

SOIL CARBON LOSSES DUE TO INCREASED CLOUDINESS IN A HIGH ARCTIC TUNDRA WATERSHED (WESTERN SPITSBERGEN)

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Abstract

Carbon pool and carbon flux measurements of different habitats were made in the high Arctic coastal tundra of Spitsbergen. The studied catchment was situated on the exposed west coast, where westerly winds produce daily precipitation in form of rain, drizzle and fog. The storage of organic carbon in the catchment of Eidembukta amounts to 5.98 kg C m⁻², mainly within the lower horizons of deep soils. Between 5.2 - 23.6 % of the carbon pool is stored in plant material. During the cold and cloudy summer of 1996, net CO₂ flux measurements showed carbon fluxes from soil to atmosphere even during the brightest hours of the day. We estimate that the coastal tundra of Spitsbergen lost carbon at a rate of 0.581 g C m⁻² d⁻¹ predominantly as CO₂-C. Carbon loss (7.625 mg C m⁻² d⁻¹) as TOC in small tundra rivers accounts only for a small proportion (1.31 %) of the total carbon loss.

Introduction

Large terrestrial carbon pools are found in the peatlands of the boreal and subpolar zones that cover in total an area of 3.5 x 10⁶ km² (Kivinen and Pakarinen, 1981). Interest in studying the carbon budget in Arctic zones results from uncertainty about the effects of climatic change on production/respiration ratios (P/R) and whether regions which are terrestrial carbon storage areas today could become CO₂ sources in the future (Billings et al., 1982). Climate models predict significant warming in the Arctic (Mitchell et al., 1990). For the Barents region a winter temperature increase of 0.55 K per decade is estimated, while the summer temperatures will rise only 0.25 K per decade (Jonsson et al., 1994). Arctic warming trends of the last decades are corroborated by meteorological measurements in the upper Arctic region (Steffensen, 1982) as well as by vertical gradients of permafrost temperatures (Lachenbruch and Marshall, 1986).

Though many plants might adapt to changed climatic conditions by genetic recombination or phenotypic adaption (Wookey et al., 1995), other species might ultimately be replaced, changing the present spatial distribution of vegetation zones (Wüthrich, 1991). The marked warming of the Arctic islands since the beginning of this century has already supported an immigration of southern plant species (Skye, 1989). Extended distribution of thermophilic species including *Cassiope*

tetragona, *Betula nana*, and *Empetrum hermaphroditum* might accompany warming on Spitsbergen (Wüthrich, 1991; Thannheiser, 1994; Elvebakk and Spjelkavik, 1995). These species include humus and peat-producers (e.g. *Empetrum* Edvardsen et al., 1988).

It is presently assumed that the warming of the Arctic region will be greatest during winter, while an increase in cloudiness is to be expected during summer (Maxwell, 1992). The increase in cloudiness would lead to a lower radiation input on the earth's surface. Since many plants in the Arctic are not growing under light-saturated conditions (Tieszen, 1973), light decrease directly reduces plant primary production. Vegetational changes are often attended by a change in soil characteristics and carbon balance is particularly important for the development of a humus or peat horizon (Wüthrich et al., 1994).

The effects of increasing CO₂ content in the atmosphere or of higher temperatures on the Arctic plant cover have been examined in several recent studies (Chapin et al., 1995; Crawford et al., 1993). So far, no experiments have addressed the influence of increased cloudiness on the carbon balance of a high Arctic ecosystem. To get an idea about the possible changes triggered by increased cloudiness, we have chosen an investigation area that is characterized by fog, cloud-cover and rain (Steffensen, 1982). The tundra ecosystem that has developed in the catchment of Eidembukta has

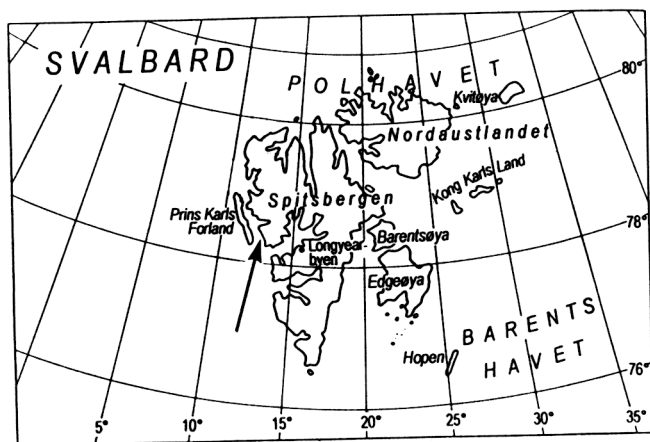


Figure 1. Location of the catchment "Eidembukta" on Svalbard.

been exposed to conditions of low light, lots of drizzle, and a short period of vegetative growth similar to what might be expected for other areas of the Arctic if there is regional increase of cloudiness.

Methods

Fluxes and pools of carbon were measured in different vegetation and soil types in the high Arctic catchment of "Eidembukta" in the piedmont of Eidembreen (West-Spitsbergen, 78.22°N, 12.44°E) (Figure 1). The research area is in the coastal area of Spitsbergen, which is exposed to westerly wind from the North Atlantic. The annual mean temperature is -4.7°C, which is a little higher than in the inner fjord area. Due to cloudiness and high annual precipitation (435 mm), the summer temperatures are 1 - 2°C lower than in inner fjord areas, where the vegetation is more varied. The selection of measurement plots within the catchment was made according to plant communities and soil status. The prevailing plant communities composed by 58 Phanerogames have been extensively influenced by the thickness and period of snow cover (Möller et al., 1998). Soils (Gelic Cambisols, Gelic Gleysols, Ornithogenic Soils and Gelic Leptosols) showed high variation in thickness and a clear geologic boundary line crossed the catchment in the northern part separating deep weathered Permian sandstone deposits from metamorphic igneous rocks (Hekla Hoek) in the southern part.

Table 1 gives a general overview of the plant communities present in the catchment area and their proportional areas. Three main plant communities (SSS, CS and DS) together cover 65 % of the catchment area. In addition, there are less widespread communities sharing similar edaphic conditions (CD, RA, DS*, SSS*) as well as a group of communities with divergent edaphic conditions (SH, CER und POD). Only 9.5 % of the catchment area was unclassified, and no data were collected in these areas.

ESTIMATION OF CARBON POOLS

SOIL ORGANIC MATTER (SOM)

Soil profiles were studied in the whole catchment (3 to 4 profiles per habitat) and soil samples (excluding living plant material) were taken from the surface to the parent material for CHN-analysis (CHN-1000, LECO, USA) and determination of bulk density and soil texture. Profile carbon pool was calculated using carbon content, thickness, bulk density and texture of each horizon. The spatial distribution of each soil type was used to calculate the soil carbon pool in the whole catchment.

PHYTOMASS

Mid-season above-ground and below-ground phytomass were determined for each plant community by taking soil-plant-cores (30 x 30 x 20 cm, three cores per habitat) and collecting living plant material into a paper bag by hand. The material was oven-dried at 80°C and dry weight was measured. Carbon pools in the phytomass were calculated using dry matter data assuming a carbon content of 50 % of the dry plant material, and spatial distribution of the plant communities taken from mapping, air photographs and GIS-analysis (Möller et al., 1998).

ESTIMATION OF CARBON FLUXES

CO₂ FLUXES

A mobile CO₂ measurement system was used for measuring carbon fluxes. The measurement system consisted of a pump (DMP1, Hegnau-Volketswil, CH), an infrared gas analyzer (IRGA, LICOR LI6252, Lincoln, USA), a recorder (GOERTZ SE110, Vienna, A), a transparent measurement chamber (35 x 35 x 10 cm), a reference chamber, a dew point sensor (METRONIC, MTR 2.3, Ilmenau, D), temperature sensing elements inside and outside the chamber and a datalogger (GRANT, SQ8-4U, Cambridge, GB). Artificial light enabled measurement of photosynthetic activity under controlled light conditions (100 μmol photons m⁻² s⁻¹). Photosynthetically active radiation (PAR) was measured using a LICOR LI-189 light meter (Lincoln, USA). The whole system was powered by a 12 V lead battery that was periodically recharged using a solar panel.

CO₂ fluxes were measured in an open gas circulation system. A metal frame (35 x 35 x 10 cm) was installed over the ground. A transparent measurement chamber was fixed hermetically onto the metal frame. Well-mixed external air was provided from a mixing piston and passed through the measurement chamber at a rate of 1000 ml min⁻¹. To avoid chamber effects, flux rates were calculated using differential equations from the increase in CO₂ concentration per unit time after having measured for 2 to 5 minutes. Depending on the respiration or photosynthesis activity, CO₂ was removed

Table 1. Symbols used, short names, short description and proportion of spatial coverage of the investigated habitats in the catchment of Eidembukta (area: 58.449 ha)

Symbol	Short name	Description	Cover
SSS	<i>Salix-Saxifraga</i> -community	<i>Salix polaris</i> - <i>Stereocaulon-Saxifraga oppositifolia</i> -community on flat debris rich sandstone soils.	25 %
CS	<i>Cetraria-Salix</i> -community	<i>Cetraria delisei</i> - <i>Salix polaris</i> -community.	19 %
DS	<i>Drepanocladus</i> -community	Moss tundra with <i>Drepanocladus uncinatus</i> and <i>Salix polaris</i> .	21 %
CD	<i>Cetraria delisei</i> -community	<i>Cetraria delisei</i> -community with few other species. Extreme site with long snow cover.	10 %
RA	<i>Racomitrium</i> -community	<i>Racomitrium</i> sites on flat debris rich soils on Hekla Hoek rocks.	0.6 %
DS*	<i>initial Drepanocladus</i> -community	Initial <i>Drepanocladus</i> -community on flat debris rich soils on Hekla Hoek rocks.	4 %
SSS*	<i>Salix-Saxifraga</i> -community	<i>Salix polaris</i> - <i>Stereocaulon-Sax. oppositifolia</i> -community on deeply weathered sandstone soils.	3 %
SH	<i>Skua-hummock</i>	Extreme site caused by heavy phosphorus and nitrogen deposition by seabirds. Development of ornithogenic soils.	<0.2 %
CER	<i>Cerastium</i> -community	<i>Cerastium regelii</i> -community of wet snow beds. Extreme site with high soil water content and long snow cover.	6.2 %
POD	<i>Polar desert</i> community	Extreme site dominated by crust lichens and <i>Sax. oppositifolia</i> with low coverage on debris-rich soils.	1.5 %
others	not classified	water surfaces and communities with low coverage	~9.5 %

or added to the air current. The resulting concentration difference was measured by the IRGA and converted into an area flux ratio, taking into consideration temperature, transpiration, and air pressure. The photosynthetic ratio (P) was calculated by subtracting the dark respiration (R) from the CO₂ flux (P+R) under natural and artificial light. R is an integral value that is composed of respiration by micro-organisms, soil fauna, plant roots and dark respiration of the above-ground plant parts.

CO₂ fluxes of the dominant vegetational communities (SSS, CS, DS) were examined at four different measurement sites and each measurement was repeated three times on three different plots (12 measurements per habitat). Measurements were made in one site with one (CER, CD, POD) or three replicates (SH, RA, DS*, SSS*) in plant communities representing a small proportion of the area. CO₂ flux measurements started on July 8 and ended on July 26 covering early- and mid-season plant activity. The four sites of the main communities

were measured successively (from early to mid season activity) starting with sites in the lower part of the catchment and ending with sites on the highest (60 m.a.s.l.) marine terraces of the catchment. All measurements were performed between 10.00 h. and 16.00 h. to exploit the highest possible PAR conditions. Measurements were interrupted only on days with heavy rainfall to prevent humidity damage to our CO₂ measurement system. At each of the measurement plots, CO₂ flux measurements were carried out under natural and artificial light. The CO₂ flux measurements under natural light were used to compute daylight CO₂ fluxes in the whole catchment assuming 8 hours per day of the given PAR conditions. The CO₂ flux measurements under artificial light were used for direct site-to-site comparisons and to estimate nighttime CO₂ fluxes assuming 16 hours per day of low PAR conditions (100 $\mu\text{mol photons m}^{-2} \text{s}^{-1}$). The measurements under light conditions were followed by measurements of the dark respiration (chambers covered by a black covering).

TOTAL ORGANIC CARBON (TOC) EXPORT BY RUN-OFF

TOC content of stream water was determined in the beginning, in the middle and at the end of the season in the main channel of the catchment. Samples were taken along a transect from the snow fields down to sea-level. Water samples were immediately acidified (pH < 3) and analysed for TOC (DC 190, DOHRMANN, Cincinnati, USA) within one month after collection. To calculate annual carbon load, run-off was estimated using available data of annual precipitation, evaporation and TOC concentration of the water samples in the watershed. To

compare TOC losses with daily CO₂-C losses, we assumed a run-off period of 80 days and calculated an average daily TOC-loss per square meter.

Results

CARBON POOLS IN THE CATCHMENT

The main soil profiles of the catchment are shown in Figure 2. The soils show large variation from habitat to habitat, especially relating to the thickness of certain horizons and soil texture.

Organic carbon contents of O-horizons (bulk density (BD) 0.2 g/cm³) range between 7-24 %. A-horizons (BD 0.6 g/cm³) showed carbon contents between 3-8 %. The lower horizons (BD > 0.9 g/cm³) of the soil profile contain surprisingly high proportions of organic carbon. Calculated per unit area, the lower horizons of these high Arctic soils contain more than twice the amount of organic carbon than the humus-rich organic top soils. Only flat soils extremely rich in rocks (e.g. POD) and soils with specially thick organic deposits (e.g. SH) have their main carbon storage in the top soil. From habitat to habitat the soil storage of organic carbon ranges from 0.48 to 7.76 kg C m⁻² (Figure 3). Using the spatial distribution of each habitat it is possible to calculate the mean soil storage of organic carbon, which for the catchment of Eidembukta amounts to 5.14 kg C m⁻².

The high Arctic vegetation contains between 0.097 kg and 1.84 kg C m⁻². The above-ground phytomass is normally lower than the below-ground phytomass

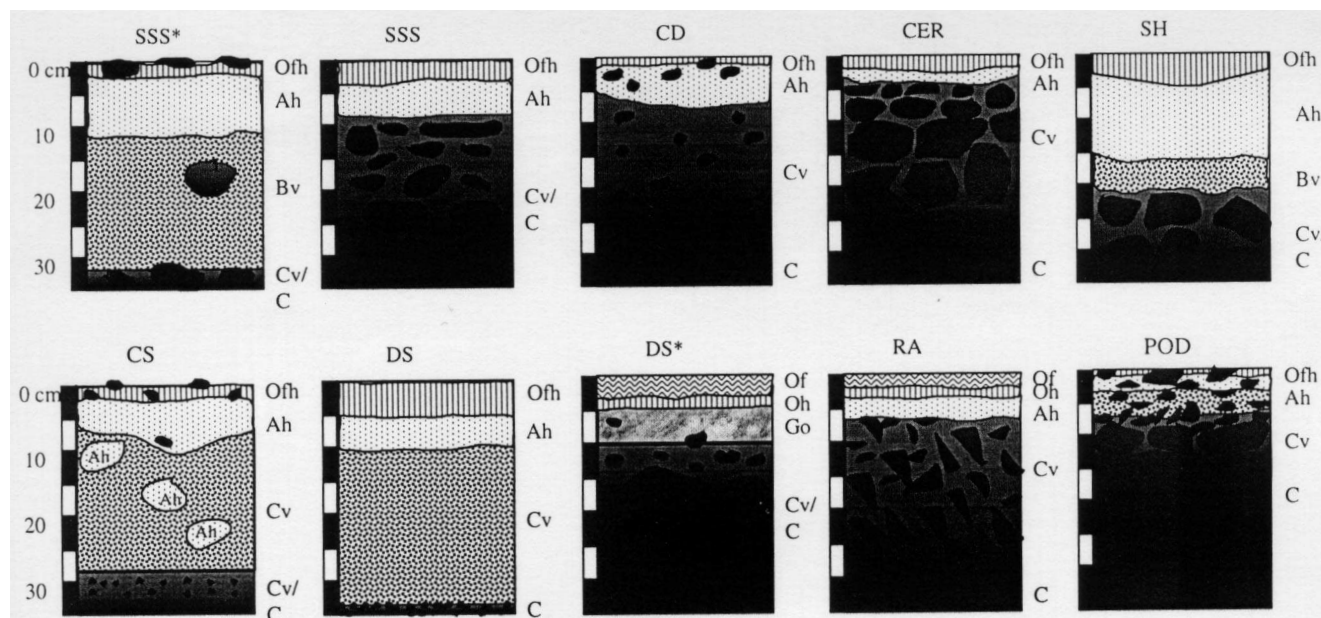


Figure 2. Soil profiles of the prevailing habitats in the high Arctic catchment of Eidembukta.

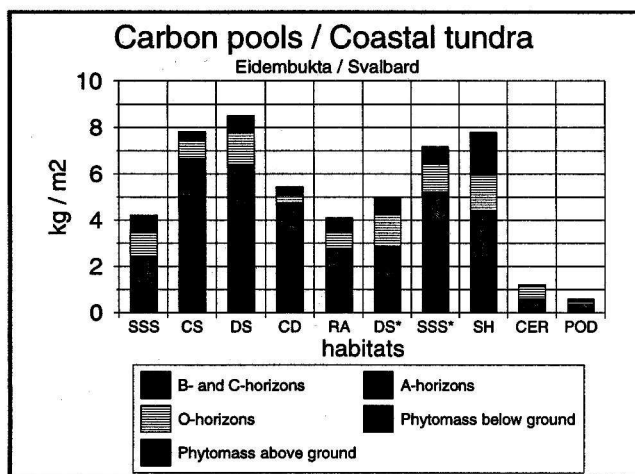


Figure 3. Carbon pools in soils and phytomass of different habitats in the high Arctic catchment of "Eidembukta".

(1 : 1.9-2.5). Only in habitats dominated by mosses (e.g. DS) is the above-ground phytomass equivalent to the below-ground part (1 : 0.8 - 1.2). The total pool of organic carbon in the high Arctic catchment Eidembukta contains about $3.164 \cdot 10^6$ kg of organic carbon (5.98 kg C m^{-2}). Between 5.2 - 23.6 % of the carbon pool is stored in plant material (Figure 3).

CO₂ FLUXES FROM THE CATCHMENT

At the $\mu\text{mol m}^{-2} \text{ s}^{-1}$ artificial light level, the carbon balance was negative for all of the investigated communities (Figure 4). This means that at light levels typical in the research area at night and in rainy weather with thick cloud cover ($<100 \mu\text{mol m}^{-2} \text{ s}^{-1}$), carbon is released to the atmosphere. Nighttime carbon efflux from the different habitats ranged between 0.245 and $7.884 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$. The lowest emission of CO_2 occurred in the Polar Desert community (POD), while the highest emission was measured in the *Skua hummocks* (SH).

On the misty west coast of Spitsbergen measured PAR for all the CO_2 -flux measurements between 10.00 h. and 16.00 h., ranged between 125 and $520 \mu\text{mol m}^{-2} \text{ s}^{-1}$ with a mean of $325 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$. Under these conditions, only a few habitats were able to fix more CO_2 than was released by soil respiration (Figure 5). Since natural light was not exactly the same in the investigated sites (different times of measurement and different cloud conditions during investigation period), Figure 5 is affected by slightly different mean PAR conditions from habitat to habitat. Net C-flux under natural light was shifted to positive values (stronger CO_2 release) in habitats with lower mean PAR values ($< 325 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$) during measurements, and was shifted to negative values (CO_2 uptake) in habitats with high

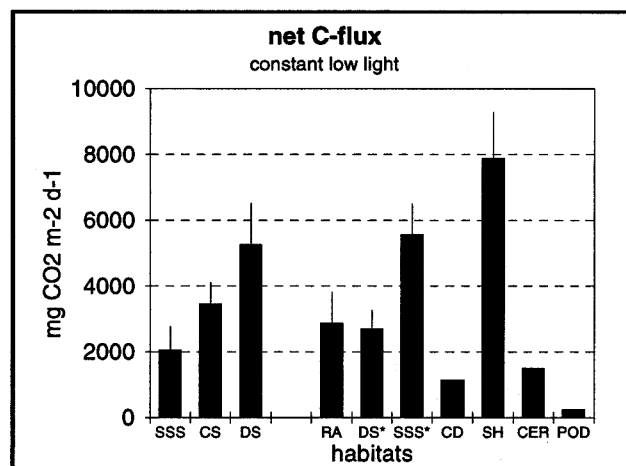


Figure 4. Net CO_2 fluxes in different habitats under low light conditions (PAR $100 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$). Mean values and standard deviations.

mean PAR values. There was net carbon uptake in the *Salix-Saxifraga* community at $350 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ ($-0.25 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$), while the *Cetraria-Salix* community showed a net carbon loss of $1.28 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ at the same light intensity. Under slightly lower light conditions ($236 \mu\text{mol photons m}^{-2} \text{ d}^{-1}$), a net carbon loss of more than $2.48 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ was measured for the *Drepanocladus* community. Apart from the *Salix-Saxifraga* community, only the *Racomitrium* (RA) and the *Cetraria delisei* communities (CD) showed an accumulation of carbon under the prevailing light conditions. In these three communities, the ecosystem light compensation point was exceeded at the prevailing natural light intensities of $260\text{-}340 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$. All of the other communities required higher light intensities to reach the compensation point.

An estimation of daily loss of organic carbon in the catchment under such cloudy conditions by CO_2 is possible using the presented CO_2 emission rates of each habitat for low light (PAR: $100 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$; 16 hours per day) and day light (PAR: $325 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$; 8 hours per day). Daily carbon loss ranged from $0.191 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in the Polar Desert habitats to $5.420 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in the *Skua hummocks*. In consideration of the spatial distribution of the different habitats, the highest proportion of the total carbon loss in the catchment occurred in the *Drepanocladus*- and the *Cetraria-Salix*-communities (42.7 %, 24.3 % respectively). Using all available CO_2 -flux data and the spatial distribution of the different habitats, we estimate the spatial daily loss of carbon by CO_2 under such cloudy and cold conditions in the catchment of Eidembukta to be $0.581 \text{ g C m}^{-2} \text{ d}^{-1}$.

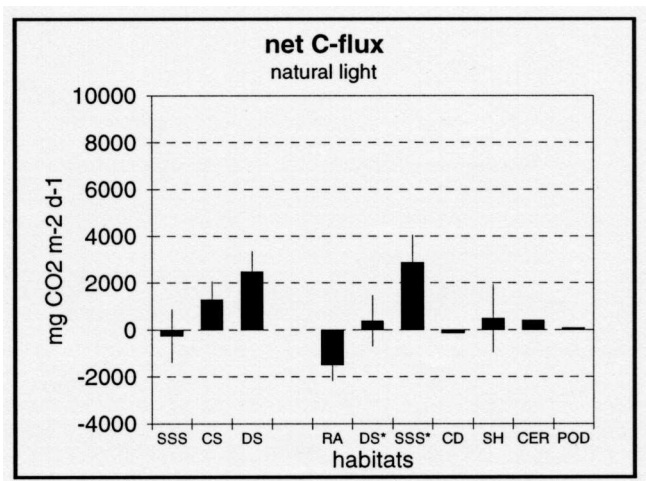


Figure 5. Net CO₂ fluxes in different habitats under daylight conditions (Mean PAR 325 $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$). Mean values and standard deviations.

TOC-FLUXES FROM THE CATCHMENT

The TOC-concentrations of stream water ranged during the season between 1.3 and 2.6 mg l⁻¹ (data not shown). For a rough estimation we supposed that at sea-level each litre of water exported 2.0 mg of organic carbon from the catchment. With an estimated discharge of $1.8 \cdot 10^5 \text{ m}^3$ the annual loss of carbon amounts to 360 kg C for the whole catchment. On a daily and square meter basis, the export of TOC accounts for 7.625 mg C m⁻² d⁻¹, which is only 1.31 % of the estimated gaseous carbon export.

Dicussion

Following a temperature increase of 0.25 K per decade in summer, Jonsson et al. (1994) estimate an increase of precipitation and cloudiness by 1.5 % in summer (2.5 % in winter) for the North Atlantic region. The prevailing conditions in the Eidembukta catchment in 1996 possibly resemble the increased cloudiness scenario that can be expected over increasingly larger areas of the Svalbard Archipelago as a result of global warming. In this study, we have measured carbon fluxes in natural coastal arctic soil-plant communities and calculated the net carbon budget of a tundra watershed. We use these data to infer the direction of CO₂ fluxes under possible cloudier conditions.

Assuming such cool and cloudy weather as in 1996, we expect daily carbon losses of 0.588 g C m⁻² from the Eidembukta catchment. For most of this export (98.7 %) the gaseous loss of CO₂ was responsible because the primary producers showed low photosynthetic activity and remained small sized. The carbon reserve in coastal tundra areas amounts to 0.58 - 8.5 kg C m⁻², most of which is in the lower soil horizons. Comparing the individual carbon loss estimation of each habitat with its

carbon pool, we found that daily carbon loss expressed as a fraction of the total storage was between 0.03-0.16 o/oo for most of the habitats (CD < CS < SSS < POD < DS* < RA < DS) including the main vegetational communities covering 80.5 % of the whole catchment area. The remaining habitats with higher carbon loss fractions (0.19-0.4 o/oo, SSS* < SH < CER) are of minor spatial significance (10 %). In relation of carbon loss the *Drepanocladus*-community (DS) with its relatively high daily carbon loss fraction of 0.15 o/oo and its high spatial significance may be the most critical habitat in the Eidembukta catchment. It is important to consider that habitats that are rich in humus show a greater stability towards environmental fluctuations (temperature, humidity, nutrients) than humus-poor habitats (Wüthrich, 1994). Thus, the consumption of humus in the high Arctic tundra which could result from increased cloudiness would reduce the buffering capacity of these habitats resulting in a deterioration of the living conditions for Arctic organisms.

The respiration rates measured in this research area correspond closely to those seen in previous work in the high Arctic tundra areas of Liefdefjord and Kongsfjord on Spitsbergen (Wüthrich et al., 1994). Photosynthesis in high Arctic ecosystems is normally tightly coupled to carbon mineralisation. Consequently, habitats with high photosynthesis rates also show high respiration rates. In this way, the carbon budget on Spitsbergen - as in most other ecosystems - is dynamically balanced close to zero. This results in limited deposition of humus and poorly developed A-horizons in most pedotopes, even though there has been a period of several thousand years for soil development.

However, relatively high contents of carbon in the lower soil profile of polar soils were also reported in other recent studies (Eberle et al., 1993; Weber and Blümel, 1994; Blume and Boelter, 1996). We have clearly shown that an accumulation of carbon under the prevailing weather conditions of 1996 is very unlikely for most of the plant communities. It is possible that - given a sunny and early snow-free summer - some of today's habitats may accumulate small amounts of carbon. Since soils on Svalbard have no burrowing rodents or lumbricids (Wüthrich, 1994) the organic material must be transferred by soil creeping or cryoturbation into the deeper soil. Both processes play a large role in the landscape development of a high Arctic coastal tundra (Lehmann, 1992; Thannheiser and Möller, 1994). Low microbial activity due to low temperatures in the deeper soil profile might be the reason that this carbon pool remains stable for a long periode of time. For the catchment of Eidembukta we have to take into consideration that the recent carbon pool might be a consequence of a period with more continental climate,

which means more light, longer snow free periods, and higher summer temperatures for the terrestrial primary producers. Possibly these were the prevailing conditions during the Little Ice Age, which ended on Spitsbergen 150 years ago (Blümel et al., 1994).

Though arctic plants are known to have low light compensation points on the leaf level, the light compensation points on the ecosystem level (including soil respiration) analysed here are surprisingly high. In typical subarctic peatlands, ecosystem light compensation points of the plant communities are already exceeded at light intensities of $110 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ (Wüthrich et al., 1997). However in this high Arctic tundra, more than $400 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$ were required for carbon fixation to exceed respiration in the *Cetraria-Salix* and the *Drepanocladus* communities. Under weather conditions with low PAR only the fog-adapted *Racomitrium* and the *Salix-Saxifraga* community were able to fix more carbon than was released by respiration. During the vegetation period of the summer of 1996, the average PAR for the daytime measurements was as low as $325 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$. This means that the ecosystem light compensation points of the plant communities in the research area were exceeded only for some hours.

Conclusions

The average storage of organic carbon in the catchment of Eidembukta amounts to 5.98 kg C m^{-2} , mainly within the lower horizons of deep soils. Between 5.2 - 23.6 % of the carbon pool is stored in plant material.

The extended periods of cloudiness in the research area in the summer of 1996 led to a net carbon loss in the catchment studied. Even in daylight, few habitats were able to fix more carbon dioxide by photosynthesis than was being emitted by respiration at the same time.

We estimate that the coastal tundra of Spitsbergen produced $\text{CO}_2\text{-C}$ at a rate of $0.581 \text{ g C m}^{-2} \text{ d}^{-1}$ under these cloudy and wet conditions. Carbon loss ($7.625 \text{ mg C m}^{-2} \text{ d}^{-1}$) as TOC in small tundra rivers accounted only for a small proportion (1.31 %) of the total carbon loss.

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