Impact of vegetation on soil and lake DOC and $\delta^{13}C$

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Degree Thesis in Biology 30 ECTS
Master’s level
Report passed: 30 October 2009
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Contents

Abstract

The climate change is expected to affect especially alpine areas negatively, replacing the alpine flora with subalpine forest. The understanding of how vegetation influences total organic carbon (TOC) in soil, streams and lakes in alpine and subalpine areas will lead to a better understanding of the effects of climate change, and will also increase the knowledge of the ecotone as a whole. In this study plant-soil relations were examined in a subalpine and an alpine catchment in the north of Sweden, by comparing dissolved organic carbon (DOC) concentrations, ^{13}C-DOC, ^{13}C-SOM and the carbon to nitrogen (C:N) ratios. The terrestrial bulk chemical properties of DOC were also compared with lake and stream water DOC, as well as sediment OC from the recipient lakes in the catchments.

The results show that subalpine forests at lower altitudes, have higher DOC concentrations, higher C:N ratios, and more depleted δ^{13}C signals in soil, and soil-solution compared to alpine areas. δ^{13}C signals from Dissolved OM and Particulate OM in water and inlets, show that allochthonous carbon influences water properties in both catchments, as does primary production by benthic and pelagic algae, separating shallow and deep sediment δ^{13}C signals. Differences between the catchments are explained with the higher primary production of organic material and root exudations from trees in the subalpine forested catchment effecting the whole catchment dynamics.

Introduction

Soil organic matter is the largest terrestrial reservoir of fixed carbon. It is about two times larger than that of atmospheric carbon and almost three times larger than that of the biotic pool (Lal *et al.* 1998). The main sources of carbon to the mineral layer in soils, where 70 to 80 % of the organic carbon is found (Callesen *et al.* 2003), is root litter, and dissolved organic carbon (DOC) (Berggren *et al.* 2008). Carbon storage in soils from alpine areas are in general greater than in others, and alpine mineral soils account for 3.5% of total carbon storage worldwide (Lal *et al.* 2000). Increased global temperatures, which are a consequence of increased levels of anthropogenic greenhouse gases such as CO_2 and CH_4, is expected to affect especially alpine areas negatively (IPCC 2007). The alpine flora is predicted to be replaced by subalpine forest types due to an upward movement of the tree line, which is thought to be a consequence of the higher settling and surviving rates of seedlings in a warmer climate (Kullman 2002; Dirnböck *et al.* 2003). Soil type, soil structure, and carbon storage capacity, affect and are affected by vegetation, and plant production in the biotope (Oksanen and Ranta 1992; Balesdent *et al.* 1993; Makipaa 1995; Austrheim and Eriksson 2001; Heer and Korner 2002; Walker *et al.* 2006; Björk *et al.* 2007). Vegetation also influences soil properties, such as carbon accumulation, and losses (Yarie and Billings 2002; Sjögersten 2003), either via soil respiration or losses of dissolved organic matter (DOM) through surface and ground water.

It is necessary to realize the importance of turnover of terrestrial Organic Carbon (OC), from soil via water systems into atmospheric systems, where it affects the atmospheric carbon balance

(Kalbitz *et al.* 2000; Xiang *et al.* 2009). The cross-boundary exchange of organic carbon between ecosystems (e.g. between riparian zones and lakes) has been acknowledged by ecologists for some time (Summerhayes and Elton 1923; Wiens *et al.* 1985). The largest bulk of allochthonous material consists of detrital organic matter in dissolved and particulate form (Polis *et al.* 1997) and is allocated by drainage. Especially in arctic and sub-arctic regions, allochthonous organic carbon, AOC, is a major contributor to lake production, supplying lakes with as much as half or more of their bioactive carbon (Hope 1994; Karlsson *et al.* 2003; 2004; Ask *et al.* 2008). Alpine lakes, that generally are net heterotrophic, act as CO2-sources to the atmosphere (Sjögersten 2003; Post *et al.* 1992; Cole *et al.* 1994; Hope 1994; Karlsson *et al.* 2004; 2007) which further stresses the importance of understanding land-lake carbon interactions, especially since DOC concentrations in lakes also vary depending on regional characteristics and catchment soil properties (Sobek *et al.* 2007).

In mountain regions, differences in air and soil temperatures along with higher altitudes, play a vital role for vegetation and soil characteristics. The cold and wet climate typical of mountain areas, where warm moist air cools off at higher altitudes, leads to temperature differences of about 0.5◦ C per 100 m rise in altitude. Colder temperatures in air and soil can lead to increased carbon and nutrient storage capacity, since decomposition is slower, but also facilitates terrestrial leaching to surroundings (e.g. to lakes and watersheds) as primary and secondary production by organisms are low (Robinson *et al.* 1997; Christensen *et al.* 1999; Stiling 2004; Parfitt 2005). Low soil temperature also typically leads to a decrease in vegetation growth, mineralization (Ross *et al.* 2004; Murphy *et al.* 2007) and available nutrients (e.g. nitrogen) in the soil. (Cassman and Munns 1980; Thiel and Perakis 2009). Therefore, decreasing soil temperatures can have a positive effect on C:N ratios (Parfitt 2005; Huber *et al.* 2007).

A decrease in altitude, implying higher temperatures, can give an advantage in vegetation growth, especially to fast growing, more generalistic species, and subsequently a higher degree of biodegradable material and carbon in the soil. The decreased influence by lower temperatures on nitrogen availability, and its impact on plant species composition may also further add to vegetative changes already occurring due to climate change, where cold enduring species, which are generally poor nutrient competitors, get outcompeted by more fast growing generalists (Chapin *et al.* 1995). As DOM is affected by litter decomposition from various heterotrophic (microorganisms, bacteria, fungi etc.) and autotrophic organisms (plants and algae) (Kuzvakov 2005) more litter decomposition from plants can increase carbon content and DOC in soil. Tree root systems also leach carbon through root exudation (Post *et al.* 1992; Cornelissen *et al.* 2004) and since tree lines are very much affected by temperature, a warmer climate could lead to higher DOC content in soil, as reported by Rattan et al. (2000). Both carbon and nitrogen soil cycles also vary with landscape mosaic, season and soil moisture as well as with temperature (Ross *et al.* 2004; Murphy *et al.* 2007; Rodinov *et al.* 2007; Xiang *et al.* 2009).

Differences in altitude are also known to affect terrestrial plant carbon isotopic signatures ($\delta^{13}C$) in mountain regions, since plant $\delta^{13}C$ values at high altitudes are typically enriched (Körner *et al.* 1988; 1991) compared to the carbon signatures of plants from low altitudes. Soil organic matter also show enrichment in ^{13}C with soil depth, which is suggested to be a consequence of humification and the loss of the lighter isotope (^{12}C) via respiration, thus concentrating ^{13}C in the soil organic matter (Kramer *et al.* 2003). This might be transitional to temperature and differences in decomposition. Moreover, the isotopic carbon signatures of autochthonous and allochthonous food-sources in aquatic ecosystems are generally separated, which is also reflected in the consumer community. Stable isotope analysis is therefore a useful method for determining the autotrophic or heterotrophic character of lake food webs (Karlsson *et al*. 2003; 2007).

The influence of changes in vegetation, how these can function as a reflection of soil properties, i.e. function as an indicator of carbon storage, and how differences in vegetation and soil properties in turn influence stream and lake properties, as well as net ecosystem production, remain poorly understood. Detecting differences between physical factors on land, i.e. vegetational differences, and their effect on total organic carbon (TOC) dynamics will lead to a greater understanding of the alpine and subalpine ecotone as a whole (Kalbitz *et al*. 2000; Xiang *et al*. 2009). In this study, plant-soil relations were examined by comparing dissolved organic carbon (DOC) concentrations, ^{13}C-DOC, ^{13}C-SOM and the carbon to nitrogen (C:N) ratios between an alpine catchment (i.e. above the treeline) and a subalpine catchment (i.e. immediately below the treeline) in northern Sweden. The terrestrial bulk chemical properties of DOC were also compared with lake and stream water DOC, as well as sediment OC of the recipient lakes in the two catchments. The specific hypotheses of this study were that (1) vegetation and/or altitude affect ^{13}C-DOC in the soil and (2) the terrestrial soil composition is reflected in lake DOC and sediment organic matter.

Material and methods

Study sites

The study sites are situated in the north of Sweden within a radius of 55 kilometers of Abisko Scientific Research Station. The area is highly affected by surrounding mountains, which provide a local rain shadow, leaving the area with roughly 300 mm precipitation. The snow-cover lasts for 200-240 days and the growth season runs for 100-120 days (Barnekow 2000; Abisko Scientific Research Station 2007). Annual mean temperature is approximately -1.0˚C, July being the warmest month (mean about +11˚C) and January the coldest (mean −12˚C) (Abisko Scientific Research Station). The two subarctic catchments and lakes chosen for this study, Lake Suoruoaivi and Chabrak, were deep enough to exclude primary production at the deep bottom, enabling the possibility to distinguish between autochthonous and allochthonous OC in the profundal sediments (Carlsson *et al*. 1999). There is a temperature difference of about 3˚ C in the two catchments primarily due to the lapse rate of about 0.5˚ C per 100 m. The vegetation is extremely varied, ranging from simple communities following retreating glaciers to more complex mountain birch forest ecosystems (*Betula pubescens* ssp. *tortuosa*), which also form an altitudinal tree line at about 700 m a.s.l. Characteristic plants in the field layer are crowberry (*Empetrum hermaphroditum*), lingonberry (*Vaccinium vitis-idaea*), bilberry (*Vaccinium myrtillus*), grasses and sedges (Heinrichs *et al.* 2006; Björk *et al*. 2007).

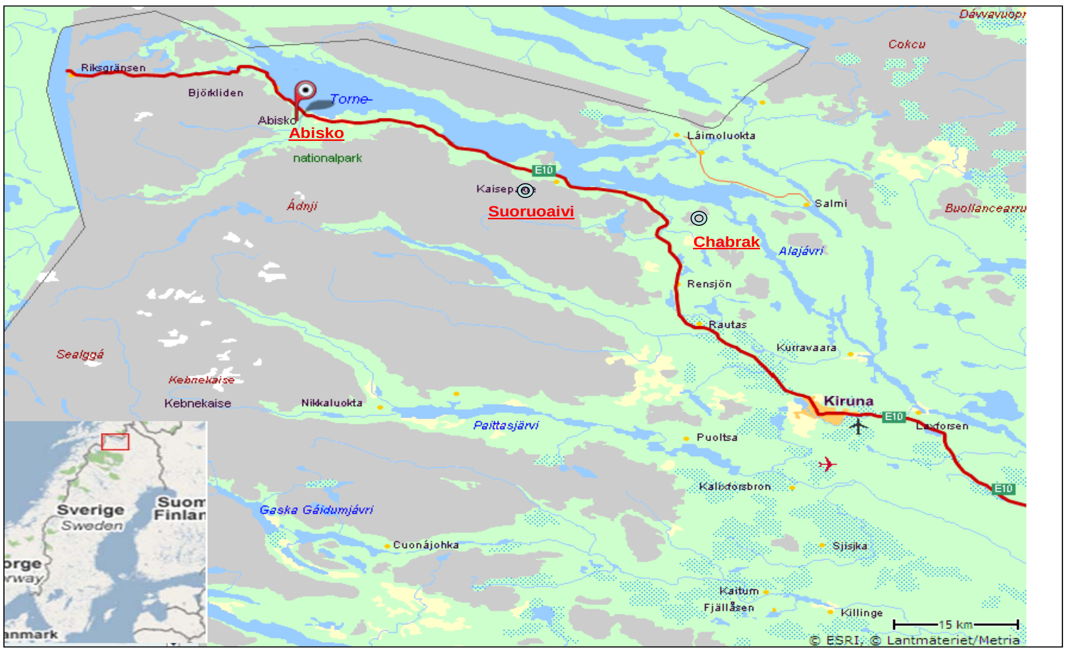

Fig. 1. Map of sample sites.

Chabrak, Cabraluoppal – Dödsjön

The lake in the Chabrak area is in native tongue called Dödsjön, meaning the dead lake, and is referred to as Chabrak throughout this study. The lake is at its deepest 11 m with one sampled major water inlet running through mountain birch forest and moss-dominated vegetation, and one sampled outlet. It is situated in the subalpine birch forest at about 520 m.a.s.l. (N: 68 101 98, EO: 19 51 879). Soil and water sampling were performed between mid July and mid August, 2006. The mean thickness of the humus layer was 7.8 cm (median 8.5 cm). The vegetation is separated into three types: Birch heath forest, Dry heath and Inlet vegetation. The **Birch heath forest**, *Betula pubescens* ssp. *czerepanovii,* covered approximately 90% of the catchment and was found all around the lake. The humus layer mean thickness is 7 cm, (median 7.1 cm) and the vegetation is distinguished by the vast amount of dwarf shrubs, mostly *Vaccinum myrtillus*, in the field layer. In the vicinity of the inlet, the heath forest show a tendency towards more of a meadow vegetation, with more herbs such as *Geranium. sylvaticum* and *Ranunculus acris* ssp. Elements of higher *Salix* sp.*, Alnus incana* and some examples of *Sorbus aucuparia* were found. The **Dry heath vegetation** with humus layer mean thickness 5.5 cm (median 4 cm) is situated above the birch tree level at an altitude of 550-560 m.a.s.l. The vegetation is characterized by small *Salix* shrubs and lichens. The moss dominated **Inlet** with humus layer mean thickness 11.3 cm (median 11 cm) is saturated with water. S*phagnum* sp. and *Hylocomium splendens* dominate the vegetation. For total vegetation lists from the catchment´s three vegetation types see appendix 1a-1c.

Suoruoaivi

Lake Suoruoaivi is situated in the low-alpine vegetation belt at about 1000 m.a.s.l. (N:68 16 712, EO:19 06 153). The lake has a maximum depth of 15 m and is served by several small inlets of which the largest three were sampled. Inlet 1 ran through the meadow snow bed and received water from a smaller pond approximately 50 m above the actual lake Suoruoaivi. Inlet 2 and 3 both ran through minerotrophic low alpine mire. For these two inlets, water originated from snowmelt and from a mountain stream (the stream did not empty into the lake). Both of these inlets decreased in size with the reduction of snowmelt water during the sampling period, and inlet 3 dried out completely towards the end of the sampling period. Soil and water sampling were performed from mid July to early August of 2006. Humus layer mean thickness for the whole catchment is 6.6 cm (median 4.8 cm). The catchment has four separate vegetation types: Mesic heath, minerotrophic low alpine mire, grassland and mesic snowbed. **The mesic heath's** vegetation was majorly consisting of *Carex bigelowii, Deschampsia flexuosa* and *Luzula* sp. The area dried early in the growth season because of its location on a sun exposed slope with no access to snowbeds during the later part of the growth season. The **minerotrophic low alpine mire** was wet all season, with several small water streams. *Eriophorum scheuchzeri* is found in large quantities. The soil smelled of sulphur suggesting anaerobic conditions. **The Grassland** lay on a flat higher up in the catchment limited on one side by a brook and on the other side by boulders. Shadowed by higher mountains it receives water from snowbeds which are present the whole summer period. Here more *Vaccinium* sp. was found than in the mesic heath, togheter with herbs such as *Erigeron uniflorus*, *Dryas octopetala* and *Astragalus alpinus*. **The Meadow snowbed** with snowbed species, that grow and reproduce with speed when snow melts away (Heegaard and Vandvik 2004), is found in the area surrounding the short end inlet of the lake. This inlet receives water from the small pond approximately 50 m above the actual lake Suoruoaivi and the soil had a constant water supply throughout the growth season. The vegetation here consists of herbs such as various sorts of *Ranunculus* sp. and mosses e.g. *Sphagnum* sp. and *Ptilidium pulcherrium*. See total vegetation lists in Appendix 2.

Abisko

A comparison site was picked about 1-2 km from the Abisko research station to assess how the measured parameters responded to variation in weather during the sampling period. This enabled validation of the single sampling occasions in the two lake catchments. The site was placed in mountain birch forest, *Betula pubescens* ssp. *czerepanovii* and had no lake or watercourse in the vicinity and should therefore foremost be influenced by rainfall and groundwater. The ground layer is of a similar nature as the one in Chabrak, heath forest with a *Vaccinium myrtillus* layer, and mosses e.g. *Sphagnum* sp. *Polytrichum* sp. *Hylocomium splendens* and *Pleurozium schreberi*. See total vegetation list in Appendix 3.

Sampling

Soil and soil-solution

In the catchments of each lake, several samples were randomly collected representing the different vegetation types. Soil samples were gathered using an earth sampler with a diameter of 10.7 cm, and all vegetation was removed from the humus before bagging. To gather 150 ml of soil-solution multiple humus layer samples were collected from each specific sampling point.

The number of subsamples increased during drier conditions. The comparison site in Abisko was sampled once every second week by the same method.

From the Chabrak area five soil samples were gathered in the heath forest at various places around the lake. Three subsamples were taken in the inlet vegetation and three samples were taken in the dry heath vegetation. In total eleven subsamples were taken in the Chabrak catchment (Fig. 2).

From the Suoruoaivi area three subsamples were gathered in the mesic heath, five in the minerotrophic low alpine mire, three in the grassland and five at the meadow snowbed. In total sixteen sub samples were gathered from the Suoruoaivi catchment (Fig. 3).

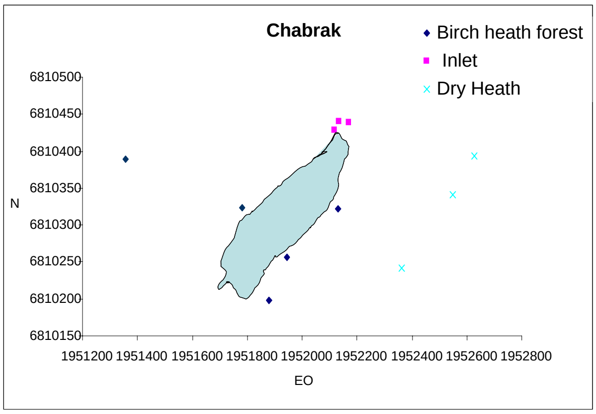

Fig. 2. Sample sites around Chabrak.

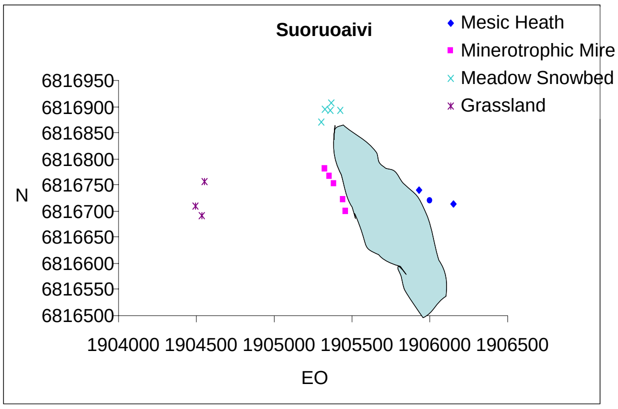

Fig. 3. Sample sites around Suoruoaivi.

Soil samples were weighed before and after every step in the analysis preparation and they were as far as possible kept cold in a refrigerator before and during processing.

The soil samples were centrifuged within 24 hours of sampling, and the water fraction was then immediately frozen. The soil was dried and split into two different subparts. Part 1; to calculate water content, dry weight and the fraction of organic and inorganic compounds in the vegetation types. Part 2; to perform isotopic analysis. The soil-solution was used for DOC, pH, $\delta^{13}C$, and $\delta^{15}N$ analysis.

Stream and lake water

10 L of water was gathered from the inlets and outlets of Chabrak and Suoruoaivi directly into cans. Also, 10 L of lake water was sampled with a Ruttner sampler from different depths at the

deepest part of each lake. The cans were, when taken into lab, kept in cold rooms as far as possible and processed within 24 hours. 100 ml of each can were taken for DOC analysis, and the remaining part used for DOM and POM analysis. $\delta\,^{13}C$, and $\delta\,^{15}N$ analysis were made on both DOM and POM fractions.

Sediment

From both lakes, triplets of sediment from three 2 m sampling locations and one deep sampling location were collected with a sediment corer. Sediments were dried and then frozen until isotopic analysis.

Chemical preparation and isotope analysis

Soil

The centrifuging was made with an Avanti® J-20XP Centrifuge, in a JA-14 fixed Angle Rotor at 14 000 RPM for 30 minutes at 10°C, corresponding to a Relative centrifugal field of 30 100 RCF. A subsample of the soil, Part 1 was dried for 72 h in 70°C and weighed. Loss On Ignition (LOI) was performed in 550°C for 5 h. On the remaining soil, part 2, sifting was performed to separate roots and humus < 2 mm from each other. The humus samples were then dried in paper bags for 72 hours in 70°C, after which they were ground to a fine powder and dried again for approximately 2 h at 70°C to evaporate residue moisture. Samples were then stored in an execator with moisture absorbent material before isotopic analysis.

Soil-solution

The centrifuged soil-solution was thawed and filtered through a 0.22 µm filter. The samples were kept cold in a refrigerator as much as possible while handled. A subpart of 40 ml of the filtered soil-solution was frozen a second time and later used for DOC and pH measurements. The major part ca 100 ml of the soil-solution was freeze-dried, in plastic bottles and the freeze dried material then used for isotopic analysis.

Inlet outlet and lakewater

The major part of the 10 L water samples from the inlet, outlet and lake water of the two lakes was filtered trough a 0.22 µm filter (tangential flow filtration) after which both the filtrate (DOM) and the particulate phase (POM) were freeze dried. Samples were stored in an execator with moisture absorbent material, until used for of isotopic analysis. The subsample from each can of 100 ml was filtered trough a GFF-filter and acidified with 100 µl 1.2 M HCl to clear samples of inorganic carbon. DOC measurements were performed at Abisko research station.

Sediment

All sediment samples were placed on a GF/C-filter and excess water was removed through vacuum suction. The samples were dried in 60°C for 48 h on the GF/C-filter and frozen until isotopic analysis.

Isotopic analysis

Isotopic signature analysis for $\delta^{13}C$, $\delta^{15}N$ ‰ as well as C % and N % was performed on 1.5-2 mg of the samples that were weighted into tin capsules. The Isotopic analyses were made at the Institution for geology and geochemistry, Stockholm University.

The Isotopic signature for carbon was then derived by:

$$\delta^{13}C\ (‰) = 1000 \times \{[(^{13}C\ /^{12}C\ \text{sample})/(^{13}C\ /^{12}C\ \text{standard})] - 1\}$$

And Isotopic signature for nitrogen

δ15N (‰) = 1000 × {[(15N/14N sample)/(15N/14N standard)] – 1}

Results are expressed by the $\delta^{13}C$ and $\delta^{15}N$ notation in per mil (‰).

C/N-ratios = C%/N%

Statistical analysis

One-way ANOVA was used to determine if there were differences in $\delta^{13}C$, C/N ratios and DOC in soil and soil water between the different vegetation types, as well as between forested and non-forested sample sites and also between catchments, lakes and sediment.

In addition all pairs Tukey-Kramer method was used to compare means for $\delta^{13}C$ and CN- ratios in the whole catchment (Fig. 7). Statistical analysis was carried out by t-tests, One-way ANOVA and All pairs Tukey-Kramer method. The software used was the SAS program JMP 7.0.2.

A correlation coefficient, r, for LOI and DOC was calculated in EXCEL. The equation for the correlation is.

$$Correl(X,Y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}}$$

Where x and y are the sample means AVERAGE (array1) and AVERAGE (array2).

Results

Vegetation type comparison

The one-way ANOVA analyses comparing vegetation types from the Suoruoaivi and Chabrak catchments show a large dispersion of values (Fig. 4 and Appendix 4). All ANOVA analyses made to compare DOC, δ^{13}C ‰ and C/N ratio for the soil and soil-solution of the two catchments show statistically significant differences between vegetation types (Fig. 4). DOC mmol in Centrifugate/dw (F=5.2398 DF=6 P=0.0019), soil-solution δ^{13}C‰ (F=14.0170 DF=6 P=0.0001), soil δ^{13}C‰ (F=11.7882 DF=6 P=0.0001), soil-solution C/N ratio (F=8.0523 DF=6 P=0.0001) and soil C/N ratio(F=12.1676 DF=6 P=0.0001). Notice the similarity of dry heath sampled at the non-forested sites in the Chabrak area and the alpine vegetation types sampled in the Suoruoaivi catchment, when looking at both DOC and δ^{13}C‰ signals (Fig. 4). Also the inlet vegetation and Birch heath forest δ^{13}C‰ are similar. The C/N ratios don't show any obvious pattern when comparing vegetation types. A correlation between DOC concentration and LOI from the Abisko site (r=-0.86784), and for all Abisko, Suoruoaivi and Chabrak samples (r=0.42515) were made. The correlation for the Abisko site, indicates a connection between DOC and humus content, despite different weather conditions, i.e. drought, during sample gathering.

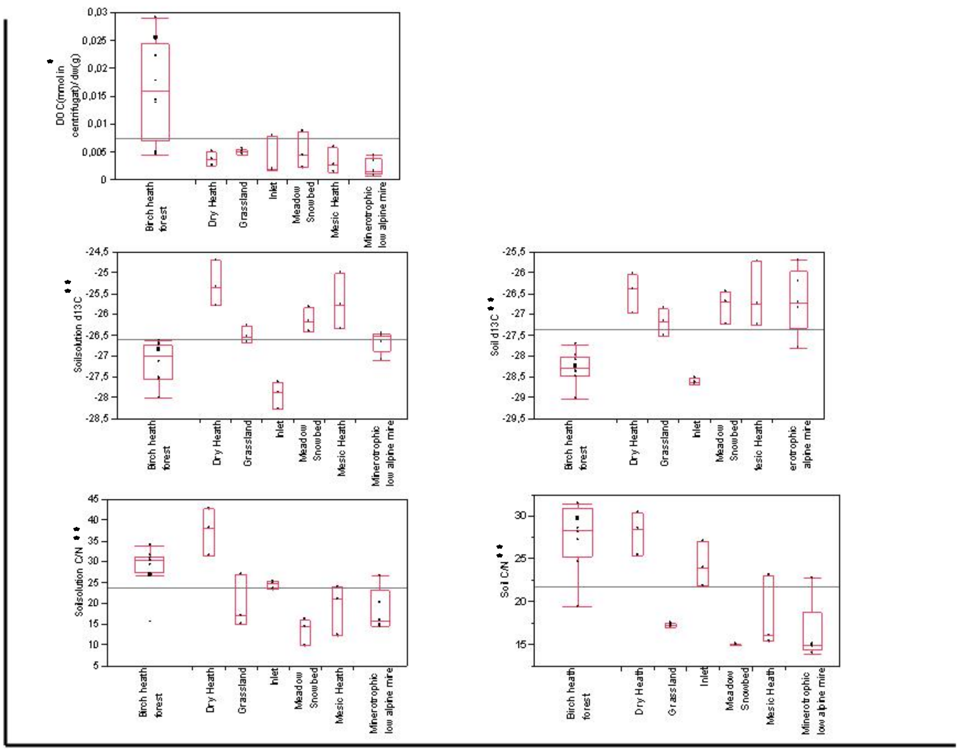

Fig. 4. One-way ANOVA was used to determine difference between vegetation types. To be read top to bottom, left to right displaying results for in order; DOC *, Soil-solution $\delta^{13}C$** , Soil $\delta^{13}C$**, Soil-solution C/N ratio**, Soil C/N ratio ** , The significance levels are * $p<0.01$, ** $p<0.001$ and when no asterisk $p> 0.01$.

Catchment comparison Soil and Soil-solution

The one-way ANOVA analyses made between samples from the two catchments and the comparison site, Suoruoaivi, Chabrak and Abisko suggest that there is much variance within the respective catchments but also between catchments (Fig. 3a-3e). Both the soil C/N ratio (F=40.9749 DF=2 P=0.0001) and the soil-solution C/N ratio (F=13.3260 DF=2 P=0.0001) show that the two catchments that have the most similar vegetation, i.e. the forested sites Abisko and Chabrak, differ from the alpine Suoruoaivi catchment although the results for Suoruoaivi and Chabrak overlap. The same goes for the soil $\delta^{13}C$ ‰ (F=8.3892 DF=2 P=0.0016). The DOC (mmol in Centrifugate/dw), (F=15.8742 DF=2 P=0.0001) shows a resemblance between the Suoruoaivi and Chabrak catchments, although the subsample variance for especially Chabrak is prominent. The soil-solution δ13C, (F=1.8693 DF=2 P=0.1752) did not give any statistically significant difference. However the overall trend when comparing the two catchments and the Abisko sampling site is similarities between Chabrak and Abisko. Abisko sampled on the same location during the whole sampling period has the least within group variance. And it is likely that the major variance when looking at Chabrak is because of the difference between the Dry heath and the Birch heath forest.

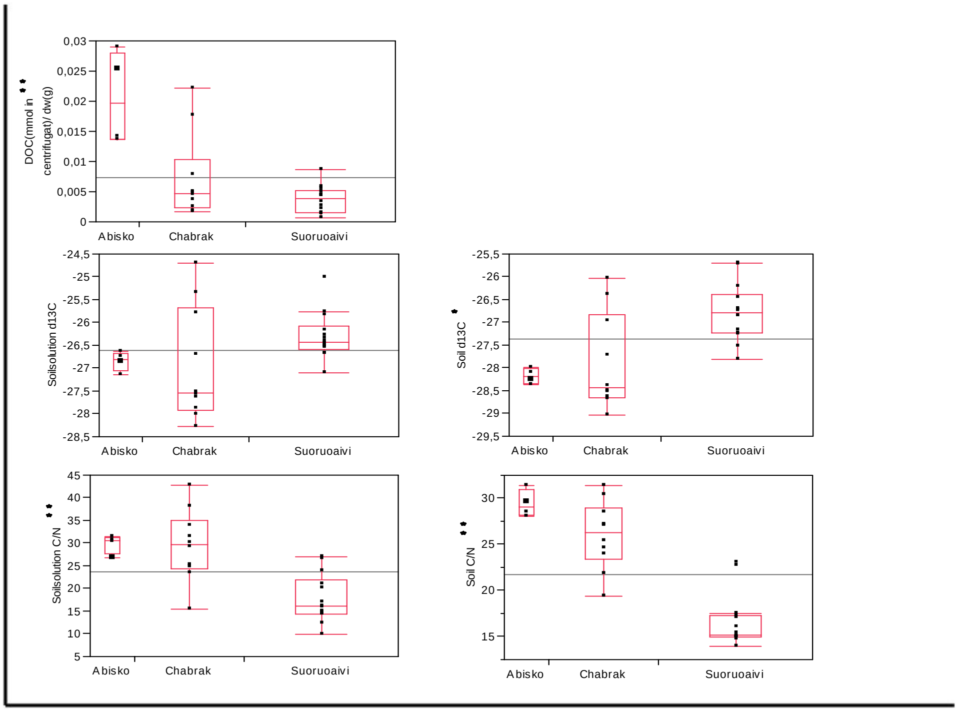

Fig. 5. One-way ANOVA was used to determine difference between the catchments Suoruoaivi, Chabrak and the comparison site in Abisko. To be read top to bottom, left to right displaying results for in order; DOC**, Soil-solution δ13C, Soil δ13C*, Soil-solution C/N ratio**, Soil C/N ratio**. The significance levels are * p<0.01, ** p<0.001 and when no asterisk p> 0.01.

Forested vs. Non-forested/alpine vegetation

To compare forested and non-forested vegetational influence, the vegetation types have been split into two groups indifferent of their respective catchments. The Chabrak site, which had both forested and non-forested vegetation types, has been divided sorting dry heath into the alpine non-forested group. All three of the sample sites data where used, Suoruoaivi, Chabrak and Abisko. Significant differences were found when comparing the one-way ANOVA analyses for forested vs. non-forested DOC (mmol in Centrifugate/dw ((t-ratio=3.860 DF=26 P<0.0007), soil-solution $\delta^{13}C$ ‰ (t-ratio=-5.197 DF=26 P<0.0001), soil $\delta^{13}C$ ‰ (t-ratio=-8.293 DF=26 P<0.0001) and soil C/N ratio (t-ratio=4.33 DF=26 P=0.0002). The soil-solution C/N ratio is found non significant but is on the verge of being significant (t-ratio=2.025 DF=26 P=0.0532). The results suggest that subalpine forests are of major importance when comparing vegetational effects on DOC, soil and soil-solution.

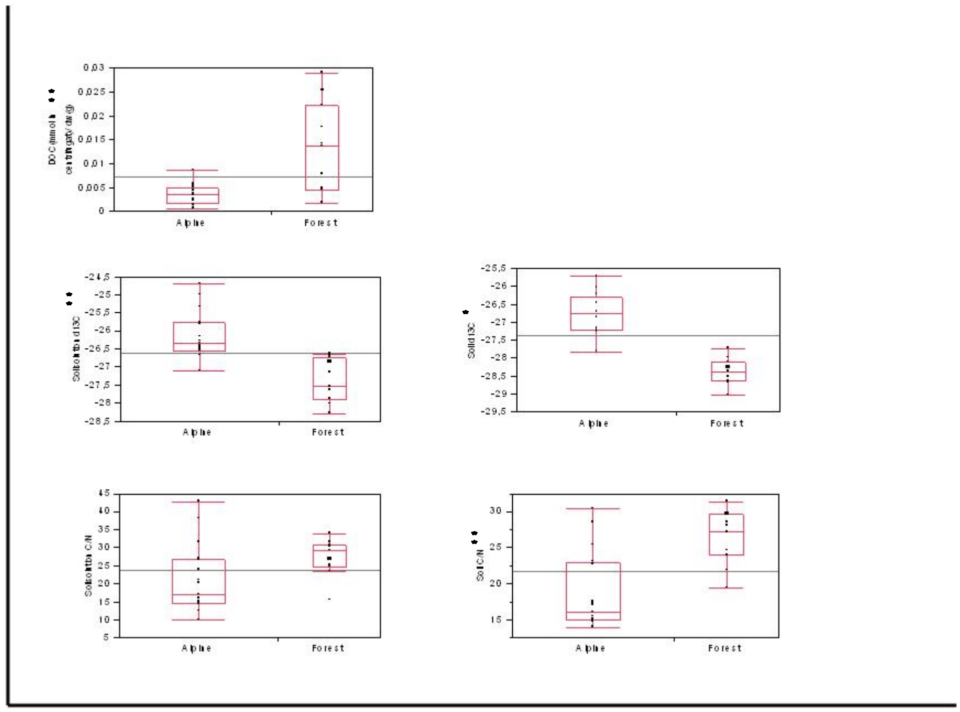

Fig. 6. T-tests were used to test for differences between alpine and forested/ subalpine vegetation types. To be read top to bottom, left to right displaying results for in order; DOC**, Soil-solution $\delta^{13}C$**, Soil $\delta^{13}C$**, Soil-solution C/N ratio, and Soil C/N**, the significance levels are * $p<0.01$, ** $p<0.001$ and when no asterisk $p> 0.01$

Water, shallow sediment and deep sediment

The POM and DOM sampling for Chabrak shows that $\delta^{13}C$ signals from inlet, the free water mass and outlet, all are more similar to soil and soil-solution signals (Tab. 1, Fig. 7), than to sediment signals. When making the same comparison for Suoruoaivi the difference is not as noticeable. Suoruoaivi POM and DOM $\delta^{13}C$ signals, especially for the different inlets, have a large signal spread. The least negative of the inlet signals and the lake water signal, are most similar to the mesic heath soil-solution. POM lake signals however, resembled the minerotrophic low alpine mire soil signal the most. T-testing on any of the water samples, was not possible as they only have one replicate.

Tab. 1. Values from sampled inlet, outlet and lake water in Suoruoaivi and Chabrak. Sites are sampled once and values are absolute.

Lake	**Subsite**	**pH**	**POM $\delta^{13}C$**	**DOM $\delta^{13}C$**	**POM C/N**	**DOM C/N**
Chabrak	Inlet	7.34	-26.97	-26.30	33.95	19.24
Chabrak	Lake	7.11	-26.89	-27.42	24.01	14.70
Chabrak	Outlet	7.65	-26.91	-25.19	22.94	17.30
Suoruoaivi	Inlet 1	6.76	-27.91	-28.40	21.19	16.98
Suoruoaivi	Inlet 2	6.68	-25.72	-25.64	18.23	13.58
Suoruoaivi	Inlet 3	7.15	-24.65	-28.99	17.53	15.18
Suoruoaivi	Lake	7.65	-25.01	-27.46	17.88	9.91
Suoruoaivi	Outlet	6.58	-24.52	-23.90	18.78	12.37

There was a statistical difference between shallow and deep sediment $\delta^{13}C$ signals from the lake (t-ratio=5.469 DF=5.557 P=0.002), confirming difference in carbon sources for deep and shallow sediment. Both of the catchments show that shallow sediment $\delta^{13}C$ are the most enriched when comparing all land and lake signals, and the 1.41‰ difference between the shallow sediments from Chabrak and Suoruoaivi show no statistical difference (t-ratio=-2.825 DF=9.485 P=0.0189). The two lakes deep sediment signals however, differ statistically from each other (t-ratio=11.869 DF=3.675 P=0.0005). Suoruoaivis deep sediment is more similar to Suoruoaivis soil and soil-solution values (Fig. 7) than to Chabrak deep sediment. Chabrak deep sediment differs not only from Suoruoaivis deep sediment, but also from Chabrak catchment soil and soil-solution signals. It is also the most depleted value of all land lake values. Both the water and sediment have low C/N ratios compared to soil and soil-solution ratios.

Fig. 7. One-way ANOVA was used to determine difference in $\delta^{13}C$ values (F=87.6296 DF=7 P=0.0001) seen in top graph and C/N values (F=25.8199 DF=7 P=0. 0001) bottom graph, between the catchments and sediments of Chabrak and Suoruoaivi. All-pairs Tukey-Kramer method was used to clarify the clustering of sample sites by comparing means.

The mean C/N ratios when comparing shallow sediments in the two lakes differed with 3.09 units (t-ratio=-7.654 DF=12.985 P<0.0001). There was no statistically significant difference when comparing the deep sediment C/N ratios (t-ratio=0.826 DF=2.008 P=0.495) although the spread for the Suoruoaivi samples is larger than for the samples from Chabrak.

Discussion

Catchments

DOC concentrations, when comparing vegetation types seem to differ mostly between forested and not forested sites. DOC concentrations were higher in forested vegetation types than at non-forested sampled sites. The difference was observed both within catchments, i.e. Chabrak, as well as between catchments, i.e. Chabrak and Suoruoaivi. The comparison between catchments, between alpine and forested vegetation types, provides an affirmative conclusion that vegetation differences can affect soil properties. The differences between forested and non-forested vegetation types can be explained by soil-feedback mechanisms (Walker *et al.* 2006) such as decomposition and root exudation. Litter decomposition forms a major part of carbon cycling

(Cornelissen *et al.* 2004) and simulations and experimental observations have shown increasing carbon storage with individual tree growth rate and increased root production (Post *et al.* 1992). In forested areas, leaf litter decomposition and big tree root systems lead to a higher degree of root exudation then in non-forested alpine areas, which affects the soil and soil organic carbon (Cornelissen *et al.* 2004) increasing the DOC in soil-solution (Fig. 6).

When comparing DOC and C:N ratios, the apparently higher C:N ratios and the higher DOC concentration in forested sites imply higher carbon storage in warmer soils, or a higher usage of N and faster mineralisation of C. With a lapse rate of about 0.5 to 1° C per 100 m (Raven *et al.* 2003) the difference between the two catchments (Chabrak at ca 500 m.a.s.l. Suoruoaivi at around 1000 m.a.s.l.) would be ~ between 2 and 5° C in temperature. Alpine areas, with a typically cold and wet climate, could according to Robinson *et al.* (1997), Christensen *et al.* (1999) and Stiling (2004), lead to soil having a greater carbon and nutrient storage capacity than soils in subalpine areas, since decomposition is slower. This study however did not support that pattern. If this is depending on lower rates of evapotranspiration in arctic soils that lead to more nutrient leaching (Raven *et al.* 2003) or tree influence in the subalpine area is hard to determine. Most likely my results are linked to both reasons and C/N ratios can depend on the differences in primary production between the catchments, where a high turnover rate and faster plant production, eg. nutrient allocation to live biomass above ground, leaves the C:N ratios higher in warmer soils. Roots that have been excluded in C:N ratio measurements, can possibly give a skew picture of C/N ratio between Chabrak and Suoruoaivi. This since roots in arctic areas can represent as much as 98% of the plant (Raven *et al.* 2003). The correlation between DOC and LOI from both catchments however, show that a higher degree of organic compounds in soil effect DOC concentration.

Both soil and soil-solution $\delta^{13}C$ signal were enriched in alpine vegetation (soil 1.48 ‰ and soil-solution 1.07‰), compared to forested vegetation (both t-tests, $P \leq 0.001$). This supports the pattern where increasing altitude give less negative $\delta^{13}C$ plant signals (Körner *et al.* 1988; 1991) linking vegetational influence to soil properties. The highest $\delta^{13}C$ signal however, was for the dry heath in the Chabrak catchment, a non-forested location at intermediate height ca 400 m below the highest altitude in the Suoruoaivi catchment. This suggests that the difference when comparing forested and non-forested vegetation types not only depends on altitude. Leaf litter, influencing all vegetation types could explain some of the divergence, but since leaf $\delta^{13}C$-signals lie between -29.5 ‰ and -26 ‰ independent of species, (Rundgren *et al.* 2003) it is not likely to be responsible for all of the difference. Tree root exudation (leaching of soluble organic constituents cellulose and hemicellulose), root symbiosis with mycel, and microbial breakdown in addition could affect soil quality and $\delta^{13}C$-signals. Aerobic and anaerobic bacteria (anaerobic bacteria contributing 5-10 % of total bacterial breakdown) prefer $\delta^{12}C$, leaving soil enriched and more fractioned compared to the source substrate. Differences in plant breakdown could also leave the soil enriched in $\delta^{13}C$ (Balesdent *et al.* 1993; Rundgren *et al.* 2003; Cornelissen *et al*. 2004; Adams 2006; Derrien *et al.* 2007). However since forested sites have a higher degree of vegetation, and thus biomass, forested vegetation should be more influenced by plant breakdown processes. It is also plausible that the larger and deeper tree root systems, when compared to smaller plants, have a higher impact on soil, depleting soil substrate.

The $\delta^{13}C$ signal of the soil was slightly depleted compared to the soil-solution. The more negative values of soil, when comparing soil and soil-solution, could depend on high proportion of $\delta^{13}C$ depleted bacteria in the soil (Ehleringer *et al*. 2000; Sollins *et al.* 2008), that is not present, i.e. filtered away, from the soil-solution. Additionally preferential degradation of $\delta^{13}C$ enriched fraction of the soil C pool could lead to differences in $\delta^{13}C$ between residual soil OC and DOM (Kramer *et al.* 2004).

Land-lake interactions

The inlet water in the catchments did not show any obvious patterns when compared to vegetation or lake water $\delta^{13}C$-signals. The $\delta^{13}C$-signals for the three inlets to lake Suoruoaivi all differed, regardless of the fact that inlet 2 and 3 in the Suoruoaivi catchment both run through minerotrophic low alpine mire. The $\delta^{13}C$ signals for the POM and DOM in the inlet water from both Suoruoaivi and Chabrak do however resemble soil and mire signals more than they do either phytoplankton $\delta^{13}C$ signal ca. -40‰ (Karlsson *et.al* 2003) or shallow sediment signals, even though primary production in the water and sediment might possibly be the sources of dissimilarity in the inlet values when looking at the Suoruoaivi catchment. The $\delta^{13}C$ signals resemblance to soil and mire also indicates the importance of allochthonous input into the respective lake carbon dynamics. The specific source of the allochthonous material, i.e. the most influencing vegetation type, is however indefinable.

Both the deep and shallow sediment in the two lakes differed from the soil and soil-solution, water POM and DOM and also when compared to each other. This result is consistent with earlier findings in subarctic lakes (Karlsson *et al.* 2003; 2007), where lake water OC is dominated by AOC because of large inputs from the catchments, relative to the autotrophic production of organic carbon in the pelagic and benthic habitats. The δ^{13}C signal of the shallow sediment can be explained by the high production of benthic algae at shallow bottoms in clear lakes. Uptake of C by benthic algae is diffusion limited leading to relatively low fractionation during C fixation and, thus, heavier δ^{13}C-signals of benthic compared to pelagic algae. At larger depths, low PAR excludes extensive growth of benthic algae and the δ^{13}C-signals of the sediment is affected by settling OC to some extent, but mostly to phytoplankton production in the pelagic. Phytoplankton that reside in an open system are more fractionated as they utilize the unlimited atmospheric carbon pool and settle at the deep bottoms when dying. The difference seen between Chabrak and Suoruoaivi deep sediment δ^{13}C-signals could be a result of the higher amount of nutrients in the Chabrak lake water, leading to a higher pelagic production, and consequently a higher amount of pelagic phytoplankton sediment at the deep bottom lowering the δ^{13}C-signal. The lack of nutrients in the Suoruoaivi lake could thus lead to a very low pelagic production, leaving the deep sediment mostly influenced by AOC, thus the correspondence between soil, soil-solution values and deep sediment δ^{13}C-signal.

Results suggest that climatic and topographic catchment characteristics set the range for variation in DOC, δ^{13}C, and C/N-ratio of lake properties. Vegetational differences in the catchment, i.e. whether the area is forested or alpine, are distinguishable in land and lake properties but it is not possible to track these differences into the vegetation types studied here.

Conclusion

Differences in alpine and subalpine vegetation were to some extent reflected in δ^{13}C-signatures, and C:N ratios. This especially when comparing forested and non-forested vegetation. These differences were also reflected in connected lake ecosystems where AOC was a dominating source of OC. However, aside from differences in vegetation, the catchment's geomorphology also has a high impact on test results and should in the future be incorporated to a higher degree than it was here. It is however difficult to see, the relative extent to which temperature and vegetation influence soil dynamics, when only comparing two catchments at different altitudes.

Acknowledgements

Thank you all who have helped me during the process of writing this thesis, especially my dad Ola Eriksson, my good friends who have read and reread the text Alistair Auffret, Jani Turunen, Emma Göthe, and Johanna Lundström and also my moral supporters and naggers Karin Runesson and Bengt Falk. I would also like to thank my supervisors for their patience and Anders Nilsson for his support.

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Appendixes

Appendix 1a

Chabrak Birch heath forest

Species	**Trivial name**
Alchemilla sp.	Daggkåpa
Angelia arcangelia	Fjällkvanne
Astragalus alpinus	Fjällvedel
Astragalus frigidus	Isvedel
Athyrium distentifolium	Fjällbräken
Bartsia alpina	Svarthö
Betula nana	Dvärgbjörk
Betula pubescens	Björk
Bistorta vivipara	Ormrot
Cicerbita alpina	Torta
Cornus suecica	Hönsbär
Deschampsia flexuosa	Kruståtel
Epilobium angustifolium	Rallarros
Equisetum sp.	Fräken
Eriophorum vaginatum	Tuvull
Filipendula ulmaria	Älggräs
Geranium sylvaticum	Skogsnäva
Geum rivale	Humleblomster
Gymnocarpium dryopteris	Ekbräken
Hieracium sect. *alpina*	Fjällfibbla
Hylocomnium splendens	Husmossa
Juniperus communis ssp. *nana*	Enbär
Luzula pilosa	Vårfryle
Lycopodium annotinum	Revlummer
Melampyrum pratense	Ängskovall
Pinguicula vulgaris	Tätört
Polytrichum commune	Björnmossa
Populus tremula	Asp
Prunus padus	Hägg
Pyrola minor	Klotpyrola
Ranunculus acris	Smörblomma
Ranunculus acris	Smörblomma
Ribes spicatum ssp. *lapponicum*	Skogsvinbär
Rubus chamaemorus	Hjortron
Rubus saxatilis	Stenbär
Rumex acetosa	Ängssyra
Salix sp.	Vide
Saussurea alpina	Fjällskära
Saussurea alpina	Fjällskära
Solidago virgaurea	Gullris
Sorbus aucuparia	Rönn
Spagnum sp.	Vitmossa
Trollius europaeus	Smörbollar
Vaccinium myrtillus	Blåbär
Vaccinium uliginosum	Odon
Vaccinium vitis-idaea	Lingon
Viola biflora	Fjällviol

Appendix 1b

Chabrak Inlet	
Species	**Trivial name**
Empetrum nigrum ssp. *hermaphroditum*	Nordkråkbär
Hylocomnium splendens	Husmossa
Juniperus communis ssp. *nana*	Enbär
Sphagnum magellanicum	Praktvitmossa
Sphagnum nemoreum	Tallvitmossa
Vaccinium myrtillus	Blåbär

Appendix 1c

Chabrak Heath	
Species	**Trivial name**
Betula nana	Dvärgbjörk
Cladina rangiferina	Renlav
Empetrum nigrum ssp. *hermaphroditum*	Nordkråkbär
Rubus chamaemorus	Hjortron
Salix lapponum	Lappvide
Vaccinium myrtillus	Blåbär

Appendix 2a

Suoruoaivi Mesic Heat

Species	Trivial name
Arctostaphylos alpinus	Ripbär
Betula nana	Dvärgbjörk
Bistorta vivipara	Ormrot
Carex bigelowii	Styvstarr
Cassiope hypnoides	Mossljung
Deschampsia flexuosa	Kruståtel
Empetrum nigrum ssp. *hermaphroditum*	Nordkråkbär
Equisetum sp.	Fräken
Hylocomnium splendens	Husmossa
Juncus trifidus	Klynnetåg
Loiseleuria procumbens	Krypljung
Luzula sp.	Fryle
Salix herbacea	Dvärgvide
Saussurea alpina	Fjällskära
Silene acaulis	Fjällglim
Solidago virgaurea	Gullris
Thalictrum alpinum	Fjällruta
Vaccinium uliginosum	Odon

Appendix 2b

Suoruoaivi Grassland

Species	Trivial name
Astragalus alpinus	Fjällvedel
Bartsia alpina	Svarthö
Betula nana	Dvärgbjörk
Bistorta vivipara	Ormrot
Bryophyte sp.	Bladmossa
Carex bigelowii	Styvstarr
Carex lachenalii	Ripstarr
Cassiope hypnoides	Mossljung
Cassiope tetragona	Kantljung
Cerastium alpinum	Fjällarv
Dryas octopetala	Fjällsippa
Gnaphalium supinum	Fjällnoppa
Hieracium sect. alpina	Fjällfibbla
Juniperus communis ssp. *nana*	Enbär
Pedicularis lapponica	Lappspira
Phyllodoce caerulea	Lappljung
Ranunculus acris	Smörblomma
Ranunculus glacialis	Isranunkel
Rhodiola rosea	Rosenrot
Salix herbacea	Dvärgvide
Salix lanata	Ullvide
Salix reticulata	Nätvide
Viola biflora	Fjällviol

Appendix 2c

Suoruoaivi Meadow snowbed	
Species	**Trivial name**
Bistorta vivipara	Ormrot
Bryophyte sp.	Bladmossa
Carex bigelowii	Styvstarr
Carex lachenalii	Ripstarr
Crepis sp.	Fibbla
Deschampsia flexuosa	Kruståtel
Equisetum sp.	Fräken
Eriophorum scheuchzeri	Polarull
Eriophorum vaginatum	Tuvull
Juncus biglumis	Polartåg
Phleum alpinum	Fjälltimotej
Ranunculus acris	Smörblomma
Ranunculus nivalis	Fjällsmörblomma
Ranunculus pygmaeus	Dvärgranunkel
Rumex acetosa	Ängssyra
Salix polaris	Polarvide
Salix	Vide
Saxifraga stellaris	Stjärnbräcka
Taraxacum croceum	Fjällmaskros
Viola biflora	Fjällviol

Appendix 2d

Suoruoaivi Minerotrophic mire	
Species	**Trivial name**
Betula nana	Dvärgbjörk
Bryophyte sp.	Bladmossa
Caltha palustris	Kabbeleka
Deschampsia flexuosa	Kruståtel
Eriophorum angustifolium	Ängsull
Eriophorum vaginatum	Tuvull
Ranunculus acris	Smörblomma
Salix lanata	Ullvide
Salix reticulata	Nätvide

Appendix 3

Abisko Birch heath forest

Species	**Trivial name**
Alchemilla sp.	Daggkåpa
Bartsia alpina	Svarthö
Betula nana	Dvärgbjörk
Betula pubescens	Björk
Bistorta vivipara	Ormrot
Cornus suecica	Hönsbär
Deschampsia flexuosa	Kruståtel
Equisetum sp.	Fräken
Hylocomnium splendens	Husmossa
Juniperus communis ssp. *nana*	Enbär
Luzula pilosa	Vårfryle
Polytrichum commune	Björnmossa
Rubus saxatilis	Stenbär
Solidago virgaurea	Gullris
Sphagnum sp.	Vitmossa
Vaccinium myrtillus	Blåbär
Vaccinium uliginosum	Odon
Vaccinium vitis-idaea	Lingon

Appendix 4

Appendix 4: Columns display sampled vegetation types, Dissolved organic carbon (DOC, mmol/L) for centrifuged soil-solution. The Carbon/ Nitrogen ratio (C:N) for both centrifuged soil-solution and soil, and finally loss on ignition in percentage (LOI%) for the Chabrak and Suoruoaivi catchments and the Abisko site. Vegetation type values are means and displayed with a 95% -confidence interval. DOC values are derived from filtered soil-solution and C:N values from isotopic analysis.

Vegetation type	Soil-solution DOC mmol/L	Soil-solution C:N	Soil C:N	Soil LOI %
Chabrak				
Birch heath forest	22.71 ± 11.10	28.26 ± 6.53	26.65 ± 4.32	88.86 ± 4.76
Inlet	8.05 ± 6.01	24.49 ± 1.05	24.29 ± 2.98	88.29 ± 8.47
Dry heath	13.19 ± 1.40	37.37 ± 6.40	28.07 ± 2.87	79.53 ± 26.47
Suoruoaivi				
Mesic heath	6.11 ± 1.87	19.16 ± 6.79	18.14 ± 4.82	54.98 ± 19.87
Minerotrophic mire	2.73 ± 1.43	18.31 ± 4.54	16.30 ± 3.19	55.42 ± 20.21
Meadow snowbed	8.36 ± 9.03	13.43 ± 3.70	14.99 ± 0.09	63.98 ± 13.10
Grassland	8.61 ± 3.34	19.68 ± 7.22	17.25 ± 0.27	57.42 ± 7.18
Abisko				
Birch heath forest	36.27 ± 14.74	29.88 ± 2.06	29.37 ± 1.49	90.66 ± 5.48

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