Polarforschung 73 (1), 5 – 14, 2003 (erschienen 2005)

Soil Ecological Processes in Vegetation Patches of Well Drained Permafrost Affected Sites (Kangerlussuaq - West Greenland)

by Ulrich Ozols and Gabriele Broll[1]

Summary: In parts of continental interior areas of West Greenland's fjords, xerocryic vegetation is characteristic and influences soil properties. The objective of the present study was to compare soil chemical and soil ecological properties as well as soil genesis influenced by three different types of continental arctic climax vegetation *(Kobresia myosuroides, Salix glauca* and *Betula nana)* close to the head of Kangerlussuaq (Søndre Strømfjord). The polypedon under the vegetation mosaic of *Kobresia myosuroides* meadow, *Salix glauca* shrubs and *Betula nana* heath was formed by Orthic Turbic Dystric Cryosols as well as by Orthic Static Dystric Cryosols. Both subgroups could be divided into three different pedons. At *Salix* sites, the Turbic and Static subgroups were specified by nutrient and humus enrichment associated with high amounts of fibric and crustic organic material. At the *Betula* sites Orthic Turbic Dystric Cryosols and Orthic Static Dystric Cryosols are common. They are low in humus content and possess translocation potential. The grass-like *Kobresia* forms nutrient- and humus-rich A horizons. Compared to *Salix* sites, however, the amount of fibric material is low. Differences in the chemical properties (pH, CEC and soil solution) are mainly based on the quality of the different plant residues. Soil reaction, CEC and the properties of the equilibrium soil pore solution at *Salix* and *Kobresia* sites are evidence of melanisation.

Zusammenfassung: Weite Teile der inneren Bereiche großer Fjorde in Westgrönland werden von einer xero-cryophytischen Vegetation bestimmt, die ihrerseits bodenökologische Prozesse beeinflusst. In der vorliegenden Untersuchung werden die bodenchemischen und bodenökologischen Eigenschaften unterschiedlicher arktisch-kontinentaler Schlussgesellschaften aus *Kobresia myosuroides, Salix glauca* und *Betula nana* am inneren Fjordende des Kangerlussuaq (Søndre Strømfjord) unter Berücksichtigung der Bodengenese untersucht. Nach den vorliegenden Ergebnissen wird die Bodengesellschaft innerhalb des Vegetationsmosaiks aus *Kobresia myosuroides*-Rasen, *Salix glauca*-Gebüschen und *Betula nana*-Heiden aus Orthic Turbic Dystric Cryosols und aus Orthic Static Dystric Cryosols aufgebaut. Die Bodentypen können pedogenetisch weiter differenziert werden. Unter den Salix-Gebüschen sind beide Untergruppen durch Nährstoff- und Humusanreicherung sowie durch hohe Gehalte aus faserigem, fermentiertem und verkrustetem organischem Material gekennzeichnet. Unter *Betula nana* sind Orthic Dystric Turbic Cryosols mit geringem Humusanteil und einem gewissen Verlagerungspotential verbreitet. Die grasartige *Kobresia* bildet humose und nährstoffreiche A-Horizonte, die aber, verglichen mit denen unter *Salix*, geringere Anteile an faserigem Material enthalten. Die bodenchemischen Unterschiede in pH, KAK und in der Bodenlösung werden maßgeblich durch die Eigenschaften der jeweiligen Pflanzenreste beeinflusst. Die Bodenreaktion, die KAK sowie die Eigenschaften der Gleichgewichtsboden-Porenlösung in den *Salix*- und *Kobresia*-Beständen weisen auf Melanisierungsprozesse hin.

INTRODUCTION

Many studies on arctic and subarctic ecosystems in general were published (e.g. CHAPIN & KÖRNER 1995, REYNOLDS & TENHUNEN 1996) as well as many regional studies (e.g. BLÜMEL 1992, 1999). A lot of investigations deal with the relationship between single factors such as soil acidity or soil moisture and vegetation or single plant species (MATTHES-SEARS et al. 1988, GIBLIN et al. 1991, SHAVER et al. 1996). Also, attention has been paid to studies on the influence of abiotic factors on ecological processes (e.g. MARION & BLACK 1987, HARRIS 1987, 1998, EDWARDS & CRESSER 1992, NADELHOFFER et al. 1992). Moreover, the influence of plants on soil properties has been discussed in many papers (HOBBIE 1995). HANSEN (1969), TEDROW (1970) as well as BROLL (1994), BROLL et al. (1999) highlighted the relationship between subarctic ericoid and lichen vegetation and different soil properties. FREDSKILD & HOLT (1993) demonstrated the influence of *Poa pratensis* on soil chemical properties at head of Kangerlussuaq (Søndre Strømfjord). Also, UGOLINI (1986) stressed the influence of herbaceous plants on arctic soils. However, there is a lack in studies on the relationship between plants and soil at xerocryic sites in continental arctic areas. Therefore, the objective of the present study is to compare soil chemical and soil ecological properties as well as soil genesis influenced by three different types of continental arctic climax vegetation *(Kobresia myosuroides, Salix glauca* and *Betula nana)* near Kangerlussuaq (Søndre Strømfjord) in West Greenland.

STUDY AREA AND STUDY SITES

The area at head of Kangerlussuaq (Fig. 1, 67°03' N, 52°30' W) is controlled by an arctic continental climate with annual air temperatures of -6 °C. In this part of West Greenland mean daily summer temperature is about 10 °C. The coldest month is February with a daily mean temperature of about -22 °C. Annual precipitation is 138 mm while summer precipitation is about 58 mm. Humidity ranges between 78 % in winter and 62 % in summer (1980-1990, unpublished data from weather station WMO 04231 at Kangerlussuaq, Danish Institute of Meteorology, Copenhagen).

The study sites are located close to Mount Keglen about 20 km west of the Russells glacier (Fig. 1). Mean annual soil temperature at 50 cm depth (MAST) is -2.3 °C and represents the "very cold soil temperature regime" (SOIL CLASSIFICATION WORKING GROUP 1998, OZOLS 2002). Strong easterly winds are common, often resulting in dust storms and relocation of sediments in all parts of the valley (DIJKMANS et al. 1989, DIJKMANS & TÖRNQUIST 1991). Usually, snow cover does not exceed 20 cm, and at wind swept topography snow is almost completely removed. Frost penetrates into the soil from December to April and lowers soil temperature almost to -10 °C at 100 cm depth (OZOLS 2002). The study area is completely underlain by permafrost (BROWN et al. 1997). Usually, permafrost does not occur within the upper 2 m at the old riverbanks and morainal ridges, above 120 m elevation,

---

[1] Abteilung für Geo- und Agrarökologie, ISPA der Universität Vechta, Postfach 1553, D-49364 Vechta, Germany; <gbroll@ispa.uni-vechta.de>

Manuscript received 10 October 2003, accepted 12 February 2004

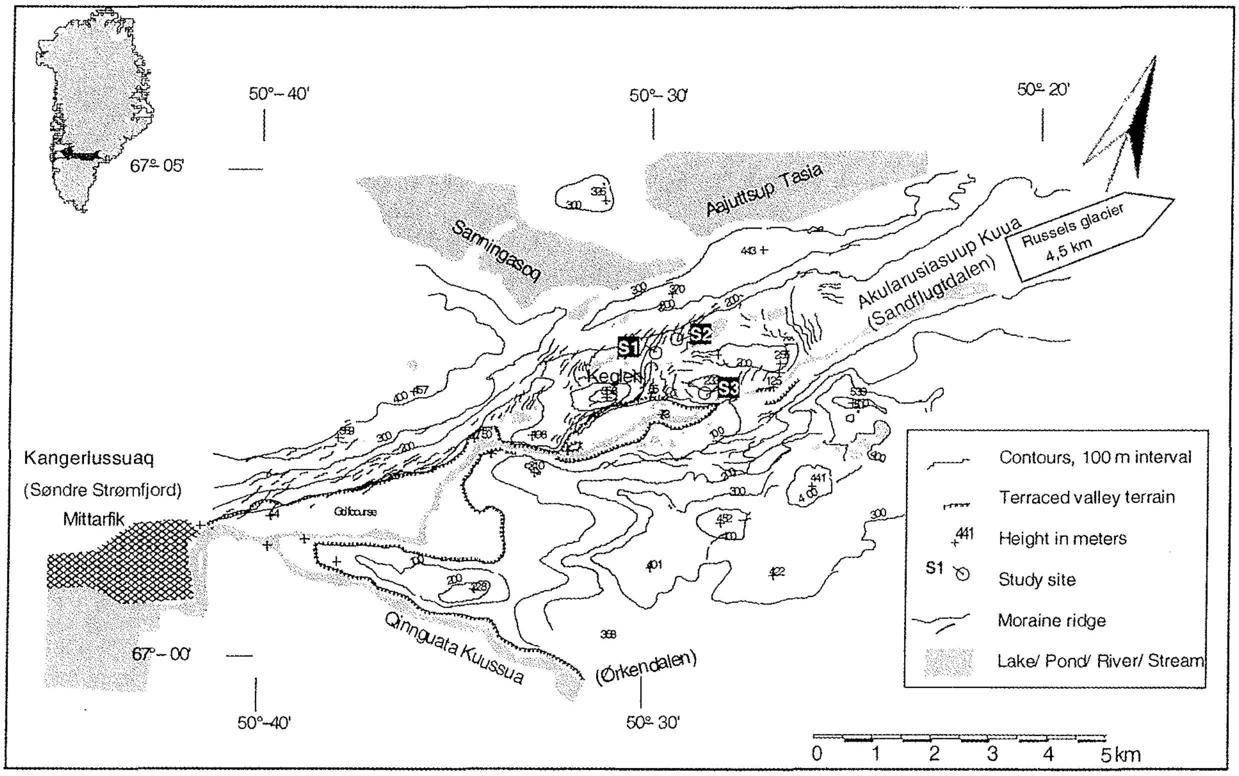

Fig. 1: Study area Mount Keglen, Kangerlussuaq, Søndre Strømfjord, West Greenland.

Abb. 1: Untersuchungsstandorte am Keglen, Kangerlussuaq, Søndre Strømfjord, Westgrönland.

northeast of Mount Keglen (STÄBLEIN 1975, TENBRING 1975, OZOLS 2002). On the level upper terraces south of Mount Keglen, on the eastern unnamed ridge, and on the valley terraces, permafrost was found between 100 and 120 cm depth. Patterned ground is common, but only some is still active.

The mountains and the east-west oriented ridges of about 500 m consist mainly of Precambrian gneiss. Around Mount Keglen, mountain slopes are covered by till. Morainal ridges, particularly on south facing slopes, are heavily influenced by fluvial processes. The valley floor is covered by till mixed with saprolite, outwash and eolian sediment. Soil parent material was derived from outwash plains located at Sandflugtdalen sandsheet (DIJKMANS & TÖRNQUIST 1991). Soil texture is loam containing high portion of coarse silt. The common Cryosols in this area can be divided into the Static and Turbic Great Group. Many of the Turbic Cryosols within the study area show evidence of strong cryoturbation and strong frost dynamics. Most of them, however, are entering a static phase. At least cryoturbation activity will be reduced because of the good recent drainage conditions. Vegetation of the valley is closely related to the Arctic Shrub Zone (DANIELS et al. 2000). The xerophytic and xerocryophytic non acidic shrub-herb-grass vegetation, mainly related to the *Carici rupestris-Kobresietea bellardii,* and the *Loiseleurio-Vaccinietea,* includes the zonal *Betulo-Salicetum glaucae* ass. prov. (DANIELS & WILHELMS 2002). At south facing slopes, the thermophytic *Arabido holboellii-Caricetum supinae* is quite common. Detailed descriptions of vegetation types at head of Søndre Strømfjord are given by BÖCHER (1954, 1963) and HOLT (1983).

The vegetation mosaic of vigorous *Kobresia myosuroides* stands, scattered *Salix glauca* shrubs and *Betula nana* stands cover the old river banks between Mount Keglen and Sandflugtdalen sand sheet at an elevation of 80-140 m (Fig. 2). The study sites are characterized by level or very slightly sloping topography. Soil depth ranges between 35 cm and 60 cm. Coarse grained sand (outwash) often forms the subsoil layer. In accordance to permafrost distribution and soil moisture, three sites were selected. The sites differ first in the presence of permafrost within 100-140 cm depth and second in soil moisture. One site (S1) is free of permafrost down to 200 cm, two of the three study sites show permafrost (S2, S3) with low ice content. At site S3, soil moisture is higher than at S1 and S2. Small earth hummocks, only 30 cm in diameter and up to 25 cm high, occur close to the study sites.

METHODS

Soils were described according to the Canadian system of soil classification (SOIL CLASSIFICATION WORKING GROUP 1998). At the three study sites (S1, S2, S3) samples were taken at four plots on each *Kobresia-*, *Salix-* and *Betula* stand (plots at each stand n = 12). Ten soil monoliths have been randomly taken in each plot (monolith, n = 40, Fig. 3). Each soil monolith was split into sections of 0-2 cm, 2-4 cm and 4-8 cm. The samples of the sections of each plot were homogenized and air dried in the field. Additionally, samples from each horizon in pits of each stand have been collected to study the influence of the different vegetation cover on soil properties such as bulk density, soil water content and chemical properties by depth. Soil profiles were described for each study site along transects (2-4 m length) from *Kobresia* stands into *Salix* and into *Betula* stands (Fig. 3).

Fig. 2: *Kobresia* meadow and shrub communities at Keglen area, head of Kangerlussuaq, West Greenland, July 1998.

Abb. 2: *Kobresia*-Rasen und Gebüschgesellschaften im Gebiet des Keglen, inneres Fjordende, Kangerlussuaq, Westgrönland Juli 1998.

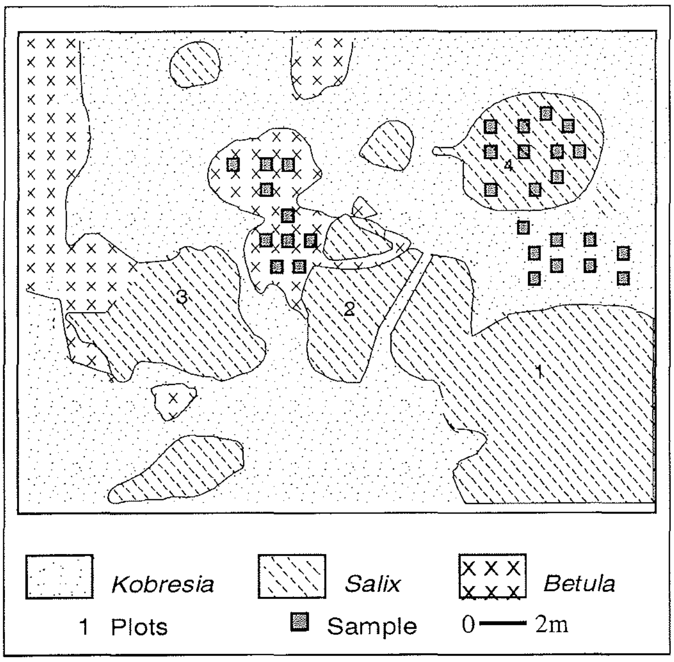

Fig. 3: Sampling pattern. At the three study sites samples were taken at four plots on each *Kobresia, Salix* and *Betula* stand.

Abb. 3: Probennahme. In den drei Untersuchungsgebieten wurden in jeweils vier "plots" der *Kobresia-*, *Salix-* und *Betula*-Bestände Proben genommen.

All solid phase analyses were performed on the <2 mm fraction of air-dried samples. Soil pH was measured in 0.01 M $CaCl_2$ with a glass electrode (INGOLD). An elemental analyzer (CARLO ERBA NA 1500) was used for measuring organic carbon and total nitrogen. Extractable iron and aluminium were determined by the dithionite-citrate method (Mehra & Jackson 1960) and the acid ammonium oxalate (Schwertmann 1959) method. Exchangeable cations were determined by 1M NH_4OAc extract. Fe, Al, Ca, Mg, K, Na were analysed by atomic-absorption spectroskopy (AAS, PERKIN ELMER 1100 B).

The soil solution was experimentally taken as the equilibrium soil pore solution (ESPS) in laboratory according to Hildebrand (1986). Therefore, 34 undisturbed fresh soil samples were taken with metal cylinders (100 cm^3) from 0-5 cm depth. These samples were taken the last day of the sampling period and were frozen. In the laboratory these samples were non-stop percolated with 200 ml deionised water for 48 h with a flow through of 0,9-1 ml min^{-1}. The solutions were analysed of pH, Fe, Al, Mn, Ca, Mg, K, Na (c.f. soil analysis). Electrolytic conductivity was measured by WTW LF-92, NH_4 by AQUATEC SYSTEM TECATOR 1990. TOC was determined by HERAEUS LIQUI TOC ANALYSATOR and the anions Cl^- and SO_4^{2-} by an Ion Cromatograph (BIOTRONIC IC 1000).

RESULTS AND DISCUSSION

Vegetation and environmental conditions

The vegetation of *Kobresia myosuroides* meadow and isolated low shrubs of *Salix glauca* and *Betula nana* communities together form the present vegetation mosaic (Figs. 2 and 4). The strong continental climate, microtopography, depth to bedrock and permafrost are factors controlling these habitats. Moreover, wind strongly affects the distribution pattern of *Salix* and *Betula* stands within the *Kobresia* meadows. The *Kobresia* community is well developed on flat to slightly convex windswept topography. Isolated *Salix* stands often grow on shallow soils and in wind sheltered locations on small terraces. As a rule, the willows show wind-sheared compacted canopies, oriented south-east. On the leeward sides, the stands are less compact. Often, *Betula* stands occur in depressions as well. The occurrence of some mosses *(Aulacomnium turgidum, Hylocomium splendens, Sanionia unicinata, Racomitrium heterostichum, Tortula rualis, Politrichum strictum)* in channels and gullies between *Kobresia* tussocks indicate more humid conditions due to long-lasting snow cover. On dry sites, the moss communities often become parched from late July to August, when soil moisture is very low.

Kobresia is closely adapted to the unfavourable conditions at these very cold wind sheltered sites. The translucency of the shallow snow cover as well as the high tolerance of drifting snow during winter and in early spring make *Kobresia* myosuroides very successful at such sites (Bell & Bliss 1979). The authors pointed out that *Kobresia's* success can be explained by leaf elongation already occurring at temperatures

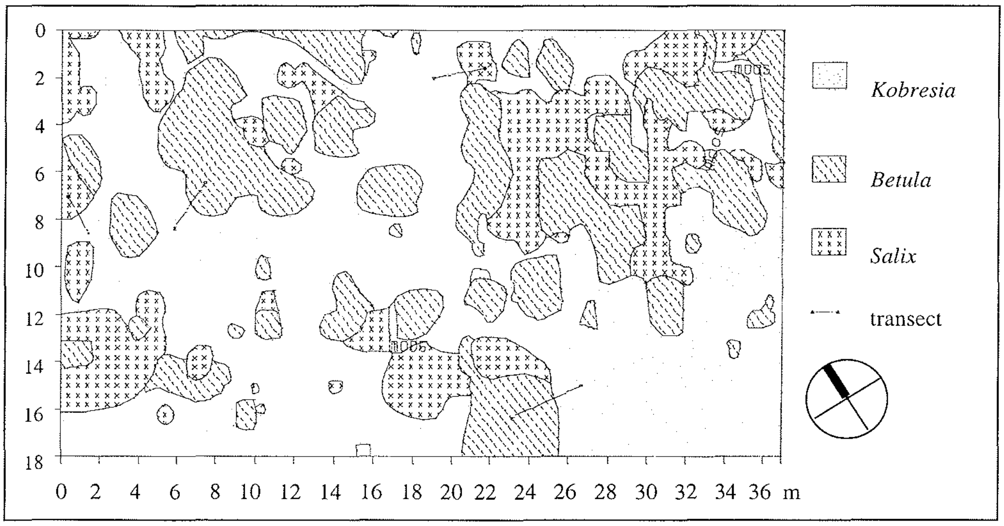

Fig. 4: Vegetation mosaic of Kobresia meadow and shrub communities at site S1.

Abb. 4: Das Vegetationsmosaik aus Kobresia-Rasen und Strauchbeständen am Untersuchungsstandort S1.

of -4 °C and water potential above -2.0 MPa in spring. In addition, when water potential is low (e.g., in July and August) leaf wilking reduces transpiration. BÖCHER (1954) and COOPER & SANDERSON (1997) emphasize the importance of high soil moisture for development of these dense *Kobresia* communities. On the footslopes as well as on the toeslopes the study sites are influenced by meltwater and interflow in spring. In 1998 and 1999 soil water content of the topsoil decreased from 34 % in June to 20 % in August (OZOLS 2002). *Salix* survived the dry summer due to its extended and deep root system. Only the height of *Salix* shrub is limited by the strong wind. Therefore, *Betula nana* mostly grows in small depressions as well as at footslopes where soil moisture is controlled by interflow and run-off. At flat, more windswept and dry locations *Betula* stands decrease and will soon be outcompeted by *Kobresia.* This succession may explain the low pH values (pH 4-5) at local sites in *Kobresia* meadows as it was observed in Iceland at similar stands (OHBA 1974). The long period of development of the dense *Kobresia* meadows (BELL & BLISS 1979), the age of the *Salix glauca* (140 yr) and *Betula nana* (70-90 yr) shrubs (OZOLS 2002), and the rejuvenation of these stands by root suckers and layering are responsible for the continuous vegetation cover and undisturbed soil development.

Soil plant relations

In most cases, soils associated with the investigated vegetation mosaic have dark and mostly undisturbed topsoils. The B horizons located below about 12 cm depth, are well brunified. Irregular broken and disturbed buried Ahy and Bmy horizons are common. In Figure 5 a transect from a *Betula nana* stand through a *Kobresia myosuroides* community to a *Salix glauca* shrub community is shown. The almost constant abiotic factors on the old river banks and the widespread stable *Kobresia* meadows restrict shrub and willow development (see vegetation and environmental conditions; BELL & BLISS 1979), creating pedons associated with *Kobresia, Salix* and *Betula* plant communities (Figs. 6, 10, 11 and 12). Indicators for the obvious diversity in pedons associated with these different vegetation are soil organic matter, soil reaction and cation exchange capacity.

The chemical and morphological properties of the different humus forms associated with the present vegetation mosaic have been analysed by MAAS (2000). Between the graminoid *Kobresia* and the shrubs *Betula* and *Salix* the differences in humus forms are obvious. A very dark, weakly acid, medium to humus-rich topsoil (up to 12-15 cm thick) has been developed under *Kobresia* stands. From Niwot Ridge (Colorado Front Range) it is known that *Kobresia myosuroides* produces a very high below-ground biomass and low above-ground biomass (FISK et al. 1998). At our present study sites a similar ratio between below-ground and above-ground biomass exists. As a result a Rhizomull with granular aggregates up to 2 cm in diameter has formed. At some sites Ah horizons contain lenses of black detritus and small grey mineral layers. The subsoils exhibit dark brown acid horizons formed in quartz-rich parent material. Permafrost deeper than 100 cm was found in areas on till. A very acid Moder humus, composed primarily of partially decomposed plant remains, occurs under *Betula* stands. When compared to topsoils associated with *Salix* and *Kobresia,* these topsoils are poor in organic carbon and nitrogen and, therefore, the aggregates contain low amounts of fine humus substances. Diffuse horizon boundaries and dark spotted horizons in the brunified subsoil indicate leaching of dissolved organic carbon (Fig. 5). Neutral to very weakly acid Moders composed of recognizable plant residues, high content of humified fine substances, as well as fine crustic organic material were associated with *Salix* stands. Thus, Ah horizons are composed of high amounts of very fine and fibric organic matter dislocated by frost churning. The organo-mineralic aggregates with grain sizes up to 2 cm in diameter contain more fibric material, leaf residues and decaying wood than those associated with *Kobresia.*

Soil chemical properties

Analyses of topsoil sections (Figs. 6, 7 and 8) reflect the different morphological features. In soils associated with *Kobresia* meadows, the uppermost section of the topsoil (0-2 cm) is enriched by organic carbon (C_{org}) and nitrogen (N_t) (Fig. 6). The lower sections contain moderate organic matter content, similar to comparable sections of topsoils associated with *Betula.* The topsoil associated with Salix is characterized by enrichment of organic matter in all sections. Nitrogen is lowest

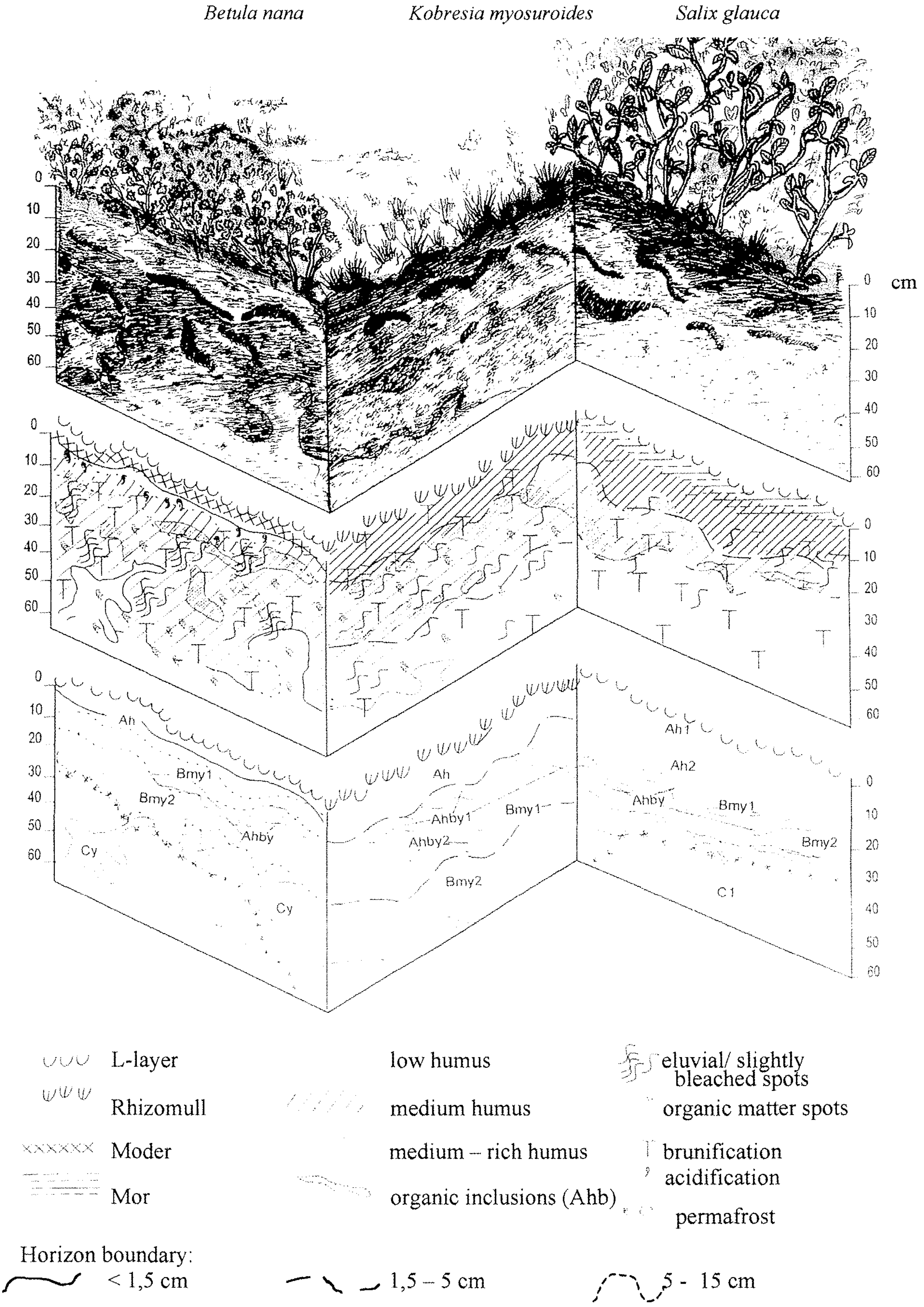

Fig. 5: Transect of a pedon under *Betula*, *Kobresia* and *Salix* cover.

Abb. 5: Bodenausschnitt unter *Betula*, *Kobresia* und *Salix*-Bedeckung.

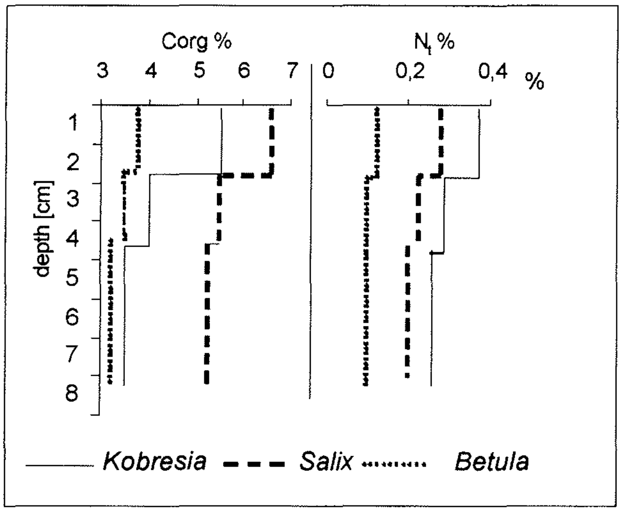

Fig. 6: Organic carbon (C_{org}) and total nitrogen (N_t) in topsoil sections, 0-8 cm, covered by *Kobresia, Salix* and *Betula.*

Abb. 6: Organischer Kohlenstoff und Gesamtstickstoff im Oberboden, 0-8 cm, unter *Kobresia, Salix* und *Betula.*

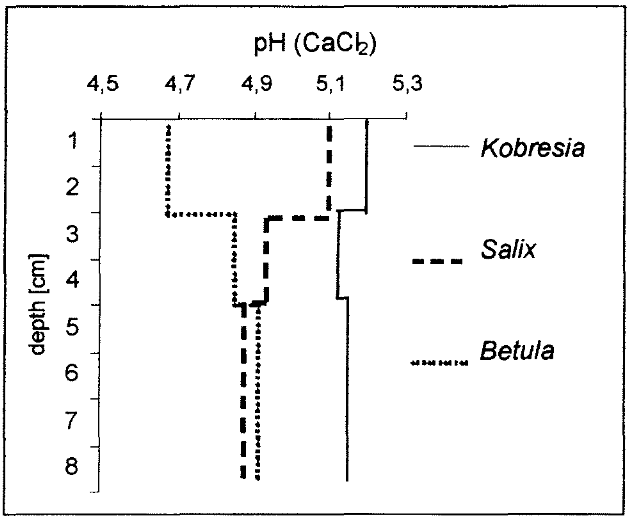

Fig. 7: Soil acidity (pH $CaCl_2$) in the topsoil sections of pedons, 0-8 cm depth, covered by *Kobresia, Salix* and *Betula.*

Abb. 7: Bodenreaktion (pH $CaCl_2$) im Oberboden, 0-8 cm, an *Kobresia-, Salix-* und *Betula*-Standorten.

under *Betula* stands. The very dark topsoil under *Kobresia* meadows indicate strong grassland effects, i.e. high nitrogen content (N_t), narrow C/N ratios and high soil biological activity (MAAS 2000). In many areas of the Arctic and Subarctic very dark topsoil is associated with grass-like communities (e.g. UGOLINI 1986). Ah horizons enriched in partially decomposed plant remains are typical for continental arctic regions (e.g. EVERETT et al. 1981, UGOLINI 1986, WEBER & BLÜMEL 1994, CHERNIAKHOVSKY 1995). Compared to *Kobresia* sites, under *Betula* stands decomposition of organic matter is very slow and limited by low soil moisture. Under *Salix* stands the decomposition rate of the surface layers is also low. However, as dead *Salix* leaves crush very easily, fine and very fine plant remains are easily incorporated into the Ah horizon by frost churning.

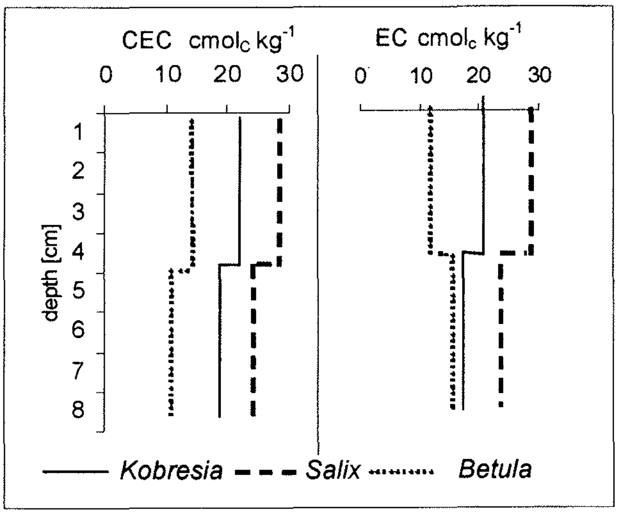

Fig. 8: Cation exchange capacity (CEC) and exchangeable cations (EC) in the topsoil sections of pedons at 0-8 cm depth, covered by *Kobresia, Salix* and *Betula.*

Abb. 8: Kationenaustauschkapazität (KAK) und Austauschbare Kationen (AK) im Oberboden in 0-8 cm Tiefe von *Kobresia-, Salix-* und *Betula*-Standorten.

The pH characteristics show clear differences between the pedons (Fig. 7). In the upper layers of the Ah horizons under *Kobresia* and *Salix* stands pH decreases by depth whereas under *Betula* stands pH increases. Under *Salix* and *Kobresia* stands the Ah horizons are weakly to strong acid. Nevertheless, in relation to the properties of the parent material only weak acidification has taken place and, in contrast to the very topsoil, no acidification gradient exists. In pedons under both stands the chemical constitution of dead plant residues from *Salix* and *Kobresia* may prevent leaching and intense acidification. The steep acidification gradient in the uppermost topsoil of *Betula* stands (Fig. 7) derived from organic acids released from the *Betula* litter (e.g. CHAPIN et al. 1986, DE GROOT et al. 1997). The acidification formed strong dystric soil properties marked by low CEC (Fig. 8) and great leaching potential (Fig. 9, Tab. 1 and Tab. 2).

The unbuffered CEC in Ah horizons of the present vegetation mosaic of *Salix, Kobresia* and *Betula* mainly ranges between 13 and 30 $cmol_c\,kg^{-1}$ reflecting the properties of the relative coarse grained soil texture and the different humus properties (Fig. 8). Highest CEC, approximately about 30 $cmol_c\,kg^{-1}$, and a single maximum about 56 $cmol_c\,kg^{-1}$ were measured under moist *Salix* stands (S3) as result of the high humus content and the very weakly acid to neutral soil reaction. The unbuffered CEC is lower but comparable to the buffered CEC of approximately 18-23 $cmol_c\,kg^{-1}$ under *Kobresia* stands (OZOLS 2002). Soils under both stands show a small decrease in the total of exchangeable cations (EC), especially in the section of 4-8 cm. In soils under *Betula* stands CEC is lowest and EC increases from about 8 $cmol_c\,kg^{-1}$ to an EC of 12 $cmol_c\,kg^{-1}$ in the depth of 4-8 cm. In case of *Kobresia* and *Salix* stands the eolian silt deposition causes a buffering effect and indicates favourable humification and stable humic substances. The relative low CEC at the very topsoil under *Betula* stands compared to *Salix* and *Kobresia* stands points to cation loss with high Al and Fe release. The analyses of experimental equilibrium soil pore solution (ESPS Tabs. 1-3) support this.

	Kobresia (n = 9)			*Salix* (n = 11)			*Betula* (n = 9)		
	mean	min.	max.	mean	min.	max.	mean	min.	max
pH	6.2	5.3	6.8	5.9	5.2	6.2	5.4	5.0	6.2
μS (cm^{-1})	196.0	127.0	222.0	98.0	62.0	147.0	173.0	101.0	312.0
TOC(mg l^{-1})	23.0	12.0	41.0	14.0	5.0	27.0	32.0	11.0	73.0
NH_4^+(mg l^{-1})	8.0	6.0	10.0	9.0	5.0	14.0	5.0	3.0	8.0
Ca (mg l^{-1})	11.0	5.9	19.3	7.0	3.0	12.0	11.0	4.2	22.3
Mg (mg l^{-1})	10.0	9.0	12.0	5.0	2.0	8.0	8.1	4.3	17.0
K (mg l^{-1})	28.0	14.0	50.0	13.0	5.5	25.0	18.0	6.4	42.0
Na (mg l^{-1})	9.0	4.0	13.0	4.0	1.8	8.0	6.3	2.2	15.0
Fe (mg l^{-1})	2.0	0.6	4.2	0.9	0.3	1.4	3.8	1.4	7.0
Al (mg l^{-1})	0.9	0.3	2.3	0.5	0.1	1.2	2.3	1.2	5.3

Tab. 1: Chemical characteristics of equilibrium soil pore solution (ESPS) from different vegetation pattern.

Tab. 1: Chemische Zusammensetzung der Gleichgewichts-Bodenporenlösung (GBPL) aus den verschiedenen Vegetationsbeständen (Mittel-, Minimum- und Maximumwerte).

Stand	pH	μS	TOC	Ca	Mg	K	Na	Al	Fe
Salix	0.3	27.0	6.1	2.2	1.8	6.4	1.9	0.4	0.5
Kobresia	0.6	38.6	12.2	4.5	3.8	11.9	3.0	0.7	1.7
Betula	0.3	75.4	22.4	6.5	5.2	11.3	4.3	1.9	2.4

Tab. 2: Standard deviation of ion concentration in equilibrium soil pore solution (ESPS).

Tab. 2: Standardabweichung der Ionenkonzentration in der Gleichgewichts-Bodenporenlösung (GBPL).

	Ca/Al	Mg/Al	Ca/H	Ca/Mg	Ca/K	Mg/K	C/Al	C/(Al+Fe)	Al/Fe	C/K	C/Ca	C/H
Salix	7.0	8.0	0.3	0.8	1.0	1.0	46.0	28.0	1.6	7.0	7.0	5.0
Kobresia	4.0	6.0	0.2	0.7	0.7	1.0	31.0	22.0	2.4	5.0	0.1	3.0
Betula	2.0	3.0	0.1	0.8	0.8	1.0	21.0	14.0	2.1	8.0	0.1	7.0

Tab. 3: Molar quotient of equilibrium soil pore solution (ESPS).

Tab. 3: Mol-Verhältniszahlen in der Gleichgewichts-Bodenporenlösung (GBPL).

Apparent differences in the equilibrium soil pore solutions of the pedons are shown by conductivity, TOC and ion concentration (Tab. 1). Variations in conductivity, TOC and ion concentrations in ESPS (Tab. 2) probably depend on plant communities, site variability, and the permafrost regime. The different amounts of cations (Tab. 1) and the increasing molar ratio of Ca/Al, Mg/Al and C/Ca from soils associated with *Betula-*, *Kobresia-* or *Salix* stands (Tab. 3) reflect increasing organic complexants and mobility of acid cations in soil solution inversely proportional related to soil organic carbon (C_{org}) content. Compared to the soils under *Betula* and *Kobresia* stands the wide ratio of molar Ca/Al, and C/Ca of the ESPS of *Salix* results from the removal of bi- and trivalent cations from solution into insoluble forms caused by relative high pH. This process is enhanced by organic matter and recent sediment deposition. The high amounts of soluble organics (Tab. 1) in ESPS of soils associated with *Kobresia* and *Betula* stands indicate a relationship first to the low content of humic substances and second to the different degree of humification in these stands (OZOLS 2002). Compared to the ESPS from topsoil under *Kobresia* and *Salix* stands, at *Betula* stands ESPS is enriched in metal complexes mainly with Al complexants, as is indicated by the wide Al/Fe and the narrow C/Al and C/(Al+Fe) ratios in the equilibrium soil pore solution (Tab. 3).

The leaching and migration potential of metal-organic complexes is illustrated by Figure 9. The correlation (R^2 = 0.9) between water soluble organic carbon and the acid metal ions confirms the strong dystric properties at *Betula* stands. At *Kobresia* sites the soil pore solution probably contain high amounts of soluble organic carbon (TOC). Compared to *Betula* stands, no acidification, CEC decrease and correlation between TOC and free or complexed iron and aluminium ions (R^2 = 0.01, Fig. 10) has been observed. This indicates the genesis of nutrient-rich soils. In general, soil pore solution at *Kobresia* sites contains low amounts of free (Fe+Al) ions. Manganese is generally very low and therefore was not determined. The high metal (Fe+Al) sum at two plots may result from a *Betula* cover before *Kobresia* invaded the sites. This succession may also explain the high standard deviation in soil chemical properties (Tab. 3). However, most of the differences in ion concentration and water soluble carbon at the *Kobresia* stands must be attributed mainly to differences in soil moisture. Data show highest nutrient content and highest CEC in all stands from moist sites represented by S3.

From profile analyses (Figs. 10-12, Fe and Al data) it is evident that brunification increase in subsoils. In view of the recent relatively cool climatic conditions in some profiles it

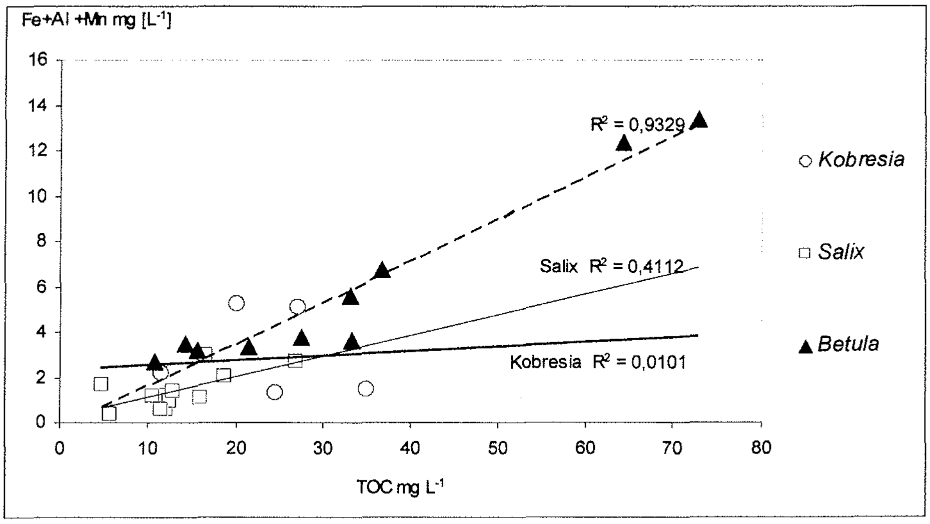

Fig. 9: Acid cations (Fe+Al+Mn) versus total organic carbon (TOC) in equilibrium soil pore solution (ESPS), 0-6 cm.

Abb. 9: Summe der sauren Kationen und der Gesamtkohlenstoffgehalte (TOC) in der Gleichgewichts-Bodenporenlösung (GBPL), 0-6 cm.

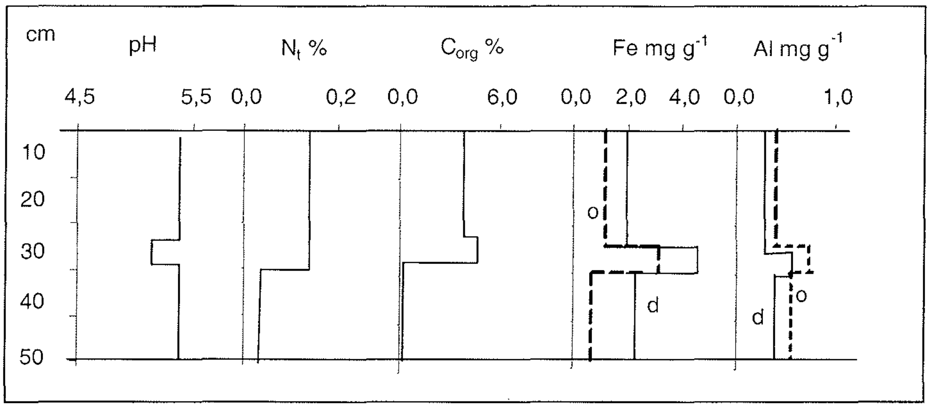

Fig. 10: Soil profile characteristics of the *Kobresia* pedon (N_t = total nitrogen, C_{org} = organic carbon, o = ammonium oxalate soluble, d = dithionite citrate soluble).

Abb. 10: Profilcharakteristik der Böden unter *Kobresia*, N_t = Gesamtstickstoff, C_{org} = Gesamtkohlenstoff, o = ammoniumoxalat-löslich, d = dithionitcitrat-löslich).

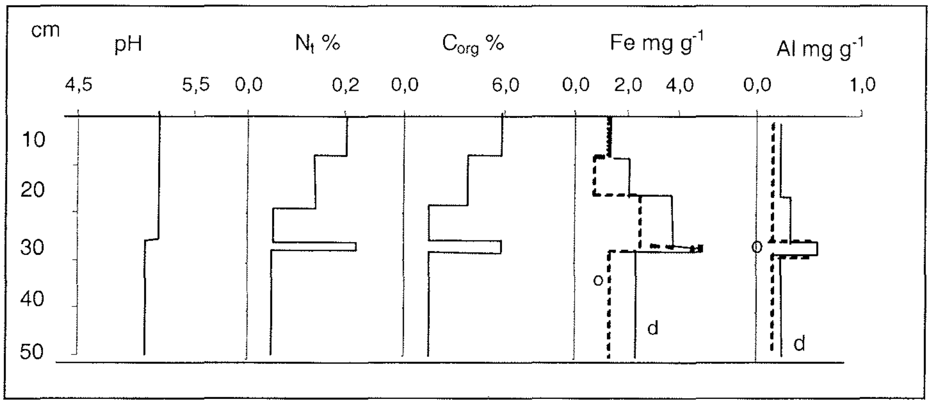

Fig. 11: Soil profile characteristics of the *Salix* pedon (N_t = total nitrogen, C_{org} = organic carbon, o = ammonium oxalate soluble, d = dithionite citrate soluble).

Abb. 11: Profilcharakteristik der Böden unter *Salix* (N_t = Gesamtstickstoff, C_{org} = Gesamtkohlenstoff, o = ammoniumoxalat-löslich, d = dithionitcitrat-löslich).

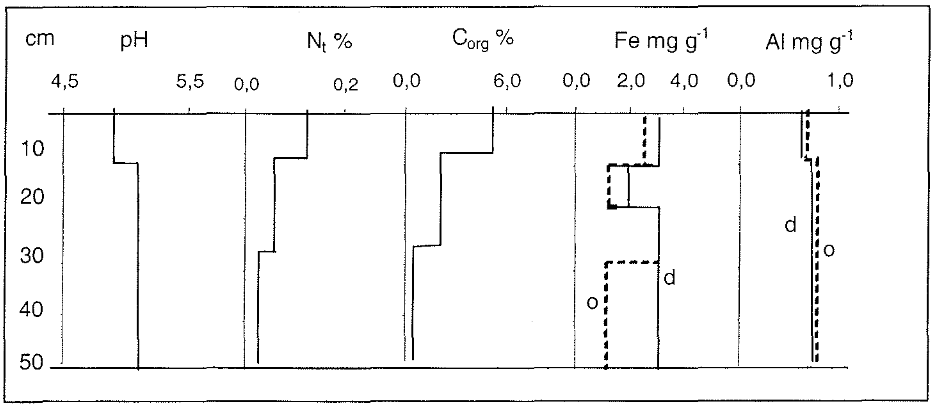

Fig. 12: Soil profile characteristics of the *Betula* pedon (N_t = total nitrogen, C_{org} = organic carbon, o = ammonium oxalate soluble, d = dithionite citrate soluble.

Abb. 12: Profilcharakteristik der Böden unter *Betula* (N_t = Gesamtstickstoff, C_{org} = Gesamtkohlenstoff, o = ammoniumoxalat-löslich, d = dithionitcitrat-löslich).

might be supposed that these features mainly result from a previous warmer climate (Holowaychuk & Everett 1972, Scholz & Grottenthaler 1988). At surface layers (0-8 cm) processes are mainly driven by vegetation and silt deposition. The most striking differences in chemical properties of these pedons are based on the properties of soil organic matter. At *Kobresia* and *Salix* pedons (Figs. 10-11) brunification is superimposed by melanisation. Melanisation will be favoured by continuous sediment accumulation and the release of cations from organic matter, especially from calcium of *Salix* litter. Ugolini (1986) emphasized that these processes are effective at non-heath vegetation and are supported by continuous sedimentation of eolian material. Root residues as well as migration of fine and very fine organic particles by frost dynamic processes are forming thick dark-coloured A horizons, which are characterized by medium to high humus content and high nutrient content. High nutrient release from plant residues, especially from Ca will prevent migration of soil organic matter and metal-organic complexes as well as weathering, what is obvious under *Salix* sites (Fig. 11). Even the low decomposed organic matter entraps cations, supported by high soil pH. High nutrient content will improve soil biological activity and drive humification processes into stable and insoluble Ca-fulvates as well as into well humified organic substances. These processes will enhance melanisation and form dark coloured, medium acid, biologically active nutrient-rich soils. Soils showing these conditions seem to be restricted to continental arctic areas (Weber & Blümel 1994, Cherniakhovsky 1995). Also, they are restricted to non-heath vegetation forms such as the *Kobresia* meadows in continental West Greenland. Undoubtedly, plants and eolian sediments as well as the continental climate are the controlling factors. Compared to *Salix* stands, the high TOC content in soil solution of *Kobresia* stands is not in contrast to this as migration of organo-metal complexes could not be observed. The strong dystric properties under *Betula* sites (Fig. 12) are forced by the quality of *Betula* leaves. Sklerenchym-rich leaf cells do not allow fast chrushing and incorporation of plant residues as is typical of the Ah horizons of the *Salix* pedons. The strong acidic reaction in the organic surface layer as well as in the very topsoil of *Betula* sites is caused by the high content of phenolic acids (Chapin et al. 1986) and other organic acids (Prudhomme 1983, De Groot et al. 1997). These organics will promote decomposition by fungi, which produce more fulvic acids and lower cation sorption. Metal leaching caused by fulvic acids occur already at weakly acid regimes (Jacobsen 1989, 1991, Ugolini & Sletten 1991) and promote strong dystric pedons at these well-drained strong continental sites. Thus, the polar continental climate promotes very dark medium to humusrich soils at non-heath sites, whereas at heath sites, and in particular under *Betula* cover, strong dystric to very slightly podzolized soils developed.

CONCLUSIONS

The study of soils at the xerocryic vegetation mosaic at head of Søndre Strømfjord gives evidence of different soil ecological processes resulting from different plant cover. The following features have been useful to show differences: humus profile morphology, organic matter quality of the A horizons, pH, CEC as well as the equilibrium soil pore solution. Soil acidity and cation exchange at these coarse loamy and quartz-rich soil fabrics and the organic matter are modified by the different properties of current plant remains. The fast chrushing leafs of *Salix* form thick A horizons rich in small fibric, often crustic organic matter. This formation is the result of strong continental climate and based on downward movement of small organic matter particles by frost dynamic processes. Nutrient content of plant remains and accumulation of eolian sediments drive the formation of stable humic substances preventing leaching and migration of cations, organics and acids. Thus, very dark nutrient-rich and, despite the chemical constitution of the parent material, relative base rich soils developed. Under *Kobresia* sites very dark grey to black Rhizomull soils with epipedons in melanic phase are formed mostly influenced by sediment accumulation and high below-ground biomass production. From soil reaction as well as the high CEC at these stands it seems to be obvious that the soluble organics do not lower pH and do not force the migration of cations. But from the study of the equilibrium soil pore solution it is obvious that the tri- and bivalent cations are more mobile in soil pores, whereas at *Salix* sites calcium, magnesia as well as aluminium are mainly entrapped in the organic matter. The constitution and the chemical composition of *Betula* leaves force the weathering and leaching processes in the A horizon. Compared to *Salix* communities, at *Betula* sites accumulated eolian sediments are not able to buffer against acidification. The low humus content at these sites reduces CEC and forces migration of organics and ions. On the other hand, low precipitation reduces leaching events.

ACKNOWLEDGMENTS

We thank Johannes Maas who assisted in the field in 1998. Mr. Bent Broederson from KISS Centre (Kangerlussuaq, Greenland) provided logistical support, for which we are grateful. Special thanks go to Dr. Charles Tarnocai, Agriculture and Agri-Food Canada, for comments on an earlier version of this manuscript.

References

Bell, K. & Bliss, L.C. (1979): Autecology of Kobresia bellardii; why winter snow accumulation limits its local distribution.- Ecological Monogr. 49: 377-402.

Blümel, W.D. (Hrsg.) (1992): Geowissenschaftliche Spitzbergen-Expedition 1990 und 1991, Stofftransporte Land-Meer in polaren Geosystemen Zwischenbericht.- Stuttgarter Geograph. Stud. 117: 1-416.

Blümel, W.D. (1999): Physische Geographie der Polargebiete.- Teubner Studienbücher, Stuttgart, Leipzig, 1-239.

Böcher, T.W. (1954): Oceanic and continental vegetation complexes in south west Greenland.- Meddel. Grønland 148: 1-337.

Böcher, T.W. (1959): Floristic and ecological studies in West Greenland.- Meddel. Grønland 156: 1-69.

Böcher, T.W. (1963): Phytogeography of middle West Greenland.- Meddel. Grønland 148: 1-287.

Broll, G. (1994): Influence of soil mosaic on biodiversity at heath sites in the European Subarctic.-Transactions 15th World Congress of Soil Science 4: 220-231.

Broll, G., Tarnocai, C. & Müller, G. (1999): Interactions between vegetation, nutrients and moisture in soils in the Pangnirtung Pass area, Baffin Island, Canada.- Permafrost and Periglacial Processes 10: 265-277.

Brown, J., Ferrians, O.J., Heginbottom, J.A. & Melnikov, E.S. (1997): Circum Pacific Map 0-607-88745-1, Permafrost and ground conditions.- US Geological - Ice Survey Series CP-45. Reston, VA, USA.

Chapin, F.S., McKendrick, J.D. & Johnson, D.A. (1986): Seasonal changes in carbon fractions in Alaskan tundra plants of differing growth form: Implications for herbivory.- Journ. Ecology 74: 707-731.

Chapin, F.S. & Körner, C. (eds.) (1995): Arctic and alpine biodiversity: patterns, causes and ecosystems consequences.- Springer Verlag, Berlin, Heidelberg, New York, London, 332.

Cherniakhovsky, D.A. (1995): Ecologic-genetic analysis of tundra-steppe soils in northeastern-siberia.- Translated from Pochvovedeniye, No 5, 541-550, in: Eurasian Soil Science (1996) 27: 12-25.

Cooper, D.J. & Sanderson, J.S. (1997): A mountain Kobresia myosuroides fen community type in the southern Rocky Mountains of Colorado, U.S.A.- Arctic Alpine Res. 29: 300-303.

Daniels, F.J.A., Bültmann, H., Lünterbusch, Ch. & Wilhelm, M. (2000): Vegetation zones and biodiversity of the North-American Arctic.- Ber. Reinhold-Tüxen-Gesellsch. 12: 131-151.

Daniels, F.J.A. & Wilhelm, M. (2002): On the way to an integrated vegetation map of Greenland.- USGS Open-file report 02 - 181: 22-34.

De Groot, W.J., Thomas, T.A. &. Wein, R.W (1997): Betula nana L. Betula glandulosa Michx.- Journ. Ecology 85: 125-264.

Dijkmans, J.W.A. (1989): Seasonal frost mounds in an eolian sandsheet near Søndre Strømfjord, W. Greenland.- Permafrost 5th Internat. Conf. Proc. Vol. 1: 728-733.

Dijkmans, J.W.A. & Törnquist, T.E. (1991): Modern periglacial eolian deposits and landforms in the Stroemfjord area, West Greenland and their paleoenvironmental implications.- Meddel. Groenland Geosci. 25. 1-39.

Edwards, A.C. & Cresser, M.S. (1992): Freezing and its effect on chemical and biological properties of soil.- Advances Soil Sci. 18: 59-79.

Everett, K.R., Vassiljevskaya, V.D., Brown, J. & Walker, B.D. (1981): Tundra and analogous soils.- In: L.C. BLISS, J.B. CRAGG, D.W. HEAL & J.J. MOORE (eds.), Tundra ecosystems: a comparative analysis, Cambridge Univ. Press, Cambridge, 139-179.

Fisk, M.C., Schmitt, K.S., & Seastedt, T.R. (1998): Topographic patterns of above- and belowground production and nitrogen cycling in alpine tundra.- Ecology 79: 2253-2266.

Fredskild, B. & Holt, S. (1993): The West Greenland "Greens" - favourite caribou summer grazing areas and late holocene climatic change.- Geografisk Tidsskrift 93: 30-38.

Giblin, A.E., Nadelhoffer, K.J., Shaver, G.R., Laundre, J.A. & McKerrow, A.J. (1991): Biogeochemical diversity along a riverside toposequence in arctic Alaska.- Ecol. Monogr. 61: 415-435.

Hansen, K. (1969): Analyses of soil profiles in dwarf-shrub vegetation in south Greenland.-Meddel. Grønland 178: 1-33.

Harris, S.A. (1987): Influence of organic layer thickness on active-layer thickness at two sites in the western Canadian arctic and subarctic.- Erdkunde 41: 275-285.

Harris, S.A. (1998): Effects of vegetation cover on soil heat flux in the southern Yukon Territory.- Erdkunde 52: 265-285.

Hildebrand, E.E. (1986): Ein Verfahren zur Gewinnung der Gleichgewichts-Bodenporenlösung.- Z. Pflanzenernährung, Düngung und Bodenkunde 149: 340-346.

Hobbie, S.E. (1995): Direct and indirect effects of plant species on biogeochemical processes in arctic ecosystems.- In: F.S. CHAPIN & C. KÖRNER (eds.), Arctic and alpine biodiversity: patterns, causes and ecosystem consequences, Springer Verlag, Berlin, Heidelberg, 213-224.

Holt, S. (1983): Vegetationskartering i et vestgrønlandsk Rensdyfourageringsområde (Holsteinborg Kommune) baseret på falskfarve-infrarøde luftfotografering og floristiske un dersøgelser.- Unpubl., Univ. Copenhagen, 1-180.

Holowaychuk, N. & Everett, K.R. (1972): Soils of the Tasersiaq area, Greenland.- Meddel. Grønland 188: 1-35.

Jakobsen, B.H. (1989): Evidence for translocations into the B horizon of a subarctic podzol in Greenland.- Geoderma 45: 3-17.

Jakobsen, B.H. (1991): Multiple processes in the formation of subarctic podzols in Greenland.- Soil Science 152: 414-427.

Maas, J. (2000): Humusformen in Kobresia myosuroides-Steppen und angrenzenden Zwergstrauchheiden bei Kangerlussuaq (West-Grönland).- Unpubl. Diplomarbeit, Univ. Münster, 1-88.

Marion, G.M. & Black, C.H. (1987): The effect of time and temperature on nitrogen mineralization in arctic tundra soils.- Soil Sci. Amer. J. 51: 1501-1508.

Matthes-Sears, U., Matthes-Sears, W.C., Hastings, S.J. & Oechel, W.C. (1988): The effects of topography and nutrient status on the biomass, vegetative characteristics and gas exchange of two deciduous shrubs on an arctic tundra slope.- Arctic Alpine Res. 20: 342-351.

Mehra, O.P. & Jackson, U.L. (1960): Iron oxide removal from soils and clays by a dithionit-citrate system buffered with sodium bicarbonate.- Proc. 7th Natl. Conf. Clay and Minerals, 317-327.

Nadelhoffer, K.J., Giblin, E., Shaver, G.R. & Linkins, A.E. (1992): Microbial processes and plant nutrient availability in arctic soils.- In: F.S. CHAPIN & C. KÖRNER (eds.) Arctic ecosystem in a changing climate. An ecophysiological perspective, San Diego, 281-300.

Ohba, T. (1974): Vergleichende Studien über die alpine Vegetation Japans (1) Carici rupestris- Kobresietea bellardii.- Phytocoenologia 1: 339-401.

Ozols, U. (2002): Bodenökologische Prozesse in permafrostbeeinflussten Böden Westgrönlands. Vergleich von Kobresia myosuroides-, Salix glauca- und Betula nana-Beständen.- Diss., Inst. Landschaftsökologie Univ. Münster, 1-119.

Prudhomme, T. (1983): Carbon allocation to antiherbivore compounds in a deciduous and an evergreen shrub species.- Oikos 40: 344-356.

Reynolds, J.F. & Tenhunen, J.D. (1996): Landscape function and disturbance in arctic tundra.- Ecological Studies 120, Berlin Hamburg.

Scholz, H. &. Grottenthaler, W. (1988): Beiträge zur jungholozänen Deglationsgeschichte im mittleren Westgrönland.- Polarforschung 58: 25-40.

Schwertmann, U. (1959): Die fraktionierte Extraktion der freien Eisenoxide in Böden, ihre mineralogischen Formen und Entstehungsweisen.- Z. Pflanzenernährung, Düngung und Bodenkunde 84: 194-204.

Shaver, G.R., Laundre, J.A., Giblin, A.E. & Nadelhoffer, K.J. (1996): Changes in live plant biomass, primary production, and species composi-tion along a riverside toposequence in arctic Alaska, USA.- Arctic Alpine Res. 28: 1-31.

Soil Classification Working Group (1998): The Canadian system of soil classification.- 3rd Edition Research Branch, Agriculture and Agri-Food Canada, Publ. 1646, Ottawa, 1-183.

Stäblein, G. (1975): Eisrandlagen und Küstenentwicklung in Westgrönland.- Polarforschung 42: 71-86.

Tedrow, J.C.F. (1970): Soil investigations in Inglefield Land, Greenland.- Meddel. Grønland 188: 1-93.

Ten Brink, N.W. (1975): Holocene history of the Greenland ice sheet based on radiocarbon dated moraines in West Greenland.- Meddel. Grønland 201: 237-243.

Ugolini, F.C. (1986): Pedogenic zonation in the well-drained soils of the arctic regions.- Quat. Res. 26: 100-120.

Ugolini, F.C. & Sletten R.S. (1991): The role of proton donors in pedogenesis as revealed by soil solution studies.- Soil Sci. 151: 59-75.

Weber, L. & Blümel, W.D. (1994): Humuszustand und typische Humusprofile bei Böden der oligotrophen Tundra NW-Spitzbergens.- Z. Geomorphol., Suppl. 97: 243-250.