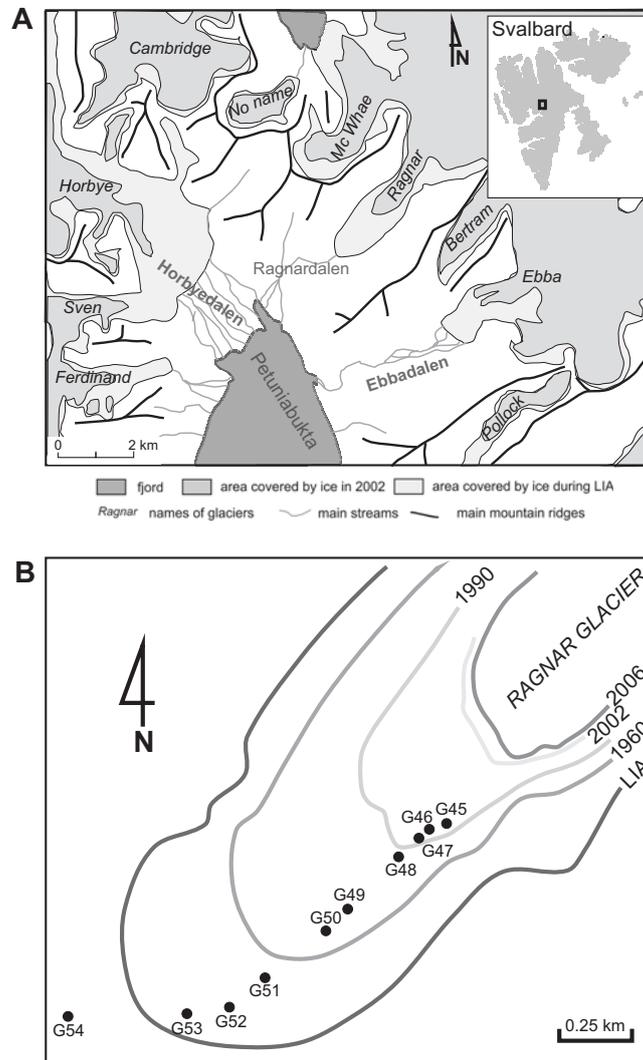


Fig. 1. Location of the studied glacial forelands around Petunia Bay (A), central Svalbard (the inset map) and detailed situation in one of the forelands of the Ragnar Glacier (B), with positions of the glacier front at different times (from Rachlewicz *et al.* 2007) and location of vegetation records (relevés).

**Data elaboration.** — Seven zones in each of the studied glacial forelands were delimited according to Rachlewicz *et al.* (2007). The approximate age of the respective succession stages was related to the year of vegetation data collection as listed below.

Inside each zone, the particular succession stages which were sampled were approximately dated regarding their positions inside the zone, assuming a constant rate of glacial front retreat. Thus, the succession age must be considered as only approximate estimates.

(I) The zone deglaciated since 2007, *i.e.* between the present and 2007 positions of the glaciers. This zone was always without vegetation, thus it was not considered further in the analyses.

(II) The zone deglaciated between 2002 and 2007 (5 years).

(III) The zone deglaciated between 1990 and 2002 (15 years).

(IV) The zone deglaciated between 1960 and 1990 (35 years).

(V) The zone deglaciated between the beginning of the 20th century and 1960 (75 years). On aerial pictures from 1936, the terminal positions of the glaciers were still near the LIA border.

(VI) The zone just on the LIA moraine dated to the beginning of the 20th century (100 years).

(VII) Nearest old tundra arbitrarily dated as 200 years old.

Detrended Correspondence Analysis (DCA) was used for data elaboration as a unimodal, unconstrained ordination technique (Ter Braak and Šmilauer 2002). The constrained Canonical Correspondence Analysis (CCA) was used to test the effect of succession age on species composition. The length of the gradient (3.38 SD-units) justified using unimodal methods (Lepš and Šmilauer 2003).

## Results

In total, 32 species of vascular plants were recorded, but only nine species attained >5% cover and just half of the species (16) had cover values <1% (Table 1).

Results of the DCA ordination are presented in Fig. 2. The samples were clearly arranged along the first axis (eigenvalue 0.765) which reflects their succession age. Age explained 19.5% of the vegetation variability in the CCA ordination. The highest vegetation heterogeneity between sites is seen among the youngest stages and then convergence is evident. The second axis (eigenvalue 0.330) is not interpretable by any environmental gradient. Succession is clearly unidirectional.

Constituent species were arranged from those being typical for initial and young succession stages on the left side of the diagram in Fig. 2 to those characterizing late succession stages and old tundra on the right side. The only species that occurred only in the old tundra and not in the succession stages was *Cassiope tetragona*.

The species sequence roughly corresponds to the time of the maximum occurrence of a species in the succession sequence. *Saxifraga oppositifolia* was often the first colonizer, but because of its common presence also in late succession stages and old tundra, its position is fairly in the middle of the temporal gradient. The first species appeared about 5 years after deglaciation, thus the first succession stage (0–2 years after deglaciation) was without vascular plants. The latest succession stages, *i.e.* those just on the LIA moraine, were nearly identical in species composition with the nearby old tundra. Even the total cover of vascular plants was the same, reaching in both cases approximately 60%.

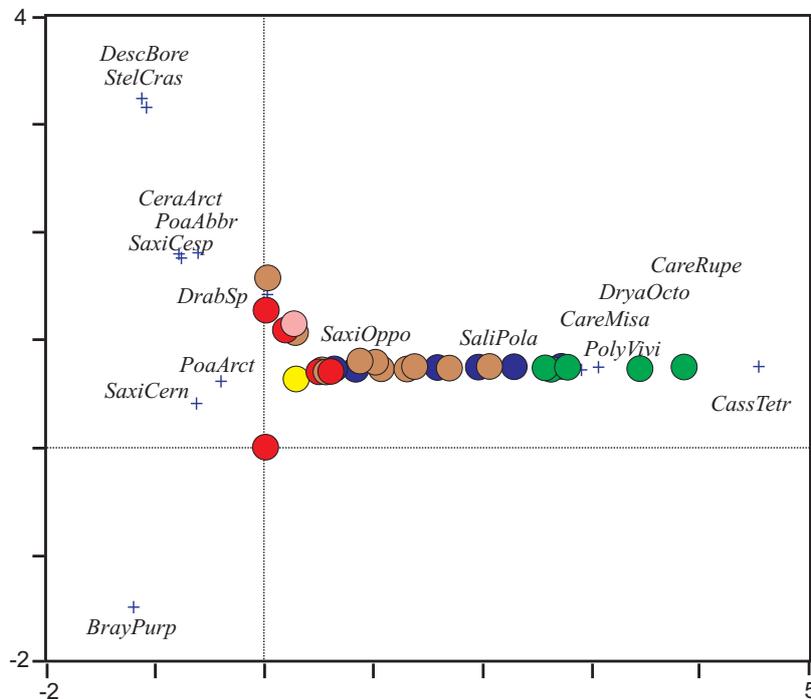


Fig. 2. Ordination (DCA) of vegetation samples and species which best fit the model. The different colours represent differently aged succession stages (average year since deglaciation is indicated): yellow – II (5 years); pink – III (15 years); red – IV (35 years); brown – V (75 years); blue – VI (100 years); green – VII (old tundra). Abbreviations of species names are composed of the first four letters of the generic and specific names (see Table 1). Due to overlaps, not all 60 relevés are visible.

The species number per relevé gradually increased during the first approximately 50 years of succession and then more or less stabilized as shown in Fig. 3, though a great variability existed. A slight decline in species number in the late succession stages is probably a stochastic artefact. The relationship between the number of species and succession age was significant.

## Discussion

The recorded succession pattern is one of the best examples of the unidirectional, non-replacement model of succession described already from the Canadian High Arctic by Svoboda and Henry (1987) and recently from Iceland by Cutler (2010). We did not observe any species turnover which is an usual feature of succession (Walker and del Moral 2003). The environmental extremity and limited local species pool, manifested in establishment failure and dispersal limitation, respectively, probably together determine the rather simple course of succession in the high Arctic glacial forelands (Jones and del Moral 2009).

Table 1  
 List of the recorded vascular plant species with their participation in the succession; + indicates cover below 1%, r indicates a negligible cover.

Species	Occurrence in succession stages	Maximum cover [%]
<i>Braya purpurascens</i>	II–VII	1
<i>Carex misandra</i>	V–VII	5
<i>Carex nardina</i>	V	r
<i>Carex rupestris</i>	VI–VII	40
<i>Cassiope tetragona</i>	VII	40
<i>Cerastium arcticum</i>	II–V	5
<i>Cerastium regeli</i>	IV–VI	+
<i>Deschampsia borealis</i>	IV, V, VII	5
<i>Draba</i> sp.	II–VII	1
<i>Dryas octopetala</i>	IV–VII	30
<i>Equisetum variegatum</i>	VI, VII	+
<i>Eutrema edwardsii</i>	VII	r
<i>Festuca vivipara</i>	VI	+
<i>Juncus biglumis</i>	V	+
<i>Minuartia biflora</i>	V	r
<i>Minuartia rubella</i>	III–VI	+
<i>Papaver dahlianum</i>	II, IV–VI	+
<i>Pedicularis dasyantha</i>	V–VII	+
<i>Poa abbreviata</i>	II–VI	1
<i>Poa alpina</i>	VI	+
<i>Poa arctica</i>	IV, VI	1
<i>Polygonum viviparum</i>	V–VII	20
<i>Salix polaris</i>	IV–VII	30
<i>Saxifraga aizoides</i>	IV–VI	+
<i>Saxifraga cernua</i>	II–V	1
<i>Saxifraga cespitosa</i>	II, IV, V	1
<i>Saxifraga oppositifolia</i>	II–VII	40
<i>Silene acaulis</i>	IV, VI, VII	+
<i>Silene apetala</i>	V	r
<i>Silene furcata</i>	IV, V	+
<i>Stellaria crassipes</i>	II–VII	1
<i>Trisetum spicatum</i>	IV	r

In studies conducted in NW Svalbard, a certain species exchange was observed (Hodkinson *et al.* 2003) or at least some early succession species decreased in their cover while some late succession species increased in sites repeatedly sampled after 30 years (Moreau *et al.* 2009). We also observed the latter trend. Al-

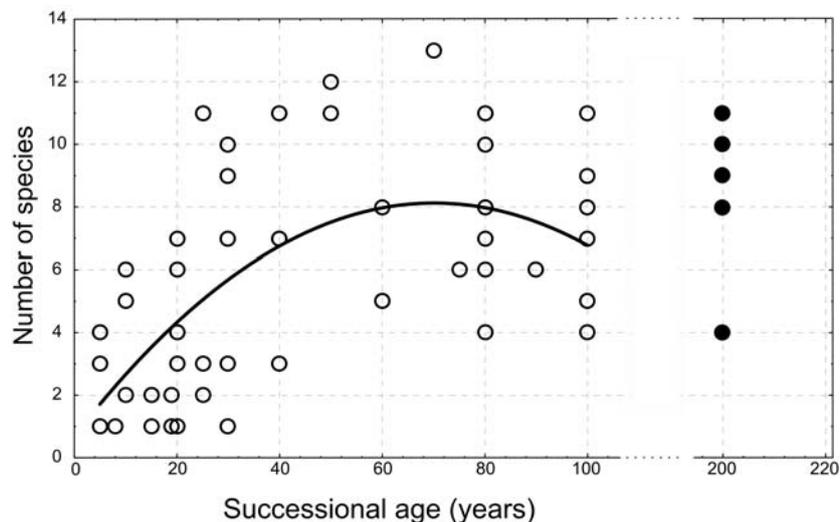


Fig. 3. Relationship between the number of species in the vegetation records and successional age (polynomial function,  $p > 0.0002$ ). Full points on the right represent old tundra samples. Due to overlaps, not all 60 relevés are visible.

though some species occurring in succession stages were not present in the reference five vegetation records from the nearby old tundra (see Table 1), they were recorded elsewhere in the old tundra (Prach *et al.* 2012 this issue). Thus, all the species which occurred in the glacial forelands also occurred in the nearby old tundra and the only species from the old tundra, which we did not observe in the glacier forelands, was *Cassiope tetragona*. This can be explained by the fact that this species is a calcifuge, while the substratum in the studied area is mostly alkaline (Elvevold *et al.* 2007). This species probably needs a sufficient organic layer to accumulate over the alkaline substratum (Acock 1940), which has not yet occurred in our case. In the study conducted in NW Svalbard (Hodkinson *et al.* 2003), *C. tetragona* colonized deglaciated sites after more than 150 years.

The most common first colonizer in our case was *Saxifraga oppositifolia* similarly as in the studies from NW Svalbard (Hodkinson *et al.* 2003; Moreau *et al.* 2005). In those studies, vascular plants represented only a minor component of ground cover for the first 100 years of succession, while cryptogams dominated. This can be attributed to the more oceanic climate than in our case, having 386 vs ca 200 mm of precipitation, respectively (Rachlewicz and Szczuciński 2008; Nakatsubo *et al.* 2010; Láska *et al.* 2012 this issue), and possibly also to the presence of some acidic substrate. Moreau *et al.* (2009) observed a very similar list of vascular plant species as we did. The authors expected a long-lasting succession towards a mature stage taking probably several thousands of years (Moreau *et al.* 2009, p. 373, fig. 7). In our case, succession seems to have nearly reached a mature stage after only approximately 100 years.

In the other parts of Svalbard, succession was only partly similar to our sequence with a higher occurrence of cryptogams in the more oceanic parts (Olech *et al.* 2011) and the absence of *Dryas octopetala* on acidic substrates (Ziaja and Dubiel 1996).

We did not observe any other interpretable gradient except time in our data set. This is probably because our study was not sufficiently detailed regarding micro-site heterogeneity. The 5 × 5 m sampling area probably encompassed different micro-sites which could not be distinguished at this scale. Usually, substrate moisture and structure play a role (Mori *et al.* 2008; Moreau *et al.* 2009). Moreover, we avoided very wet and other extreme (very inclined) sites (see above). But the environment in the studied glacial forelands, as well as in the whole area around Petunia Bay and the respective vegetation, were generally highly uniform (Prach *et al.* 2012 this issue). Thus, the succession trajectory was also uniform in contrast to some other studies conducted in glacial forelands in less extreme geographical areas (*e.g.* Doležal *et al.* 2008; Garibotti *et al.* 2011).

Succession in glacial forelands is in any case the fastest vegetation change we can nowadays observe in Svalbard, and the only obvious one which can be related to climate warming. Average annual temperature increased about 1.8°C between 1912 and 2002 at the airport in Longyearbyen some 60 km south-west of the area studied (Karlén 2005), with some temperature maxima just in the past several years (Láška *et al.* 2012 this issue). Thus, also the melting of glaciers is accelerating (Rachlewicz *et al.* 2007). In the case of further warming, further and faster glacial retreat can be expected, resulting in the increased occurrence of new deglaciated areas to be colonized by plants, but probably by the same species and in the same sequence, and possibly by the same rate as described here. We do not expect expansion of any non-native species, which are still very restricted in their occurrence and abundance in central Svalbard (Liška and Soldán 2004; own observations), nor species from regional hot-spots (Elvebakk 2005). The vegetation in central Svalbard still seems to be highly resistant to warming (Prach *et al.* 2010). These predictions can be confirmed or rejected by future repeated studies in the same sites.

Finally, we can answer the questions stated in the Introduction. All, except one constituent species present in the nearby old tundra colonized the glacial forelands since the end of LIA, *i.e.*, approximately during the past 100 years. The first species appeared about 5 years after deglaciation. No species turnover was observed. The latest succession stages closely resembled the old tundra.

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