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Source: Arctic, Antarctic, and Alpine Research, 36(1) : 21-32

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(2004)036[0021:ROVDTS]2.0.CO;2

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Arctic, Antarctic, and Alpine Research, Vol. 36, No. 1, 2004, pp. 21–32

Relationship of Vegetation Distribution to Soil Properties in Kärkevagge, Swedish Lapland

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Abstract

Kärkevagge, an alpine ecosystem in the subarctic, has been the subject of scientific study for half a century. We investigated the relationship of its vegetation to soil properties. At the lowest elevations, on stable portions of the landscape dominated by *Betula* and *Empetrum*, are found Spodosols developed in glacio-fluvial sediments. Cryosaprists occur in scattered bedrock depressions with bog-type vegetation. Cryofluvents are found in flood-prone areas covered by dwarf-willow thickets. Intermediate elevations have meadow-type vegetation with Cryofluvents on floodplains and on lower colluvial slopes, Cryaquents in wetter areas, and Cryorthents on steeper soliflucted slopes. Above that, on steep, west-facing *Dryas*-covered colluvial slopes, soils are Ca-rich Eutrocryepts and Haplocryolls. The highest-elevation soils are infertile with poor horizonation, despite their possible antiquity, and vegetation that is largely cryptogams. Dystrocryepts occur on more stable alpine locations; Cryorthents on soliflucted areas; and Haploturbels, with shallow permafrost, above 1400 m. Measured annual soil temperatures range from +2.4°C at a *Dryas* site to −3.4°C at 1585 m at an alpine cryptogam site. Vegetation distribution in Kärkevagge is related to climatic factors, which are controlled by elevation and landscape position, and edaphic factors, which control soil moisture and nutrient availability.

Introduction

One striking feature of arctic-alpine landscapes is the zonation of plant communities (Isard, 1986; Billings, 1987). This is particularly noteworthy in a low arctic-alpine environment such as Kärkevagge, Swedish Lapland, where elevation differences allow a wide range of plant communities to coexist in a small area. The boundaries between plant communities are often abrupt and generally related to elevation. However, other factors associated with vegetation distribution under arctic-alpine conditions may be less obvious (Chapin, 1987). In particular, depth and duration of snow cover, which influence moisture and temperature, have been shown to be important variables in cold regions (Shaver et al., 1996; Stanton et al., 1994), as have soil moisture and chemistry (Isard, 1986; Knapik et al., 1973; Rune, 1953).

Kärkevagge is a glacially sculpted valley in the subarctic of Swedish Lapland (Fig. 1). It has a special scientific interest because it is the study area where Anders Rapp (1960) quantitatively determined the factors controlling local landscape denudation. Rapp also noted that soil pH, although commonly about 6.0, was as low as 2.9 in certain areas. He found that these differences had a profound effect on vegetation, which he described as primarily distributed by elevation with secondary controls by moisture and snow cover. More recently, the source of the low pH was found to be sulfuric acid produced by oxidation of pyrite found in some local rock units (Darmody et al., 2001, 2002). These findings come from a concentrated research effort into weathering and soil development in the valley (Schlyter et al., 1993; Thorn et al., 1999, 2001, 2002a, 2002b; Darmody et al., 2000a, 2000b; Allen et al., 2001; Campbell et al., 2001, 2002; Dixon et al., 2002;). Although there has been some preliminary work describing the vegetation of the valley (Klintenberg, 1995) and one published report including the total elemental composition of plants from a meadow on a colluvial slope (Darmody et al., 2001), there has been no systematic study of the edaphic and climatic factors associated with vegetation distribution in Kärkevagge. The objective of this research, therefore, was to determine the relationships of vegetation distribution in Kärkevagge to soil climatic, chemical, and physical properties.

Study Area

LOCATION AND CLIMATE OF KÄRKEVAGGE

Kärkevagge is a 5-km-long, U-shaped glacial valley trending NNW-SSE in Swedish Lapland (Fig. 1). Its southern terminus is a steep cirque-like headwall, while at the north end the floor of its mouth hangs at about 600 m a.s.l. above the much larger, west-east-trending Vassijuare valley at approximately 18°18′E, 68°26′N. The steep valley walls of Kärkevagge reveal a complex geology of essentially horizontally bedded metamorphic rocks (Kulling, 1964). Kärkevagge is in the western Abisko Mountains, a transition zone between the maritime arctic climate along the Norwegian coast, some 80 km to the west, and a more continental climate to the east (Eriksson, 1982). In general, regional precipitation decreases and seasonal temperature differences increase to the east. Annual precipitation is evenly distributed and is about 1000 mm (Rapp, 1960), although it varies with elevation. Snow, which represents about 50–75% of the precipitation, covers the region 220 to 240 d yr^{-1}. Snow depth reaches a maximum thickness of 0.75 to 1.5 m in March/April (Ångström, 1974). Mean annual air temperature recorded at a midvalley station at 760 m, was ~1.7 °C September 1995 through August 1996 (Thorn et al., 1999). The Kärkevagge region was deglaciated about 9000 to 8500 ^{14}C yr B.P. (Karlén, 1979). Through the Holocene the climate has changed from generally warm and moist, to warm and dry, to cold and moist, and the vegetation responded accordingly (Kullman, 1998; Barnekow, 2000; Barnekow and Sandgren, 2001).

Vegetation of Kärkevagge

The general distribution of major vegetation belts in the Scandinavian mountains is governed largely by latitude and elevation,

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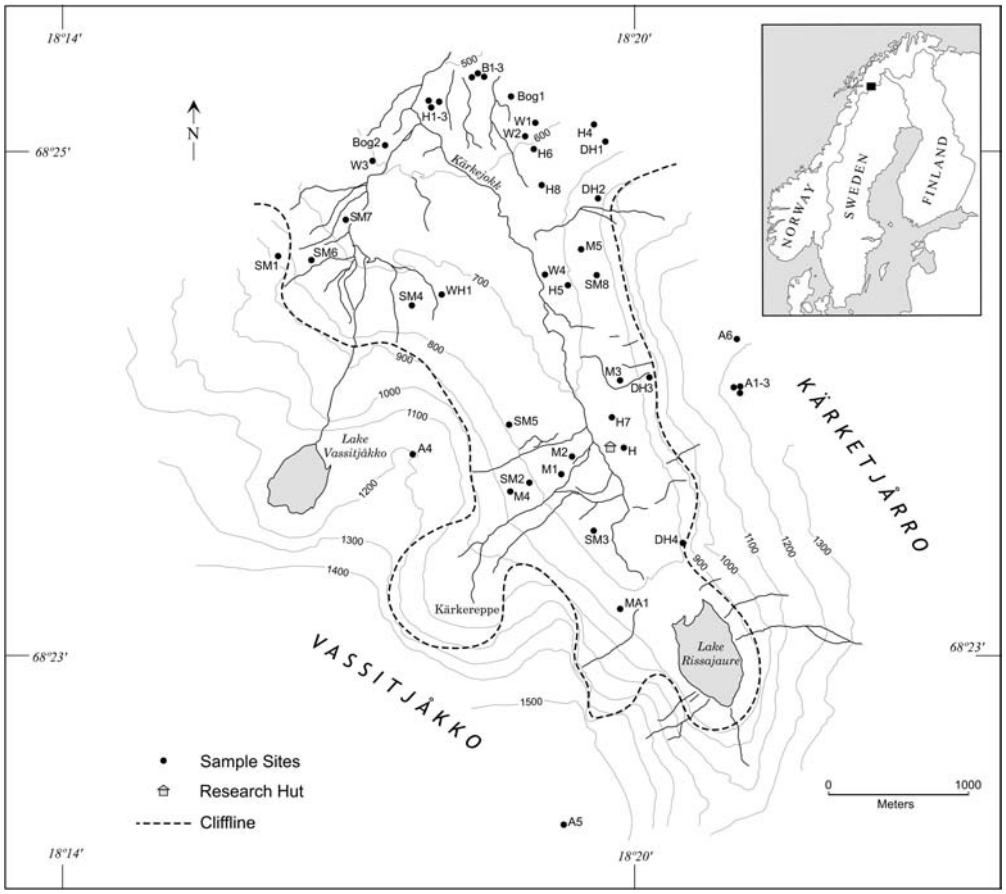


FIGURE 1. Location of Kärkevagge, Swedish Lapland showing vegetation group soil sample site locations: H, Empetrum *heath; B, birch; Bog, bog vegetation; W, willow; DH,* Dryas *heath; M, Meadow; A, alpine; MA, midalpine; SM, solifluction meadow; WH, wind heath. Numbers indicate replicate sites within a vegetation group.*

which are the primary controls on temperature and precipitation. At the local scale, the occurrence of a specific vegetation community type depends on, or is mediated by, edaphic conditions, depth and duration of snow cover, aspect, exposure, and human influence (Gjaerevoll, 1950, 1965; Sjörs, 1956). The vegetation in the Kärkevagge catchment is representative of the major vegetation community types in the northern Scandinavian mountains, from the treeline to barren rock on the highest parts of the watershed.

The mouth of the Kärkevagge catchment is occupied by subalpine mountain birch forest (*Betula pubescens* ssp. *tortuosa* [Ledeb.] Nyman), and the local forest limit is at an altitude of about 530 m a.s.l. Isolated birch trees occur up to 580 m along Kärkejokka, the main stream draining the valley. Treeline has moved upward during recent years, which may in part be an effect of climate amelioration. However, human activity has clearly affected the forest distribution both through previous forms of reindeer husbandry in the area (Emanuelsson, 1987) and from tree cutting during the building of the Kiruna-Narvik railway at the turn of the previous century (Schlyter et al., 1993). The birch forest is luxurious with an undergrowth of meadow-type vegetation that includes *Geranium sylvaticum* L., *Lactuca alpina* L., *Ranunculus platanifolius* L., *Angelica archangelica* L., and *Trollius europaeus* L. along with various *Salix* species, e.g., *S. caprea* L., *S. glauca* L., *S. lanata* L., and *S. lapponum* L. At slightly higher elevations, and at more exposed and well-drained sites, the birch forest grades into heath with typical species such as *Empetrum hermaphroditum* Hagerup, *Vaccinium vitis-idaea* L., *Betula nana* L., and scattered *Juniperus communis* L. Also in this zone *Vaccinium myrtillus* L. is found in more sheltered positions with better snow protection.

The low-alpine vegetation belt is composed of heath, meadow, and willow communities. In Kärkevagge, it ranges from 980 m a.s.l. in shaded areas of the southern parts of the valley to 1100 m on the west-facing slope. The development of the heaths is governed by wind exposure, snow cover, and water availability. Exposed, windy sites with poor snow cover have an incomplete vegetation cover that includes stunted *E. hermaphroditum*, *Diapensia lapponica* L., and *Saxifraga oppositifolia* L. The more continuous vegetation cover on less exposed, dry sites is dominated by *E. hermaphroditum*, *V. vitis-idaea*, and *V. myrtillus*. On more moist sites, *B. nana* and *Salix* sp. become more abundant. In wetter areas in the lower parts of the low-alpine belt, *Salix* dominates, where low- and medium-height species *S. lanata*, *S. lapponum*, and *S. glauca* form thickets.

Alpine meadows are common in the low-alpine belt in areas with extensive snow cover. Large belts of low-herb meadows occur in Kärkevagge above the heaths and in sheltered positions with sufficient snow cover in the heath areas, i.e., along smaller streams and other topographically favored places. Common species are *Viola biflora* L., *Alchemilla alpina* L., *Polygonum viviparum* (L.) Gray, *Oxyria digyna* (L.) Hill, *Ranunculus acris* L., *Festuca ovina* L., *Phleum alpinum* L., *Deschampsia flexuosa* (L.) Trin., and *Carex bigelowii* Torr. Ex Schwein. At well-drained and climatically favorable sites, tall-herb meadow vegetation may develop with typical species such as *Angelica archangelica*, *Geranium sylvaticum*, *Melandrium rubrum* (Weigel) Garcke, *Trollius europaeus*, and *Myosotis decumbens* Host. The influence of more base-rich lithologies is evident in the meadow flora on the eastern slopes of the valley as evidenced by the presence of *Dryas octopetala* L., *Salix reticulata* L., *Saussurea alpina* (L.) DC., *Parnassia palustris* L., and *Silene acaulis* (L.) Jacq. At better-drained

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sites this vegetation grades into a *Dryas* heath community typical of calcareous soils, which shares a large stock of species with base-rich meadow communities.

The meadows at the western side of Kärkevagge are more moist, solifluction is more pronounced, and snow patches more numerous and extensive, as compared with the eastern side, owing to a greater deposition of snow controlled by dominating winter westerly winds. Snow cover exerts a strong influence on vegetation patterns. Where snow cover duration is longer, snow-patch vegetation is present but includes meadow species such as *Viola biflora* and *Oxyria digyna*. Typical snow-patch vegetation is very species poor and dominated by *Salix herbacea* L. and *S. polaris* Wahlenb., together with species such as *Cassiope hypnoides* (L.) D. Don, *Gnaphalium supinum* L., and *Veronica alpina* L. that can cope with the very short growing period. Extensive areas of snow-patch vegetation occur at lower elevations on the western side of the valley than on the east side. Where snow cover is more extended, snow-patch vegetation becomes very sparse and species poor. *Salix polaris* and a few moss and lichen species dominate the vegetation of the most long-lived snow patches.

At the highest elevations on thin soils, regolith, or coarser rock rubble substrate, plant cover is minimal with only a limited number of higher plant species represented, e.g., *Ranunculus glacialis* L. and *Luzula arcuata* (Wahlenb.) Sw. Cryptogams, i.e., mosses and lichens, are found at the highest and most exposed sites.

Methods and Materials

FIELD METHODOLOGY

Sites were selected to represent most of the common vegetation community types in the valley (Klintenberg, 1995) on typical geomorphic surfaces (Fig. 1). Soil pits were excavated by hand to 1.5 m or until the water table or immovable rock was encountered. Soils were examined and described in the field using standard techniques (Soil Survey Staff, 1993), and the soils were sampled by horizon. In total, 42 soil pits were sampled from 10 vegetation community types, and 227 soil samples were retrieved for later analyses (Darmody et al., 2000a). Two of the vegetation types, referred to as "wind heath" (WH), a stunted *Empetrum* community, and "midalpine" (MA), an alpine-meadow transitional community, were not replicated. Therefore, they were excluded from the statistical analyses and will only be discussed in passing.

Soil temperature was monitored at 11 selected sites by means of miniature loggers buried at 10 cm that recorded temperatures 4 times daily for 1 yr in 1995–1996 (Thorn et al., 1999). Air temperature was recorded at the research hut in the center of the valley at 760 m a.s.l. (Thorn et al., 1999). Growing degree days were calculated as the annual sum of the degrees exceeding a reference temperature of 0, 0.5, 5, or 10°C, but no upper limit was applied (Maxwell, 1992). Isothermal days were computed as the sum of days when the soil temperature was 0 ± 0.5°C.

Lab Methodology

The soils were oven-dried in the lab and passed through a 10-mesh sieve to isolate the <2-mm fraction, which was saved for further analysis. Particle-size analysis was by sieving for sands and by hydrometer for silt and clay (Gee and Bauder, 1986). A 1:1 soil to distilled water suspension was used to determine pH (McLean, 1982). Extractable elements were determined by inductively coupled plasma spectroscopy on 1:10 soil : Mehlich 3 extracts (0.2N CH_3COOH + 0.25N NH_4NO_3 + 0.013N HNO_3 + 0.015N NH_4F + 0.001M EDTA) (Mehlich, 1984). Cation exchange capacity (CEC) was estimated by summation of Mehlich 3 extracted cations. Base saturation (BS) was determined using exchangeable H estimated from SMP buffer pH at pH 7.8 (McLean, 1982). Organic carbon content was determined with a Leco C analyzer; as there were no free carbonates in the soil, total C was attributed to organic matter. Total N was determined with a Kjeldahl digestion followed by detection of ammonia using a Lachat Flow Injection Analyzer. Statistical evaluations were done at the $\alpha = 0.05$ level using Sigma Stat statistical software (SPSS Inc., Chicago, IL). Statistical tests included ANOVA on means or ranks followed by pairwise multiple comparison procedures by SNK or by Dunn's method, as appropriate.

Results

PHYSICAL PROPERTIES

Our findings are consistent with generalized descriptions of vegetation zonation in the watershed (Rapp, 1960; Klintenberg, 1995), where elevation is the primary controlling factor (Table 1). Slope gradients ranged up to 78% and were steepest on the colluvial slopes, which were covered with *Dryas* and meadow vegetation types. Bog-type vegetation was confined to semiclosed bedrock depressions, which had the lowest slope gradients, 1 to 4%. Willow-type vegetation was primarily confined to wetter areas, such as along the floodplains, and consequently had low slope gradients, 1 to 14%. Soil texture was generally coarse, with clay contents nowhere exceeding 7%. Coarse fragment contents were great, typically ranging from 10 to 66% by volume (Darmody et al., 2000a). Consequently, particle size families were coarse-loamy to sandy-skeletal (Soil Survey Staff, 1999). The coarsest-textured soils were found at the wind heath and *Empetrum* heath sites and at one willow site. Low clay content and high coarse-fragment contents make for poor soil moisture storage and, together with landscape position, dictate soil drainage and plant available water. Bog vegetation was confined to ponded sites. At the other moisture storage extreme, *Empetrum* heath was largely confined to the excessively drained soils formed from coarse outwash deposits on kame terraces and eskers, or on the tops of the large boulders that litter the valley floor and gives it its name. Vegetation community types in order of decreasing wetness were bog, willow, solifluction meadow, meadow, midalpine meadow, alpine, birch, *Dryas*, *Empetrum*, and wind heath.

Soil classification was not universally well correlated with vegetation community types as used in this study (Soil Survey Staff, 1999). This reflects the edaphic effects of small-scale topography on microclimate, snow cover, and hydrology as well as landscape history and dynamics. However, some general associations were identified. Bogs were associated exclusively with Cryosaprists, highest-elevation alpine sites with Haploturbels, *Dryas* sites with Eutrocryepts and Haplocryolls, and birch and *Empetrum* sites at the lower elevations with Haplocryods (Table 1). As Rapp (1960) noted, the best-developed soils in the valley, those showing the most contrasting horizons, were found at the lowest elevations under birch and *Empetrum*. These vegetation types are the most vigorous in the area, with abundant above-ground biomass, and they produce organic acids that promote soil profile development. The well-developed soils also suggest that these landscape positions are stable, as opposed to most other locations in the valley that show evidence of instability. The unstable landscape positions include floodplains and colluvial and soliflucted slopes. At these locations the soils are Cryorthents or Cryofluvents with buried soils that indicate mass movement, solifluction, erosion, or deposition.

Chemical Properties

Despite Kärkevagge's relatively small geographical area, its soils exhibit a wide range of chemical properties (Table 2). Measured

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TABLE 1

Generalized site characteristics of vegetation community/geomorphic sampling sites in Kärkevagge

Vegetation type/location	Elevation range (m)	Slope range (%)	Landforms	Soil drainage	Parent materials	Soil texture family*	Soil classification*
Alpine	1190–1590	3–26	mountain and ridge tops and highest valley side slopes	moderately well to somewhat poorly	residuum and colluvium from schist	Coarse-loamy	Typic and Oxyaquic Dystrocryepts, Cryorthents, and Lithic Haploturbels
Birch	500–550	17–26	moraines at valley mouth	well	glacial till	Coarse-loamy	Typic Haplocryods
Bog	550–600	1–4	bedrock depressions near valley mouth	very poorly/ponded	peat	—	Lithic Cryosaprists
Dryas	650–880	10–78	upper valley side slopes	well to moderately well	colluvium	Coarse-loamy/ Sandy-skeletal	Typic Cryorthents, Eutrocryepts, and Haplocryolls
Empetrum	550–690	6–47	kame terraces	well to excessively	outwash	Sandy/Loamy-skeletal	Typic Haplocryods
Midalpine + meadow	720–850	5–31	valley side slopes, mostly east side, upper floodplains	well to moderately well to poorly in floodplains	colluvium/alluvium	Coarse-loamy	Typic Cryofluvents, Cryothents, and Cryaquents
Solifluction meadow	680–870	12–45	lower valley side slopes, mostly west side	somewhat poorly to poorly	colluvium/alluvium	Coarse-loamy	Aquic and Oxyaquic Cryorthents
Willow	600–650	1–14	lower floodplains and cascades	moderately well to somewhat poorly	alluvium	Coarse-loamy/ Sandy-skeletal	Typic and Oxyaquic Cryofluvents

*Soil Survey Staff, 1999, Darmody et al., 2000a.

pH ranged from a high of 8.2 to a low of 3.5. High-pH soils were associated with high extractable Ca content, which was the most variable parameter measured, ranging from 30–5010 ppm. The Ca is derived from weathering of localized calcareous rocks (Campbell et al., 2001). Likewise, the macronutrient K is generally abundant throughout the area due to the prevalence of micaceous schists; its content ranges from 4–303 ppm. Another potentially important nutrient derived from local rocks is S, which ranged from 15–180 ppm and may originate, in part, through pyrite weathering (Darmody et al., 2001). One floodplain site, W4, produced enough H_2S to smell of rotten eggs (Darmody and Fanning, 1977). Phosphorus and N are generally considered the most limiting plant nutrients in the subarctic (Jonasson and Michelsen, 1996). In Kärkevagge, extractable P content ranged from 6 to 107 ppm. The source is presumably apatite in the bedrock. The other macronutrient, N, ranged from 0.04 to 2.1% in the surface soil samples. It was closely related ($R^2 = 0.89$, $n = 40$) to the soil organic carbon content, which ranged from 0.1 to 48% in all the samples, with the highest organic matter contents in the surface A and O horizons (Table 2). Plotting the distribution with depth of measured soil parameters shows the importance of bioaccumulation of nutrients in the soil organic matter at the soil surface. The surface O and A horizons were higher in CEC, organic C, S, P, Ca, Mg, K, Mn, Cu, and Zn than the subsurface horizons (Figs. 2–6).

When surface soil fertility parameters are evaluated over the vegetation groups, some general patterns emerge (Table 3). The bog and *Empetrum* heath soils had statistically the highest amounts of both C and N and the alpine soils the lowest. However, the C/N ratio did not follow the same pattern. The highest C/N ratio, 33, was in the *Empetrum* heath soils, but a statistically indistinguishable C/N ratio, 31, was found in the soil with the lowest organic C content, the alpine soil. This high ratio indicates that the organic matter is resistant to decomposition in both situations, but production of organic matter is enhanced in the *Empetrum* soils and inhibited in the alpine soils.

Extractable P and K contents in the surface soils, along with S, did not vary by vegetative group. In contrast, the important element Ca showed strong associations with vegetative groups; it was greatest in the *Dryas*, meadow, solifluction meadow, and willow sites. The *Dryas* sites are on the upper slopes below the cliffs where calcareous rocks are exposed. Other high-Ca sites are on stream courses where Ca-rich waters are common (Campbell et al., 2001), or below the *Dryas* sites on the colluvial slopes. In contrast, the alpine sites had the lowest measured Ca as well as the lowest Mg content. These sites are on the ridge crests, stratigraphically above the calcareous rock and, in addition, may be the most leached due to their antiquity (Allen et al., 2001). Both pH and base saturation tend to follow the Ca content and are statistically related to it ($R^2 = 0.84$ and 0.81, respectively; $n = 46$ for both). The highest surface horizon pH was with the *Dryas* soils and the lowest were with the alpine, birch, and *Empetrum* heath soils. The low pH in the birch and heath soils was reflected in the strong podzolization that these soils showed. As would be expected, the base saturation trends followed soil pH, with the highest base saturation in the *Dryas* soils and the lowest in the alpine soils. Cation exchange capacity showed similar trends and was strongly correlated ($R^2 = 0.77$, $n = 46$) with Ca content. Extractable Al followed trends generally opposite to pH and Ca: it was lowest in the *Dryas* soils and highest in the alpine soils. Most micronutrients did not show an association with vegetation groups, although the meadow sites were highest in Fe and Cu, and B was highest in the *Dryas* soils.

When grouped by drainage class, the poorly drained soils tended to have higher levels of the parameters measured (Table 3). These include pH, base saturation, Ca, Mg, and B. This is probably due to the conveyance of Ca and other nutrients to the poorly drained sites in ground and surface water. Many ephemeral streams that feed the wet locations in the landscape are charged with nutrients, particularly Ca (Darmody et al., 2000b; Campbell et al., 2001). Organic C was not different between the two drainage groups, due to the high amount of organic C accumulated both in the poorly drained bog soils and in the well-drained heath soils. However, the C/N ratio was higher, 28, in the well-drained soils than in the poorly drained soils, 17. This indicates that the organic matter in the well-drained soils is more resistant to decomposition.

Thermal Properties

At the drainage basin scale, topography, which largely controls soil moisture and most importantly soil temperature, is the dominant

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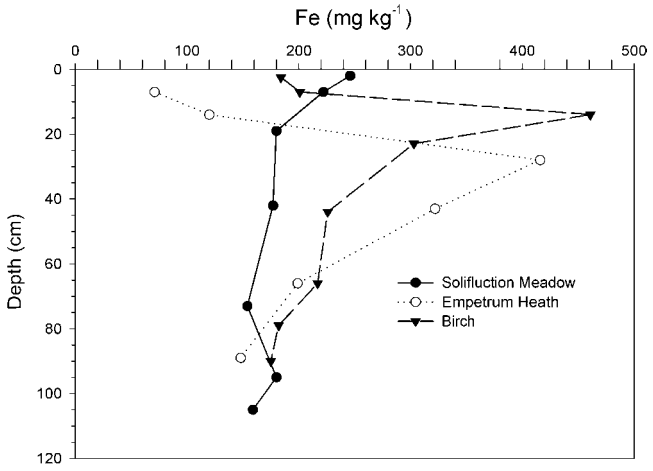


FIGURE 2. Extractable Fe contents by depth in selected solifluction meadow, Empetrum *heath, and birch soils. Note the increase in the Bs horizons of the* Empetrum *and birch soils, indicating podzolization, not seen in the soils from less stable sites such as the solifluction soils.*

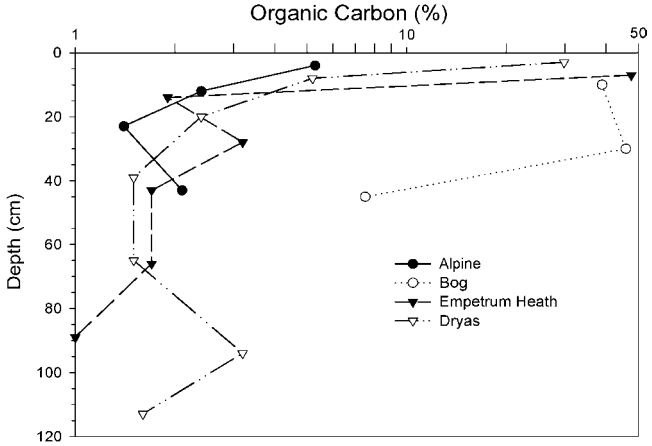


FIGURE 4. Organic carbon (OC) contents by depth in selected alpine, bog, Empetrum *heath, and* Dryas *soils. Note the overall high OC in the bog soils, in the surface of the* Empetrum *and* Dryas *soils, and in the Bs horizon of the* Empetrum *soils and the low OC in the alpine soils.*

control over plant distribution in Kärkevagge. The alpine sites, at the highest elevation, had lowest mean annual (MAT) and winter (MWT) soil temperatures (at 10 cm) as well as the lowest minimum temperatures recorded (Table 4). The other sites did not vary much in MAT, ranging from 1.2 to 2.4°C, or in MWT, ranging from a low of −1.6°C in one *Dryas* site to a high of 0.2°C in the solifluction meadow site. Mean summer temperatures (MST) overlapped somewhat, with the alpine sites coolest, ranging from 0.8 to 6.2°C, and the *Dryas* sites warmest, ranging from 7.7 to 8.0°C. Although permafrost is theoretically present in soils with MAT <0°C, which includes all the alpine sites, that special climatic situation was encountered only at site A5 at an elevation of 1590 m. Permafrost may be found at lower elevations in Swedish Lapland, particularly in organic soils where palsas are found, generally east of Abisko. However, it can be expected within 2 m of the soil surface only at elevations above 1400–1500 m in the area of Kärkevagge, according to Åkerman and Malmström (1986). Where there is evidence of permafrost within 2 m and cryoturbation, as at site A5, the soil classification is Haploturbel (Darmody et al., 2000a).

Snow cover is an important factor influencing soil temperature (Williams and Gold, 1976). It insulates the soil, keeping it cool in summer and warm in winter. The minimum air temperature we recorded was −26.6°C, but most of the soils never experienced temperatures below −2°C at the 10-cm depth where they were recorded. Snow falls in Kärkevagge before many of the soils freeze, and isothermal conditions existed for more than 250 d at 10 cm deep in the soils at the midalpine meadow, solifluction meadow, and birch sites and at one *Dryas* site. The daily mean temperature recorded at birch site 1 clearly showed the effect of a deep snow cover. The soil temperature at 10 cm never dropped below 0°C, whereas at alpine site 4, the snow cover was not sufficient to prevent the temperature dropping to −15°C (Fig. 7).

Growing degree days (GDD) are often used to assess the progress of plant growth and maturation (Maxwell, 1992). They are calculated by subtracting from the daily mean air temperature a reference threshold temperature, then summing over days, excluding degrees over a maximum threshold reference temperature. For conventional

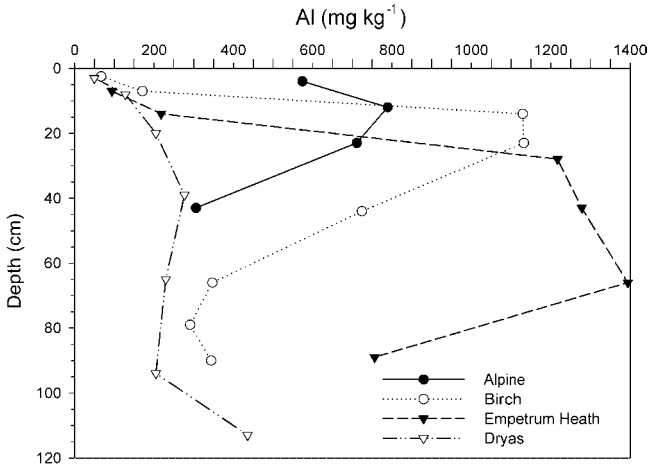


FIGURE 3. Extractable Al contents by depth in selected alpine, birch, Empetrum *heath, and* Dryas *soils. Note the increase in the Bs horizons of the* Empetrum *and birch soils and in the Bw horizon of the alpine soil, indicating podzolization, not seen in the soils from less stable sites or where Ca dominates the soil chemistry, as in the* Dryas *soils.*

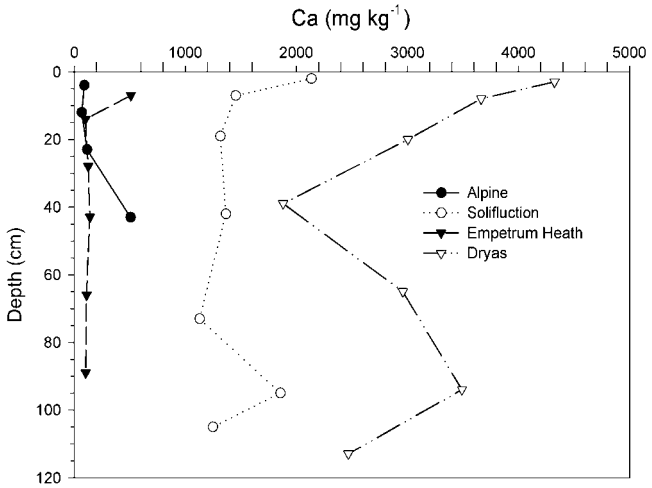


FIGURE 5. Extractable Ca contents by depth in selected alpine, solifluction meadow, Empetrum *heath, and* Dryas *soils. Trends mimic base saturation and pH. Source of Ca in these soils is calcareous rocks exposed in the cliffs of Kärkevagge.*

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TABLE 2

Range of soil fertility parameters found at the vegetation research sites

Thickness (cm)	Soil horizons	CEC (meq/100g)	pH	B.S.[b]	O.C[b]	N[b]	S[c]	P[c]	Ca[c]	Mg[c]	K[c]	Na[c]	B[c]	Fe[c]	Mn[c]	Cu[c]	Zn[c]	Al[c]
				%			Extractable (mg kg^{-1})											
Alpine (9)[a]																		
0–1	O	12.7	3.7	10	7	0.1	55	28	116	65	50	11	<0.2	187	9	2.7	2	325
1–9	A	3–19	3.6–5.0	7–41	2–8	0.1–0.4	24–93	11–67	81–336	38–78	23–95	10–15	<0.2–0.6	113–342	1–29	1.1–5.8	0.6–4.0	460–900
0–8	E	2–12	4.1–4.7	5–37	2–3	—	38–67	18–33	56–67	20–73	22–32	8–14	<0.2–0.5	130–316	<1–10	1.5–3.9	0.7–1.3	605–887
0–33	B(C)(w)(g)	1–8	4.2–5.1	9–58	1–2	—	20–55	13–37	30–154	18–98	14–40	7–31	<0.2–0.5	121–229	<1–26	1.1–5.0	0.5–2.2	505–897
0–67	C(g)(r)	2–10	4.1–5.2	10–61	0–2	—	18–30	20–82	49–507	24–196	11–51	9–39	<0.2–0.6	130–306	<1–51	1.3–8.5	0.6–6.8	306–916
37–>95	Total thickness of soil above bedrock																	
Birch (3)																		
2	Oa	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1	A	8–16	3.9–4.4	34–43	7–20	0.3–0.9	29–51	51–68	340–448	97–149	83–149	16–20	0.3–0.4	99–184	30–115	0.8–1.1	3.3–5.4	67–153
6–8	E	3–7	3.6–4.7	31–49	1–2	—	19–30	26–43	109–166	35–64	10–22	11–15	0.3–0.4	77–201	2–6	0.7–1.2	1.1–1.5	71–212
6–12	Bs1	3–6	3.9–4.7	34–49	1–2	—	30–44	11–17	141–245	23–68	10–14	12–14	0.6–0.7	340–621	4–6	0.6–1.6	0.6–1.2	668–1129
12–16	Bs2	3–5	4.3–4.6	41–47	1–3	—	42–49	17–26	99–305	28–48	8–14	12–16	0.5–0.7	236–303	5–21	1.3–2.1	0.7–1.1	613–1279
19–20	Bw1	2–7	4.7–4.8	49–51	1	—	19–29	13–26	84–378	19–97	6–23	7–19	0.3–0.6	133–334	34–45	1.3–2.0	0.8–1.6	296–826
11–35	(2)Bw2	3–6	4.6–5.1	47–58	1	—	16–24	12–21	168–415	54–85	16–24	11–17	0.3–0.5	217–264	32–119	1.3–1.5	0.7–1.1	291–500
7–25	(2)BC	4–10	4.9–5.4	53–67	1	—	15–19	12–19	236–659	66–109	21–26	13–19	0.3–0.5	175–185	28–57	1.0–1.7	0.9–2.2	281–344
>99	Total thickness of soil above bedrock																	
Bog (2)																		
20–25	Oa1	7–14	5.7	76	38–39	2.0–2.1	45–63	22–36	794–1701	109–146	18–41	11–15	0.3–0.6	75–223	2–3	1.5–2.3	1.1–1.5	350–695
20–25	Oa2	8–9	5.4–5.5	67–70	38–46	—	46–65	19–39	785–874	79–107	17–25	11–17	0.3	98–138	3–5	1.4–1.8	0.5–1.9	403
0–10	Cg	8	4.7	49	8	—	180	13	493	100	18	11	0.3	170	1	4.2	3.1	331
50–60	Total thickness of soil above bedrock																	
Dryas (4)																		
0–15	O	19–35	5.4–6.5	67–93	35–41	1.3–1.9	28–42	35–68	1892–4396	115–392	81–162	10–36	0.6–0.7	43–156	9–75	0.6–2.2	3.8–4.5	30–131
0–30	A	18–31	6.3–7.1	89–100	5–14	0.4–0.9	34–41	26–33	3112–4985	96–135	28–430	10–16	0.7–1.0	231–278	70–72	5.8–6.6	4.9–19.8	97–287
0–36	Bw	16–27	6.3–6.4	90–91	1–2	—	26–34	17–39	2349–3860	237–373	21–27	12–13	0.3–0.7	160–175	12–13	1.3–2.1	0.6–0.7	403–515
0–19	C&A[d]	16–19	7.0–7.8	100	2–4	—	30–49	9–15	3005–3513	73–95	27–33	10–14	0.6–0.7	256–333	74–161	6.6–15.0	1.2–5.5	170–277
40–72	C	5–20	6.1–8.0	86–100	1–6	—	16–46	10–38	777–3681	64–95	23–38	7–25	0.3–0.8	179–273	9–111	1.4–24.5	0.7–5.4	205–520
>120	Total thickness of soil above bedrock																	
Heath (4)[a]																		
5–18	Oi(e)	16–20	3.4–3.9	30–34	43–48	1.2–1.4	30–54	43–54	425–578	137–156	82–153	16–24	0.3–0.6	71–87	8–30	0.6–1.4	4.3–11.2	76–119
4–14	E	2–5	3.8–4.2	33–39	1–3	—	19–29	18–31	78–156	19–43	7–25	9–17	0.2–0.4	47–131	0.1–2	0.5–1.1	0.7–1.8	82–256
8–82	Bs	2–7	4.1–4.7	37–49	1–3	—	33–43	15–26	80–283	28–64	4–17	10–21	0.3–0.7	156–513	3–31	0.7–2.7	0.9–2.3	1122–1484
0–34	BC	2–3	4.5–4.8	45–51	1-2	—	25–35	17–26	69–118	23–35	6–7	9–18	0.3–0.6	158–199	35–47	1.4–2.3	1.5–2.3	792–1394
>16–>46	C	2–4	4.6–5.0	47–55	1–2	—	22–44	15–21	103–212	17–49	8–77	10–31	0.3–0.6	148–397	12–31	1.4–3.0	1.6–2.0	756–1318
>120	Total thickness of soil above bedrock																	
Meadow (5)																		
2–8	A	12–27	4.5–6.2	35–76	6–12	0.3–0.9	29–53	13–107	1159–3584	89–202	10–216	13–25	0.3–0.8	334–525	41–158	2.8–22.1	4.7–23.1	209–792
0-12	Bw	8.6	6.0	85	3	—	34	10	1213	79	20	9	0.6	276	52	18.0	8.7	524
0–76	A&C[d]	7–20	4.0–6.5	35–92	2–5	—	4–86	9–77	427–2999	37–164	14–21	10–24	0.5–0.7	225–350	21–125	3.8–12.5	1.3–4.1	299–777
>5–>45	C(g)	7–20	4.7–6.5	41–93	1–4	—	21–44	9–30	384–2177	62–120	13–26	9–25	0.5–0.7	125–412	6–192	1.1–14.5	0.8–4.8	191–765
>95	Total thickness of soil above bedrock																	

TABLE 2
(CONT.)

Solifluction Meadow (8)																	
0–12	O(e)(a)	15–32	5.4–6.3	67–89	22–41	1.4–1.7	28–49	47–84	1971–3544	161–252	82–266	12–26	0.6–0.8	41–238	26–171	1.0–5.6	5.8–20.1	34–399
0–5	A	18–27	4.3–5.7	41–76	3–9	0.1–0.6	31–69	32–66	754–2416	102–180	24–59	12–46	0.6–0.7	218–371	34–228	4.6–1.7	1.6–6.1	311–530
7–153	C&A[d]	10–41	4.5–6.2	45–88	1–18	—	21–57	11–100	655–4116	73–211	13–31	7–33	0.3–0.7	135–377	8–95	1.4–7.4	0.7–1.9	373–805
>10–>90	C	5–18	4.5–6.4	45–91	0–1	—	18–43	8–46	305–1524	44–212	14–39	9–33	0.3–0.6	129–278	9–84	1.0–4.2	0.9–2.5	359–941
>160	Total thickness of soil above bedrock																	
Willow (4)																		
0–3	Oe	25	6.2	88	35	1.9	54	85	3418	371	303	18	0.6	130	56	2.3	16.7	105
0–7	A	15–23	4.8–5.5	51–70	3–10	0.2–1.0	38–48	29–99	1070–1939	125–216	35–127	11–17	0.6–.07	180–369	17–37	1.6–5.8	2.0–4.2	250–574
0–42	C&A[d]	8–39	4.4–5.9	43–82	2–28	—	32–64	11–42	540–5010	71–489	11–94	10–20	0.5–0.7	161–504	2–37	1.2–7.3	0.7–2.7	225–752
>40–>80	C	3–22	4.8–6.4	51–91	1–6	—	18–35	6–59	202–2994	34–344	10–31	11–16	0.3–0.6	62–418	0.5–43	0.7–3.4	0.5–2.4	235–684
>100	Total thickness of soil above bedrock																	

[a] ( ) Number of sites sampled. Not all horizons listed were found at each site.
[b] Base saturation, total organic carbon, and total N (%).
[c] Mehlich 3 (Mehlich, 1984) extractable elements (mg kg^{-1}).
[d] Includes buried thin A and/or O horizons.

FIGURE 6. Extractable P contents by depth in selected alpine, Empetrum *heath, and* Dryas *soils. Note higher amounts at the surface associate with organic matter except with the alpine soils, where P tends to decrease toward the surface.*

midlatitude agricultural crops the low reference temperature is 10°C and the upper is 30°C. However, it is unclear what reference temperatures we should use. Arctic and alpine plants are very cold tolerant; alpine plant roots may grow at temperatures as low as 0°C (Billings, 1974). However, at soil temperatures below 5°C, *B. pubescens* root growth and N uptake are nil, and raising the temperature above 15°C does not increase the rates (Karlsson and Weih, 1996). Only one site, SM6, had temperatures that slightly exceeded 15°C on a total of only 5 d. Given the uncertainties, we calculated GDD at low reference soil temperatures of 0, 0.5, and 5°C, with no upper reference temperature.

GDDs at 0, 0.5, and 5°C are all closely related with correlation coefficients ranging from 0.95 to 0.99, so they essentially are equivalent and tell a similar story. All GDDs were lowest at the alpine and midalpine meadow sites. This is obviously attributable to the high elevation of the alpine sites (Fig. 8, Table 1). However, at the midalpine site, long snow cover and location at the head of the valley, where there is little direct sunshine, accounts for the cold soil temperatures (Fig. 1). Indeed, maximum temperature recorded at MA1 is less than that of site A4, located 340 m above it. The highest GDD_0 was found at the *Dryas* and the *Empetrum* heath sites. The *Dryas* sites were at midelevations, generally well drained, and on west-facing slopes, so they had relatively low heat capacity and received maximum insolation. The *Empetrum* sites were at low elevation and excessively drained, giving them higher air temperatures and low heat capacity. Despite lush vegetative growth, the birch sites had low GDD due not to low minimum temperatures, but to their long period of snow cover and isothermal conditions.

Cryptogam vegetation found at alpine site A4 testifies to a harsh climate despite the fact that it had a GDD similar to the more lushly vegetated midalpine and birch sites. This discrepancy can be explained when the GDD is plotted against minimum temperature, where all alpine sites stand out with low minimums in contrast to the midalpine and birch sites (Fig. 9). Another way to compare the soil climates is to look at the accumulation of GDD through the summer (Table 5). The *Dryas* sites are the first to accumulate 50 GDD units and continue to accumulate GDD units past Julian day 260, keeping pace with the air temperatures. The growing seasons at the alpine sites and the snow-covered and wet sites (B1, MA1, SM6) start late. However, after the snow melts, the birch and solifluction sites continue to accumulate

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TABLE 3

Mean values of surface soil parameters[a] by vegetation community type and drainage

Veg. type	CEC	pH	B.S.	O.C.	N	S	P	Ca	Mg	K	Na	B	Fe	Mn	Cu	Zn	Al
Alpine	8b[b]	4.1b	27d	4b	0.2b	48	36	143b	52b	50	13	0.3b	235b	8	3ab	2	616a
Birch	13ab	4.1b	38cd	14ab	0.6ab	41	57	409ab	127ab	125	18	0.4b	147b	80	1b	4	108b
Bog	11ab	5.7a	76ab	38a	2.1a	54	29	1248ab	128ab	30	13	0.5b	154b	3	2ab	1	523a
Dryas	24a	6.3a	87a	23ab	1.1ab	36	41	3578a	139ab	118	17	0.8a	170b	57	4ab	8	79b
Heath	18ab	3.8b	33d	41a	1.3a	44	48	497ab	140ab	118	18	0.4b	88b	15	1b	7	104b
Meadow	21a	5.6a	59bc	12b	0.5ab	40	61	2078a	134ab	106	17	0.5b	399a	76	9a	10	484a
Solifluction	22a	5.5a	69abc	18ab	0.8ab	44	57	2328a	180a	102	20	0.6b	197b	102	3ab	7	290a
Willow	20a	5.4a	66abc	13ab	0.8ab	44	61	2002a	231a	138	15	0.6b	239b	35	4ab	7	351a
Drainage																	
good	16	4.8b	45b	16	0.9	43	47	1225b	105b	92	16	0.4b	235	39	4a	6	390
poor	20	5.4a	68a	18	0.6	46	55	2010a	181a	101	18	0.6a	226	76	3b	7	335

[a] See Table 2 for parameter definitions and units.

[b] Values in any column within a group followed by different letters are significantly different ($P < 0.001$).

GDD units well into the fall, unlike the alpine sites and site MA1, which cool rapidly in the fall. In terms of their maximum accumulation of $GDD_{0.5}$ units, the solifluction site SM6 kept increasing until Julian day 336, while the highest-elevation site, A5, stopped at Julian day 252. Other sites with similar late-season accumulation of $GDD_{0.5}$ units were H1 and B1. With GDD_5 units, there is a different pattern. The *Dryas* sites remain warm longer into the fall than do the lower-elevation sites B1, H1, SM6, or the alpine sites. Site A5 stopped accumulating GDD_5 units on Julian day 239 and $GDD_{0.5}$ units on Julian day 252. Thus, the growing season, defined as the number of days between when the first $GDD_{0.5}$ unit is accumulated and the day when no additional units are added, is as short as 49 d at A5 or as long as 157 d at SM6. Similarly, the extremes for the GDD_5 growing year are only 19 d for A5 but 108 d at DH2, again showing the harsh climate at the alpine sites and the warmer climate at the midelevation sites with favorable aspect. It should be noted that length of the growing season may not be as important to plant productivity and species composition as soil fertility and protection from wind (Shaver et al., 1996). This is exemplified by the wind heath (Fig. 1, site WH1) of sparse and stunted vegetation with very poorly expressed soil found on the exposed summits of coarse-textured eskers in the lower valley.

Discussion

The gross control of vegetation distribution in Kärkevagge is climatic, but at a smaller spatial scale, snow cover and soil drainage, texture, and chemistry are significant. Both the minimum temperatures experienced and the length of the growing season are important. Latitude controls the general climate, but microclimate is largely controlled by topoclimatic factors, snow cover, soil moisture, exposure, aspect, etc. Snow cover has a great role in modifying the microclimate, both preventing low air temperatures from reaching into the soil and delaying warmup in the spring. Soil moisture is controlled by soil texture as influenced by topography. The wettest sites in Kärkevagge (Fig. 1, bog 1 and 2) had organic soils associated with small bedrock depressions isolated from the main stream channels, which otherwise over time would deposit mineral matter to fill in the depressions and dilute the organic matter content below organic soil levels. In contrast, the driest soil, found at the wind heath site (Fig. 1, site WH1) on an esker in the lower valley, was very coarse textured and poorly developed.

EMPETRUM *AND BIRCH SOILS*

These vegetation types were at the lowest elevation in the valley. This is also the most stable area owing to low slope gradients and isolation from both depositional and erosional forces that are very active in much of Kärkevagge. Here, parent materials were less influenced by Kärkevagge's lithology and reflect materials transported by the larger glacier that occupied Vassijuare valley. The stability of the landscape, as well as the low pH parent materials, allowed processes driven by organic acids produced by *Empetrum* and *Betula* to reduce parent material pH from a high of 5.0 in the C horizon to as

TABLE 4

Climate data for the vegetation community types

Vegetation type/location	MAT[a] (°C)	MWT[a] (°C)	MST[a] (°C)	Max. temp (°C)	Min. temp (°C)	Days[b] ~0°C	Days[b] >0°C	Days[b] >0.5°C	Days[b] >5°C	Degree[c] days (0°C)	Degree[c] days (0.5°C)	Degree[c] days (5°C)
Alpine[d]	−3.4–−1.7	−9.2–−5.0	0.8–6.2	8.0–12.9	−15.3–−9.2	45–97	44–101	42–96	11–65	161–649	139–601	22–237
Birch	2.1	0.1	6.3	10.9	−0.1	251	198	134	80	783	693	244
Dryas[d]	1.5–2.4	−1.6–−0.1	7.7–8.0	13.2–14.1	−5.3–−0.3	110–250	148–185	126–139	83–93	857–929	777–861	301–389
Empetrum	2.1	−0.2	7.2	11.7	−2.0	193	230	154	83	870	768	281
Midalpine meadow	1.2	−0.3	4.1	12.7	−0.4	286	105	91	50	497	447	145
Solifluction meadow	2.3	0.2	6.6	16.6	−0.3	254	214	163	71	843	746	323
Air temperature	−1.6	−8.9	8.3	17.6	−26.6	70	147	141	83	932	860	355

[a] MAT, mean annual; MWT, mean winter (December, January, February); and MST, mean summer (June, July, August) temperatures, soil temperatures taken at 10 cm.

[b] Count of number of days that were 0 ± 0.5, >0, >0.5, or >5°C in 1996.

[c] Degree days are calculated by summing over a year the differences between the daily mean and the reference temperature, 0, 0.5, or 5°C.

[d] Range of three sites, see Table 5 for site codes and Figure 1 for locations.

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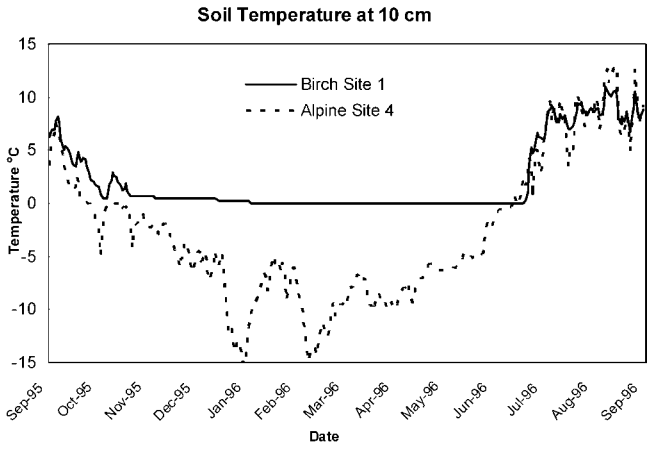


FIGURE 7. Daily mean soil temperatures at 10 cm depth at birch site B1 and alpine site A4. At B1 the logger was in the upper Bs horizon. There was a 2-cm-thick Oh horizon on the mineral soil surface. At A4, the logger was in the upper Bw horizon; there was no organic surface at this site.

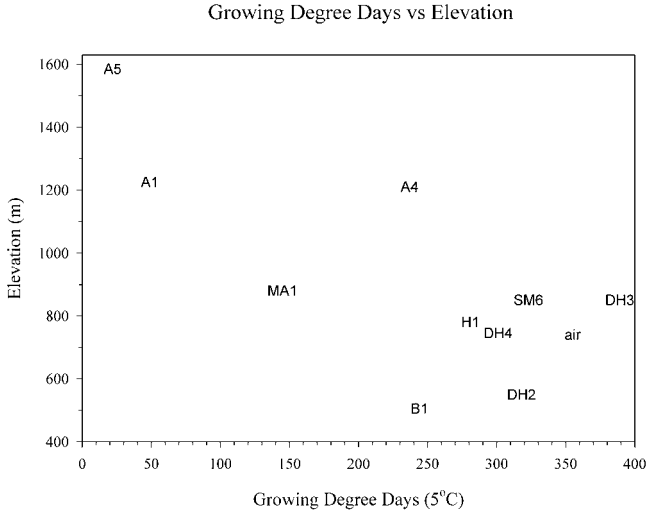


FIGURE 8. Effect of elevation on growing degree days. Legend: A, alpine; B, birch; DH, Dryas*; MA, midalpine; H,* Empetrum *heath; SM, solifluction meadow; air, air temperature at midvalley.*

low as 3.5 in the surface horizons. Lower soil pH was found only where soils were impacted by sulfuric acid generated by pyrite oxidation (Darmody et al., 2001). In addition, soil horizonation is best expressed under *Empetrum* and birch vegetation because the organic acids promote movement of Fe, Al, and organic C, i.e., the process of podzolization, forming spodic horizons, and thus Spodosols.

Empetrum is efficient at mobilizing nutrients and accumulating them at the surface. For example, the associated soils had the lowest overall levels of Ca, but the mean ratio of Ca in the topsoils to the subsoils (A/C) was highest, 2.7, with this vegetation type (Fig. 5). Despite the fact that *Empetrum* heath soils are excessively drained, they have the thickest histic epipedons and most organic C at the surface of the soils in Kärkevagge (Table 2). The organic matter produced by *Empetrum* may not be easily decomposed due to its high C/N ratio and the droughty conditions. Overall, *Empetrum* soils were infertile and lowest in micronutrients Cu, Zn, and Fe but highest in extractable Al. The low metal contents show the effect of the chelating agents produced by the *Empetrum* plants that complex metals and expedite their movement in the soil profile. The high Al content may be a significant challenge for most plants growing on these soils. An extractable Ca/Al ratio of <1 may be phytotoxic (McLean, 1982), and in the *Empetrum* subsoil the Ca/Al ratio is 0.3.

Soils at the birch sites were chemically and pedologically similar to the *Empetrum* heath sites but did not have thick fibrous surface O horizons. Like *Empetrum* soils, birch soils classify as Haplocryods, which show influence of chelating agents on soil chemistry. The difference between the two is soil moisture storage. Birch vegetation in Kärkevagge is predominantly found on finer-textured tills than the heath at the same elevation, which is found on coarse-textured outwash. The finer texture imparts greater soil moisture storage. In addition, birch sites occur in less exposed locations and thus capture more snow. However, the boundary between the two vegetation types has shifted. This change is evidenced by decomposing birch roots found in the *Empetrum* soils, away from any live birch trees,

TABLE 5

Julian date at which cumulative growing degree days (GDD) are achieved at individual sites in Kärkevagge for the year 1996

	Cumulative GDD													Max GDD			
	50		100		200		300		400[b]	500	600	700	800	Julian date		Growing season	
Site[a]	0.5	5	0.5	5	0.5	5	0.5	5	0.5	0.5	0.5	0.5	0.5	0.5	5	0.5	5
A1	193[c]	—	206	—	224	—	243	—	—	—	—	—	—	262[a]	250	98[e]	63
A4	185	202	191	215	205	238	218	—	227	240	262	—	—	263	252	94	69
A5	219	—	227	—	—	—	—	—	—	—	—	—	—	252	239	49	19
B1	183	197	191	212	203	238	215	—	226	239	253	—	—	309	253	135	75
DH2	161	191	173	206	188	225	202	248	212	222	232	244	259	292	262	148	108
DH3	176	188	184	201	194	220	205	235	216	224	234	244	258	293	261	128	91
DH4	170	192	180	207	193	226	206	251	217	226	237	249	—	291	252	139	87
H1	176	195	187	208	197	228	209	—	221	230	242	258	—	305	257	147	83
MA1	201	214	207	226	220	—	233	—	251	—	—	—	—	285	251	94	57
SM6	191	204	198	212	208	225	218	245	225	236	247	267	—	336	255	157	68
Air	159	188	172	205	187	223	201	239	212	222	228	240	255	292	263	275	116

[a] Soil temperature (10 cm) records at A1, 4, 5, Alpine sites 1, 4, 5; B1, Birch site 1; DH2-4, Dryas Health sites 2-4; H1, Empetrum Heath site 1; MA1, Mid-Alpine site 1; SM6, Solifluction Meadow site 6; Air, air temperature, mid valley.

[b] 400 GDD at 5°C was not achieved at any site.

[c] Julian day on which GDD at the reference temperature (0.5 or 5°C) was reached.

[d] Julian date on which maximum GDD shown in Table 4 at the reference temperature (0.5 or 5°C) was reached.

[e] Count of days from cumulative GDD = 1 to GDD = maximum at the reference temperature (0.5 or 5°C).

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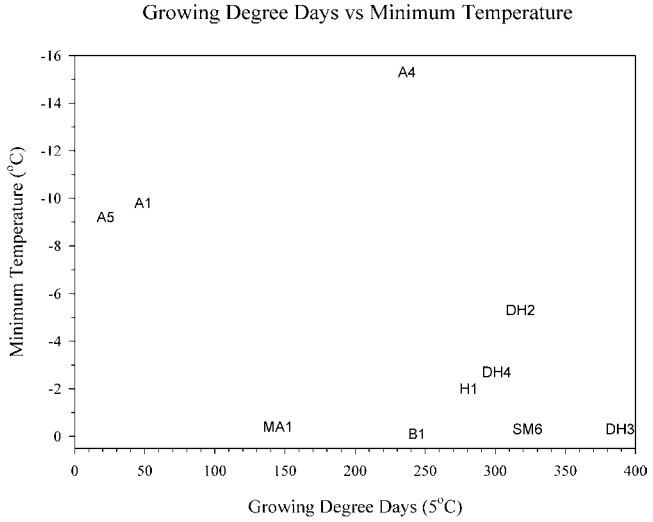


FIGURE 9. Minimum temperature compared to growing degree days. Legend: A, alpine; B, birch; DH, Dryas*; MA, midalpine; H,* Empetrum *heath; SM, solifluction meadow.*

likely due to deforestation associated with railroad construction (Rapp, 1996; Schlyter et al., 1993). This indicates that birch trees could grow on the very coarse-textured soils but have yet to reoccupy those soils. As with the *Empetrum* soils, birch soils have relatively low CEC, pH, BS, Ca, Mg, Cu, and Zn and show strong horizonation as evidenced by Fe and Al distributions (Figs. 2 and 3). Although the *Empetrum* and birch soils were the only Spodosols in Kärkevagge, there is evidence of weak podzolization occurring in some alpine, *Dryas*, and meadow soils, where Bw horizons have been recognized (Table 2).

DRYAS

Dryas octopetala is well known as a calciphilic species, and it stands out as the dominant species on high-pH, calcium-rich soils in Kärkevagge. For example, extractable Ca content in the *Dryas* surface soils averaged 25 times greater than that in the alpine surface soils (Table 3). However, in contrast to the *Empetrum* soils, the *Dryas* soils had less Ca increase in the surface horizon, giving these soils a low A/C horizon Ca ratio of 1.4 (Fig. 5). In addition, the *Dryas* soils had the highest Ca/Mg ratios of all the soils. *Dryas* sites were on the upper colluvial slopes, where they received drainage water from the calcareous rocks exposed above them in the cliffs. The high Ca content and productive vegetation allowed these *Dryas* soils to accumulate a relatively large pool of organic matter. This led to the development of a Mollisol in one *Dryas* location, assumed to be the most northerly documented in the world (Darmody et al., 2000a). *Dryas* soils also stood apart in that they had the lowest extractable Al, as expected given the high pH. Their extractable Ca/Al ratio was 54.4 in the surface and 11.6 in the subsoil, the highest of all the sites.

ALPINE

In contrast to the highly fertile *Dryas* soils, the alpine soils had the lowest levels of soil fertility. Their stratigraphic position places them above local calcareous rocks, and they are developed in residuum from schist, so the bedrock is not a particularly good source of nutrients. The cold, harsh conditions contribute to the poor productivity of these soils, which may be the oldest in Kärkevagge. They are protected from water erosion and deposition, as is commonly found at lower elevations, and are often armored by a pavement of coarse fragments, which, although indicative of frost heaving and past wind erosive forces, affords some protection from current erosion. In addition, there is evidence that regional glaciation involved cold-based ice in some ridge crest locations, which would preclude glacial erosion and deposition (Kleman and Hättestrand, 1999; Allen et al., 2001). Thus, the low fertility of these soils can largely be explained by their antiquity, which has caused considerable loss of plant nutrients over the millennia.

Poor plant productivity, together with the cold that both prevents more efficient plants from growing and causes cryoturbation, can be evoked to explain the lack of well-expressed horizonation in the alpine soils. Alpine plants were the worst at accumulating nutrients in their topsoils, having mean A/C horizon ratios of 0.9, 2.9, 1.0, 1.9, and 1.2 for Ca, organic C, Mg, K, and P, respectively (Figs. 4, 5, and 6). Owing to their windswept location, any nutrients that plants have translocated to their aboveground tissues are liable for removal by wind erosion as the tissues die. The CEC, base saturation, organic C, and extractable Ca, Mg, Ca/Mg ratio, and B were lowest in the alpine soils (Table 3). Alpine soils also were highest in extractable Al, giving them a mean Ca/Al ratio of 0.25 in the surface and 0.27 in the subsoil, the lowest we measured and within the phytotoxic range (McLean, 1982).

MEADOW AND SOLIFLUCTION MEADOW

Meadow and solifluction meadow soils were more moist than the *Dryas* or *Empetrum* soils. They were chemically and physically similar and both supported luxurious stands of grasses and forbs. Solifluction meadow sites were on the wetter, western side of the valley and contained buried A or O horizons due to the solifluction lobes overriding surfaces downslope. On the eastern slopes, meadow soils also contain buried surfaces due to intermittent deposition of colluvium. Both vegetation types had fertile soils, as evidenced by the relatively high values of CEC, pH, BS, P, S, Ca, and Mg (Fig. 5).

WILLOW AND BOG

Willow sites occur in the wetter portions of the landscape, and their soils show influence of increased organic matter production, reduced decomposition, and groundwater discharge. While their composition varied from place to place, these soils generally were among the highest in CEC, pH, Ca, Mg, and K. The bog soils were in the wettest locations and had the greatest amount of organic C and N throughout the soil profile (Fig. 4).

Summary

Soils in Kärkevagge are quite variable and show a wide range in chemical and physical properties controlled by local soil conditions operating on general elevational trends. Based on our research, the soil-vegetation relationships in Kärkevagge can be simplified into four general groups. First, at the lowest elevations, about 500–700 m a.s.l., are the podzols, Typic Haplocryods associated with birch and *Empetrum* heath vegetation. These soils are developed on well-drained, coarse-textured, glacio-fluvial deposits of generally low fertility. They have the best soil horizonation of all soils found in the area, and the heath soils have the thickest histic epipedons. They are intermediate in soil temperature, with a growing season, when soil temperatures at 10 cm are above 5°C, of about 75–83 d.

The second group, at about 600–900 m a.s.l., is the more poorly drained meadow, willow, and solifluction meadow soils. These are developed on coarse, loamy-textured alluvium or colluvium of moderately high soil fertility. They commonly have multiple buried thin O or A horizons and exhibit only slight horizonation, if any. The soil classifications include Cryofluvents, Cryorthents, and Cryaquents. Soil temperatures here are cooler, with a growing season of about 57–

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68 d. Included in this group are small patches of organic soils, Cryosaprists, in bedrock depressions with bog-type vegetation.

The third group is the highly fertile soils that support *Dryas* vegetation. These are at about 650–900 m a.s.l., and are developed on steeply sloping, well-drained, coarse-loamy colluvium. They have the highest pH, base saturation, and Ca content of any soil in the area and are also the warmest, with a growing season of about 87–108 d. The soils occasionally have buried A or O horizons and, at most, weakly developed profiles. Their classifications include Cryorthents and Eutrocryepts. At one location, the presence of a dark, organic-rich Mollic epipedon supports a soil classification of Haplocryoll.

The fourth group presents the greatest challenge for plant growth, with the most infertile, coldest soils in the area. These are the alpine soils, developed in colluvium and residuum on the mountain summits, at elevations above about 1100 m a.s.l. They are on the oldest land surfaces in the area. They have the lowest levels of pH, base saturation, Ca, N, and most other soil fertility parameters measured, except Al, which is greatest in this group. The Ca/Al ratio in these soils averages 0.3, which may indicate Al phytotoxicity. These soils also have the shortest growing season, about 19–69 d, and the coldest winter temperatures. The soils are classified as Dystrocryepts or Cryorthents, but where permafrost is within 2 m, they are classified as Haploturbels.

At the lower elevations in Kärkevagge, except where plants are sparse due to damage by late-lying snow, rock falls, mass movements, or animals (including people), growth is vigorous and essentially prevents soil erosion. Indeed, Rapp (1960) said that slope wash was of minor importance on the grass-covered slopes. However, erosion has occurred in Kärkevagge in the past, as evidenced by buried soils commonly found in *Dryas*, willow, meadow, and solifluction meadow sites. Recently, radiocarbon dating of buried soils in one meadow site (Holmqvist and Schlyter, 2000) supports Rapp's observation. Five buried soils down to 22 cm radiocarbon date from 130 to 1280 yr B.P. This indicates that despite steep slope (16%) and harsh climate, there has been little or no erosion at this site, only deposition of materials eroded from upslope. The calculated deposition rate was low, 0.08 to 1.40 mm yr^{-1}. The highest deposition rates date from the Little Ice Age, when the climate was presumably more harsh. We know from digging in these soils that the meadow-type vegetation forms a strong sod, but the alpine cryptogam soils do not enjoy that strengthening at the surface. Consequently, there may have been mass movement off the high alpine sites onto the meadow sites below, burying the surface soils (Rapp, 1960; Allen et al., 2001). Fortunately, the high fertility of the soils allows the meadow vegetation to quickly reestablish itself and stabilize the slopes after a depositional event. This resilience in resisting erosion will be tested in the future as Kärkevagge responds to increased recreational and grazing pressures.

Acknowledgments

This work was conducted as part of a larger project concerning weathering in Kärkevagge sponsored by a variety of sources. Fieldwork over several years has been funded in part by the Universities of Arkansas, Illinois, and Lund (Sweden) and supported logistically by the Royal Swedish Academy of Sciences Field Station at Abisko. Funding was also provided by grants 5479-95 and 5674-96 from the National Geographic Society and grants BCS-9818917 and BCS-9818667 from the National Science Foundation. We would also like to acknowledge the personal support and encouragement of the late Anders Rapp.

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Ms submitted August 2002
Revised ms submitted May 2003

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