Is the subarctic landscape still a carbon sink? Evidence from a detailed catchment balance

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Abstract Climate warming raises the question whether high-latitude landscape still function as net carbon (C) sinks. By compiling an integrated C balance for an intensely studied subarctic catchment, we show that this catchment’s C balance is not likely to be a strong current sink of C, a commonly held assumption. In fact, it is more plausible (71% probability) that the studied catchment functions as a C source (−11 ± 20 g C m⁻² yr⁻¹). Analyses of individual fluxes indicate that soil and aquatic C losses offset C sequestering in other landscape components (e.g., peatlands and aboveground forest biomass). Our results stress the importance of fully integrated catchment C balance estimates and highlight the importance of upland soils and their interaction with the aquatic network for the catchment C balance.

1. Introduction

A key to accurately predicting future climate warming scenarios is to fully understand the carbon (C) cycle [Intergovernmental Panel on Climate Change (IPCC), 2013]. From the large pools of C stored in arctic and subarctic terrestrial ecosystems, it is evident that high-latitude systems have acted as atmospheric net CO₂ sinks over a Holocene time scale [Harden et al., 1992; Hayes et al., 2011; McGuire et al., 2009]. Here low rates of degradation relative to C inputs have resulted in the establishment of large C stocks in high-latitude peatlands, mineral soils, and lake sediments. Concerns that a future warmer climate will release this C have served as a rationale for numerous studies [Lundin et al., 2015; Tarnocai et al., 2009; Zimov et al., 2006]. However, subarctic and arctic regions have experienced a general warming since the end of the nineteenth century (i.e., since the end of the little ice age) and a pronounced warming over the last several decades [Callaghan et al., 2010; Serreze and Francis, 2006]. This ongoing warming has induced plant community changes and enhanced terrestrial productivity in tundra areas, which has resulted in increased sequestering of aboveground C [Elmendorf et al., 2012; Melillo et al., 1993; Wolf et al., 2008]. There are, however, indications that individual terrestrial vegetation regimes (e.g., peatlands, forest, and tundra biomes) become weaker CO₂ sinks as a response to increasing temperatures [Belshe et al., 2013; Frey and Smith, 2005; MacDougall et al., 2013].

So far, the main focus on high-latitude ecosystems has been on the terrestrial components of the landscape. Nevertheless, a significant proportion of the terrestrial C is exported laterally downstream in aquatic systems [Aufdenkampe et al., 2011]. Globally, more than half of the terrestrial C export is estimated to be lost during transit through the inland waters, mainly as gas evasion to the atmosphere [Aufdenkampe et al., 2011; Tranvik et al., 2009]. This atmospheric loss occurs directly via evasion of CO₂ and CH₄ from supersaturated groundwater entering the aquatic ecosystems [Hope et al., 2004; Klink et al., 1991; Walter et al., 2007] or indirectly after mineralization of terrestrial organic C by biological and photochemical processes in the aquatic systems [Cory et al., 2014]. Independent of its origin, the C emitted from aquatic systems represents a loss of C from the catchment to the atmosphere that needs to be accounted for in net ecosystem C balances (NECB) [Battin et al., 2009; Jansson et al., 2008; Maberly et al., 2013]. Still, studies integrating both aquatic and terrestrial C fluxes are rare, implying major gaps in the understanding of interactions between these ecosystem components and their contribution to the landscape C cycle.

In this paper, we compile several years of C flux data from all terrestrial and aquatic components of a subarctic catchment. This study aims not only to resolve the source-sink strength of the studied landscape but also to quantify the importance of major ecosystem components and uncertainties in the NECB.
2. Study Site

We compiled an integrated terrestrial-aquatic NECB of the Stordalen catchment (68°N, 19°E), 10 km east of the village Abisko in northern Sweden. Stordalen represents a unique catchment for assessing the NECB because there are multiyear annual C flux data available from all the different ecosystem components found in the catchment, except the alpine tundra [Bäckstrand et al., 2010; Christensen et al., 2012; Jackowicz-Korczynski et al., 2010; Lundin et al., 2013; Olefeldt et al., 2012b; Wik et al., 2013]. Mean annual air temperature between 2000 and 2009 was 0.6 ± 0.4°C (mean ± standard deviation (SD)), and the coldest and warmest months were February (−9.5 ± 3.1°C) and July (12.5 ± 1.2°C), respectively. The average annual total precipitation for the same period was 340 ± 56 mm. All climatological data were recorded at Abisko Scientific Station (www.polar.se/abisko). The 15 km² catchment includes alpine tundra terrain dominated by heaths and dwarf shrubs (e.g., Empetrum hermaphroditum, Vaccinium sp., and Betula nana) at high altitudes (770–600 m asl) and sub-alpine terrain at low altitudes (360–600 meter above sea level (m asl)) covered with mountain birch forest (Betula pubescens ssp. Czerepanovii) and peatlands (Sphagnum mosses or Ericaceae shrubs in bogs and Eriophorum in the fens). Hence, the catchment represents all the major vegetation regimes found in the Abisko area and in the subarctic landscape in general. The catchment is located in the zone of discontinuous permafrost [Johansson et al., 2006], and the bogs contain areas of palsas [Malmer et al., 2005]. As the mean annual air temperature during the last decades has increased and presently exceeds the 0°C threshold [Callaghan et al., 2010], the active layer depth has increased, accompanied by palsa collapses and thermokarst erosion [Johansson et al., 2006; Malmer et al., 2005]. In 2004, the forested part of the catchment was disturbed by intensive insect herbivory (Epirrita autumnata and Operophtera brumata), which resulted in reduced forest CO₂ uptake. However, by 2006, forest C sequestration had returned to rates approaching those of undisturbed years [Heliasz et al., 2011]. The catchment contains 27 lakes (with an area of 0.001 to 0.145 km² and a max depth of 0.5 to 8.5 m) of which one is alpine and the others are sub-alpine [Lundin et al., 2013]. Most of the lakes are connected by a network of streams. The streams all start small (<1 m wide and <0.5 m deep) in the part of the catchment, where it is relatively steep, but subsequently flow through flatter peatlands, where they become deeper, wider, and less turbulent.

3. Methods

The catchment area was modeled in a 10 m resolution digital elevation model (DEM) with the hydrology tools available in ArcGIS 9.3.1 (Environmental Systems Research Institute, United States). The elevation values and length calculations were conducted using a high-resolution Lidar-derived DEM with a 1 m resolution. The elevation accuracy in the DEM is 0.03 m due to high-density sampling and low-flying altitude [Hasan et al., 2012]. We estimated areas of the alpine tundra, forests, peatlands, outcrops, and water surfaces by analyzing aerial imagery. The aerial imagery was obtained during a helicopter flight on 1 August 2008. The altitude was approximately 500 m and generated ortho images with a pixel resolution of 0.08 by 0.08 m. The spectral range of the images was in the visible wavelengths (RGB). The classification of the imagery was carried out with object-based image analysis [Blaschke, 2010]. First, we segmented the different objects in the image using an automatic multisolution algorithm that uses color and contrast to determine similar pixels in the adjacent area. Next, we classified all the objects according to a classification scheme in a supervised classification in the software eCognition (Trimble Navigation Limited, U.S.). Peatlands were subdivided into wet areas (fen) and dry areas (bog) proportionally to what was found by Malmer et al. [2005].

We compiled new unpublished and previously published annual net C flux estimates together with associated analytical uncertainties for each ecosystem component in the Stordalen catchment (Table 1). The estimates are based on measurements in or adjacent to the catchment between 1999 and 2012 except for the alpine tundra (supporting information Figure S1). Because most fluxes were measured directly for more than 1 year, we were also able to assess interannual variability. The exception was measurements of CH₄ emissions from streams and the catchment export of particulate organic C (POC), which were measured during 1 year only (Table 1). Forest CO₂ flux and wetland CO₂ and CH₄ flux were estimated by eddy covariance [Christensen et al., 2012; Heliasz et al., 2011; Jackowicz-Korczynski et al., 2010; Olefeldt et al., 2012b]. Complementary forest CO₂ flux measurements were carried out between 2007 and 2010 using the same eddy covariance setup as in Heliasz et al. [2011]. Footprint analysis showed that the influence of vegetation components other than targeted components using eddy covariance was minor [Christensen et al., 2012;
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Table 1. Listed References From Where the Data Were Compiled

| Ecosystem Component | C Flux                     | Method              | Period          | Reference                                      |
|---------------------|----------------------------|---------------------|-----------------|-----------------------------------------------|
| Alpine tundra       | NEE                        | Literature mean value | 1990–2009       | McGuire et al. [2012]                          |
| Alpine tundra       | Atm. CH₄ flux              | Chambers            | 1999–2000       | Sjögersten and Wookey [2002]                   |
| Forest              | NEE                        | Eddy covariance     | 2006–2010       | Heliasz [2012] (new data)                     |
| Forest              | Atm. CH₄ flux              | Chambers            | 1999–2000       | Sjögersten and Wookey [2002]                   |
| Bog and palsa       | NEE                        | Eddy covariance     | 2008–2009       | Olefeldt et al. [2012b]                       |
| Bog and palsa       | Atm. CH₄ flux              | Chambers            | 2003–2006       | Bäckstrand et al. [2010]                      |
| Fen                 | NEE                        | Eddy covariance     | 2001–2008       | Christensen et al. [2012]                     |
| Fen                 | Atm. CH₄ flux              | Eddy covariance     | 2006–2007       | Jackowicz-Korczynski et al. [2010]            |
| Lakes               | Ice thaw NEE and CH₄ flux  | Grab sampling       | 2008–2010       | Karlsson et al. [2013] and Lundin et al. [2013] |
| Lakes               | Summer atm. NEE and CH₄    | Grab sampling and loggers | 2009–2011     | Lundin et al. [2013] (new data) and Lundin et al. [2015] |
| Lakes               | Summer CH₄ ebullition       | Floating chambers   | 2009–2012       | Lundin et al. [2015] and Wik et al. [2013]    |
| Streams             | Summer NEE and CH₄ flux    | Grab sampling and loggers | 2009–2011     | Lundin et al. [2013] (new data)               |
| Whole catchment     | Lateral export             | Grab sampling       | 2007–2009       | Olefeldt et al. [2012a]                       |
| Whole catchment     | Deposition                 | Literature mean value | –              | Kortelainen et al. [2006]                     |

Heliasz et al., 2011; Jackowicz-Korczynski et al., 2010; Olefeldt et al., 2012b. Random errors in the eddy covariance methodology were assumed to annually introduce a relative standard deviation (RSD) of 15%, a percentage that is based on error estimations listed by Baldocchi [2003]. Forest and alpine tundra CH₄ fluxes were estimated by chamber measurements [Sjögersten and Wookey, 2002]. The only ecosystem component flux that was not directly measured was flux of CO₂ from the alpine tundra (which covers 13% of the catchment). Alpine tundra CO₂ flux was instead assumed to be characterized by the average dry tundra estimates presented by McGuire et al. [2012]. In 2009, stream (23 locations) and lake (27) diffusive fluxes were estimated from partial pressures and diffusion coefficients integrated over time [Lundin et al., 2013].

To assess interannual variability in stream and lake CO₂ emissions, we used new high-resolution concentration data collected in 2010 (eight streams) and in 2011 (four streams and six lakes). In both years, the instrumental setup was the same as in Lundin et al. [2015] (see supplementary information). Lake CH₄ ebullition was estimated for six lakes using floating chambers in 2010 [Bastviken et al., 2010]. We also included multiyear CH₄ ebullition estimates from three lakes in the Stordalen catchment published by Wik et al. [2013]. For lakes where no ebullition measurements were carried out, we added calculated average ebullition to estimate diffusive fluxes. As done by Lundin et al. [2013], we determined the analytical uncertainties in diffusive aquatic-atmospheric C flux. For CH₄ ebullition, we also included spatial uncertainties within and between lakes. We assumed that the deposition of organic C was similar to that of northern Finland (0.7 ± 0.1 g m⁻² yr⁻¹) [Kortelainen et al., 2006] and that summer precipitation is saturated in CO₂ [IPCC, 2013]. We calculated annual net CO₂ and CH₄ flux from each ecosystem component by multiplying the annual mean atmospheric flux with the area of each ecosystem component. The mean lateral catchment C export and associated analytical uncertainties were determined by a Monte Carlo simulation of integrated C loads based on measurements of catchment runoff and concentration data [Olefeldt et al., 2012a].

The annual catchment NECB was defined as the net rate of catchment C accumulation [Chapin et al., 2006]:

$$\text{NECB} = -\text{NEE} + F_{\text{CH}_4} + F_{\text{DIC}} + F_{\text{DOC}} + F_{\text{PC}}$$

(1)

where the Net Ecosystem Exchange (NEE) is the aquatic and terrestrial net CO₂ flux, $F_{\text{CH}_4}$ is the aquatic and terrestrial CH₄ flux, and $F_{\text{DIC}}$, $F_{\text{DOC}}$, and $F_{\text{PC}}$ represent the net lateral catchment export of dissolved inorganic C (DIC), dissolved organic C (DOC), and particulate C, respectively. $F_{\text{DIC}}$, $F_{\text{DOC}}$, and $F_{\text{PC}}$ also include dry and wet deposition. Because fluxes of volatile organic C (VOC) are relatively minor, they have no impact on the total NECB [Bäckstrand et al., 2008; Holst et al., 2010]. Accumulation of C into soils and sediment and exports of terrestrial C into aquatic systems were not added to the catchment NECB, as they are fluxes between C pools within the catchment.

We present the NECB as the average for the investigated period (Table 1). The NECB, associated analytical uncertainties, uncertainties introduced by interannual variation, and total propagated uncertainties were estimated by Monte Carlo simulations. We ran 10,000 permutations where each variable was allowed to vary...
around its mean value and where the variation was calculated as the SD multiplied by a factor drawn from a normal distributed population (mean = 0, SD = 1). Because stream CH4 emission and particulate organic C (POC) export were estimated for only one season, we assumed the relative interannual variation to be equal to the variation in CO2 emissions and DOC export (i.e., about 40 and 20%, respectively). Furthermore, because it is not possible to distinguish between analytical and interannual uncertainties introduced when upscaling C deposition and alpine tundra CO2 fluxes, we included total uncertainties when simulating both propagated interannual and analytical uncertainties. The importance of each individual flux estimate to the NECB was determined by a sensitivity analysis where the average individual flux was adjusted by one SD and the subsequent impact on the catchment NECB was used as a relative measure of the importance of the flux. We present all fluxes normalized to the catchment area (±1 SD) if not stated otherwise.

4. Results

According to the image analysis, birch forest was the most dominate vegetation of the catchment (58%), and alpine tundra was the second most dominate vegetation of the catchment (13%) (Figure 1). Notably, outcrops constitute frequent features in the landscape, accounting for 13% of the catchment and more dominant than peatlands (6%). Peatlands were subdivided into fen (3%) and bog (3%). Aquatic systems cover minor areas, only about 5% (lakes: 4.8% and stream: 0.2%) of the total catchment. Annual means of lateral catchment export, C emissions, and associated uncertainties are presented in Table 2. For all vegetation classes, only peatlands showed on average atmospheric CO2 net uptake. Although the total C fluxes were similar between fen (1.9 ± 1.6 g C m⁻² yr⁻¹) and bogs (2.8 ± 1.0 g C m⁻² yr⁻¹), fens compensated the higher CO2 uptake by releasing considerable amounts of CH4. Birch forest and the alpine tundra both tended to have positive mean CO2 effluxes, emitting on average −0.5 ± 19 and −1.4 ± 2.4 g C m⁻² yr⁻¹, respectively. The aquatic systems had a disproportional large importance in the NECB relative to its area. Streams

Figure 1. Vegetation types and their distribution within the Stordalen catchment. The black dot marks the catchment outlet. Coordinates are given in decimal degrees (WGS 84).
constituted the largest atmospheric C source in the catchment, emitting on average $-10.7 \pm 0.16$ g C m$^{-2}$ yr$^{-1}$ as CO$_2$ and $-0.6$ g C m$^{-2}$ yr$^{-1}$ as CH$_4$. Lakes emitted about $-2.6 \pm 0.7$ g C m$^{-2}$ yr$^{-1}$ as CO$_2$ and $-0.14 \pm 0.05$ g C m$^{-2}$ yr$^{-1}$ as CH$_4$. In addition, about $-3.8 \pm 0.6$ g C m$^{-2}$ yr$^{-1}$ was exported out of the catchment ($-2.6 \pm 0.7$ g C m$^{-2}$ yr$^{-1}$ as DOC, $-1.2 \pm 0.6$ g C m$^{-2}$ yr$^{-1}$ as DIC, and $-0.1$ g C m$^{-2}$ yr$^{-1}$ as POC).

On average, the calculated NECB for the Stordalen catchment suggests that this landscape served as a net source of C during the last decade. In 71% of the random permutations, the simulated NECB resulted in the catchment losing more C than what was sequestered, with an average annual net loss of $-11.7 \pm 20$ g C m$^{-2}$ yr$^{-1}$ (Table 2) (Figure 2). All C fluxes showed high variability overall. Interannual variations generally introduced larger uncertainties than the analytical procedures (Table 2), although there were exceptions (e.g., scaling stream diffusion coefficients introduced relatively high levels of uncertainties). In addition, CH$_4$ emission estimates from both fens and lakes showed a high uncertainty due to the large spatial variability. The sensitivity analysis (Table 2) showed that the uncertainty related to forest

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**Table 2.** Data on Areas and C Fluxes and Propagated Uncertainties (Expressed as Annual Means ± 1 SD) of the Ecosystem Component and Integrated Catchment Ecosystem C Balance$^a$

| Ecosystem Component Specific Flux (g C m$^{-2}$ yr$^{-1}$) | Catchment Flux (g C m$^{-2}$ yr$^{-1}$) | Interannual Variation of Means (RSD %) | Propagated Uncertainties Introduced by Analyses and Modeling (RSD %) | NECB Sensitivity of 1 SD (%) |
|----------------------------------------------------------|----------------------------------------|----------------------------------------|---------------------------------------------------------------|---------------------------|
| **Catchment C deposition** n/a 0.7 ± 0.16 n/a 23$^b$ 1 | | | | |
| **Catchment DOC export** n/a $-2.6 \pm 0.7$ 20 7 | | | | |
| **Catchment DIC export** n/a $-1.2 \pm 0.6$ 41 5 | | | | |
| **Catchment POC export** n/a $-0.1$ n/a 0.3 | | | | |
| **Birch forest NEE** 9.0 (58%) $-0.9 \pm 0.3$ $-0.5 \pm 19$ 3600 233$^c$ 170 | | | | |
| **Alpine tundra NEE** 2.1 (13%) $-10 \pm 18$ $-1.4 \pm 2.4$ n/a 173$^d$ 36 | | | | |
| **Fen NEE** 0.6 (3.9%) 66 ± 39 2.7 ± 1.6 44 6$^c$ 12 | | | | |
| **Bog and palsa NEE** 0.9 (2.6%) 50 ± 16 2.9 ± 1.0 32 11$^c$ 8 | | | | |
| **Stream NEE** 0.03 (0.2%) $-5400 \pm 4400$ $-10 \pm 8$ 43 50 74 | | | | |
| **Lake NEE** 0.7 (4.5%) $-11 \pm 4.5$ $-0.5 \pm 0.2$ 40 22 2 | | | | |
| **Birch forest CH$_4$ flux** 9.0 (58%) 0.06 ± 0.3 0.04 ± 0.2 500 n/a 2 | | | | |
| **Alpine tundra CH$_4$ flux** 2.1 (13%) 0.06 ± 0.3 0.01 ± 0.04 500 n/a 0.4 | | | | |
| **Fen CH$_4$ flux** 0.6 (3.9%) $-20 \pm 3$ $-0.8 \pm 0.1$ 14 11$^c$ 1.3 | | | | |
| **Bog and palsa CH$_4$ flux** 0.9 (2.6%) $-1 \pm 1$ $-0.06 \pm 0.06$ 17 60 1 | | | | |
| **Stream CH$_4$ flux** 0.03 (0.2%) $-34$ $-0.06$ n/a 50 0.5 | | | | |
| **Lake CH$_4$ flux** 0.7 (4.5%) $-2.9 \pm 1.1$ $-0.14 \pm 0.05$ 15 36 0.5 | | | | |
| **NECB** 15.4 (100%) $-11 \pm 20$ $175^c$ 51 | | | | |

$^a$Negative fluxes and balances indicate an annual net C loss. Fluxes are presented normalized to the catchment area and to ecosystem component specific areas. Uncertainties introduced by interannual variation and propagated uncertainties introduced during the analytical procedure are expressed as relative standard deviations of means (RSD %). Unavailable data are indicated by n/a.

$^b$Uncertainty estimates from Kortelainen et al. (2006).

$^c$Analytical uncertainties are assumed to introduce RSD of 15% annually [Baldocchi, 2003].

$^d$Uncertainty estimates from McGuire et al. (2012).

$^e$We make the assumption that stream CH$_4$ and POC fluxes are the same as for CO$_2$ and DOC, respectively. We also assume that the total propagated uncertainty is similar to the interannual variation.

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Figure 2. Uncertainty range of the Monte Carlo simulated distribution of catchment NECB. A negative balance indicates an annual net C loss.
CO₂ flux has the largest effect on the NECB (potentially affecting the NECB by up to 170%), followed by stream CO₂ flux (74%) and alpine tundra (36%). Uncertainties introduced by the C flux in peatlands, lakes, and catchment export had a relatively minor impact on the total NECB.

5. Discussion

Ongoing climate warming may have weakened the C sink at high latitude, and in some ecosystem components may have generated a shift toward net emissions of atmospheric C [Cahoon et al., 2012; Dorrepaal et al., 2009; Hayes et al., 2011]. However, most studies so far have focused on single ecosystem components [Belshe et al., 2013; Dorrepaal et al., 2009; Elmendorf et al., 2012] or single C species [Gudasz et al., 2010; Laudon et al., 2012], making it difficult to evaluate the importance of these changes at a landscape level and for the overall NECB. In our study system, peatlands are clear atmospheric C sinks and aquatic systems are clear sources, but it is more uncertain whether the forest and tundra are sinks or sources. Importantly, comparisons between individual landscape components tell very little about the landscape’s C sink capacity. By integrating aquatic and terrestrial ecosystems, we show that although there is a higher likelihood for net losses compared to net gains of C, the Stordalen catchment NECB is close to neutral.

Most of the uncertainty in the NECB estimations was related to forest, alpine tundra, and stream CO₂ fluxes, whereas uncertainties introduced by the C flux in peatlands and lakes and by the downstream export from the catchment had a relatively minor impact on the total uncertainty (Table 2). As with circumpolar lakes and peatlands [Kling et al., 1991; Roulet et al., 2007], in Stordalen all the lakes were net atmospheric C sources and all the peatlands were net atmospheric C sinks. It is therefore unlikely that our results are strongly affected by seasonal variations in fluxes from these systems. On the other hand, forests cover major parts of the Stordalen catchment (approximately 58%) and show high interannual C flux variability. For example, out of the 4 years of measurements in the forest, 2 years had negative NEE and 2 years had positive NEE. Furthermore, even though streams cover only a minor area, the difficulties associated with estimating gas fluxes introduce large levels of uncertainties [Wallin et al., 2011] that may affect the whole catchment budget. Because the spatial and temporal resolution of the data available from the relatively large alpine tundra is low due to technical difficulties and lacking infrastructure, its NEE estimate introduces another source of uncertainty. However, summer NEE measurements from the study region indicated that alpine freeze-thaw disturbed soil pedons that served as net C sources [Becher et al., 2015], whereas the undisturbed vegetation showed to be weak sinks [Fox et al., 2008]. When also accounting for the occurrence of winter respiration, the net result would most likely add up to alpine tundra being a weak net C source, which is consistent with the global average used in the NECB estimate. Altogether, propagated uncertainties in forest, alpine tundra, and stream emissions have the potential to affect the NECB by a factor of almost 3. Soil respiration is suggested to be the overall most important determinant of the C flux in forests and tundra [Cahoon et al., 2012; Oberbauer et al., 2007; Valentini et al., 2000] and the main contributor to both the temporal and spatial variation in forest CO₂ flux in Stordalen [Heliasz, 2012]. Furthermore, groundwater rich in CO₂ from soil respiration is the most important driver of stream CO₂ supersaturation [Hope et al., 2004; Hotchkiss et al., 2015]. This suggests that the three most influential ecosystem components in the NECB depend on soil respiration rates. It is possible that there is a covariation between the terrestrial and aquatic-atmospheric C flux [Jansson et al., 2008; Maberly et al., 2013], which, if accounted for, could help decrease the levels of uncertainties. Unfortunately, there is only a minor overlap in the data series from these ecosystem components in the Stordalen catchment (Table 1), which makes it difficult to test to what extent these components interact with each other.

The major parts of sequestered C in tundra and forest at high latitudes are stored below ground [Mack et al., 2004; Ping et al., 2008; Tarnocai et al., 2009], and this soil C has accumulated mainly before the twentieth century, when colder conditions constrained respiration processes [Becher et al., 2015; Harden et al., 1992]. It is suggested that as the climate at high latitudes becomes warmer [Callaghan et al., 2010], respiration from these large soil C stocks will offset the steady state between litter input and degradation and induce C emissions [Cahoon et al., 2012; Kirschbaum, 1995; Laudon et al., 2012]. Hence, it is reasonable to believe that respired deep soil organic C will release from the catchment’s peatlands [Dorrepaal et al., 2009], forests, and alpine tundra [Hartley et al., 2012]. Many studies suggest that although the storage of aboveground C increases at high latitudes, the pool of belowground C decreases [Belshe et al., 2013; Cahoon et al., 2012;.
Hartley et al., 2012. Hedénäs et al. [2011], for example, showed that the forest in our studied catchment increased its biomass by 19% during the last decade, although the overall NECB for the catchment showed limited indication of increased C sequestering.

Our results stress the importance of fully integrated NECB and give direct support to modeling approaches, indicating that high-latitude ecosystems are unlikely to be strong C sinks [Hayes et al., 2011; McGuire et al., 2010]. We therefore conclude that there are strong reasons to question the assumption that high-latitude systems serve as stable C sinks, a view that may arise when focusing on single ecosystem components such as peatlands or aboveground forest biomass. Furthermore, we conclude that the most important unknowns lie in the C flux estimates from the forests, alpine tundra, and the catchment stream network. To make more precise balance estimates and further narrow the uncertainties, it is necessary to increase the spatial and temporal resolution of sampling in the key ecosystem components. We therefore suggest future research should focus on the large areas of upland soils and their integration with the aquatic network.

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