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Integrating aquatic carbon fluxes in a boreal catchment carbon budget

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Summary In this paper, we assess the extent to which the export of terrestrially fixed carbon to aquatic systems and the aquatic metabolism of this carbon affect the overall accumulation of organic carbon in a boreal catchment. We estimated the contribution of stocks and processes in aquatic environments to the carbon balance of a boreal catchment in northern Sweden. We used published data concerning the net ecosystem exchange (NEE) of CO_2 in terrestrial environments, and calculations of loss of terrestrial carbon to surface water and the turnover of terrestrial carbon in aquatic systems. The NEE of terrestrial environments was estimated to be 139 g C/m^2 of catchment area per year. The export of terrestrially fixed carbon to aquatic systems was 8.6 g C/m^2/yr, resulting in a net accumulation of organic carbon in terrestrial systems of 131 g C/m^2/yr. Almost 45% of the terrestrial export was mineralized in streams and lakes and evaded as CO_2, while most of the remaining (approximately 55%) terrestrial export was transported to the sea as organic carbon or as dissolved inorganic carbon emanating from soil respiration. The sedimentation of organic carbon and input of organic carbon via aquatic primary production were insignificant when compared to the mineralization and river transport of terrestrial organic carbon. Aquatic fluxes were small compared to the terrestrial NEE, which we consider to be largely a consequence of the studied catchment being subject to intensive forestry resulting in a large annual accumulation of carbon in growing tree biomass.
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Introduction

It has become increasingly important to quantify carbon pools and fluxes in the environment due to the role of carbon in global warming and climate change. Northern latitude ecosystems have been identified as especially important for CO_2 exchange between ecosystems and the atmosphere, with boreal forests regarded as a net sink of CO_2 (Chapin et al., 2000). Aquatic systems in boreal areas are, in contrast to terrestrial systems, net sources of CO_2 to the atmosphere due to the mineralization of organic carbon imported from terrestrial systems, and the resultant degassing of inorganic carbon in lakes and streams (Cole et al., 1994; Algesten et al., 2004a). However, there are few quantitative estimates of lake and stream emissions in relation to catchment carbon cycling. The metabolism of terrestrial carbon in aquatic systems has been an important focus in studies of both lakes (Jordan and Likens, 1975; Jonsson et al., 2001) and streams (e.g., Edwards et al., 1990; Hudson et al., 1992: Dawson et al., 2004). In contrast, the significance of the aquatic metabolism of terrestrial carbon for the carbon balance of terrestrial ecosystems has been largely neglected.

The link between the terrestrial and aquatic environments is obvious in boreal landscapes because of the substantial input of allochthonous organic carbon to streams and lakes (Hope et al., 1994). The export of organic matter and inorganic carbon from soils is regulated by the climate, terrestrial production, mineralization, and geohydrological characteristics (Thurman, 1985) in combination with the water flux through the soils (Hinton et al., 1997; Bishop et al., 2004). Consequently, the proportion of wetlands in the catchment tends to control the export from land to streams (Koprivnjak and Moore, 1992; Kortelainen, 1993; Laudon et al., 2004). Organic matter imported from terrestrial systems affects the aquatic environment in many ways (Hessen and Tranvik, 1998; Steinberg, 2003) and is an important carbon and energy source for aquatic secondary production (Tranvik, 1988; Moran and Hodson, 1990; Karlsson et al., 2003). In most boreal lakes, the respiration of allochthonous carbon makes community respiration higher than the net primary production (Tranvik, 1989), and the lakes become net sources of CO_2 to the atmosphere (Cole et al., 1994; Sobek et al., 2003). Mineralization of allochthonous organic carbon occurs mainly, but not only, by means of bacterial degradation (Jonsson et al., 2001). Photochemical degradation (Granéli et al., 1996) and its interaction with bacterial mineralization (Bertilsson and Tranvik, 1998) may also add substantially to total mineralization. Mineralization of allochthonous carbon in lakes and streams constitutes a spatial and temporal displacement of the mineralization and return of CO_2 to the atmosphere, which is generally not considered when the carbon cycle is studied at the landscape level. Hence, the net ecosystem exchange (NEE) of boreal terrestrial systems is typically studied without taking into account the runoff of carbon to the aquatic environment and its subsequent loss.

Possibly, the neglect of aquatic allochthonous organic carbon as a component of the carbon cycle at the landscape level is due to the generally accepted highly recalcitrant nature of this organic matter. This view is largely based on short-term degradation experiments in which often less than 10% of the total organic carbon is degraded (e.g., Moran and Hodson, 1990; Tranvik, 1988). A different pattern emerges when susceptibility to degradation is considered at time scales — typically years — similar to the hydraulic retention time of surface water in the catchment. A recent study (Algesten et al., 2004a) addressed the role of lakes in the mineralization of allochthonous organic matter at a large scale, examining almost 80000 lakes in northern Sweden; it demonstrated that as much as 30–80% of the terrestrial losses of organic carbon were mineralized in freshwaters and emitted back to the atmosphere as CO_2 during transport from terrestrial sources to the sea. The low percentage was obtained in catchments where the water residence time was <1 year and the high percentage in catchments where the water residence time was between 5 and 10 years. The study of Algesten et al. (2004a) did not compare aquatic and terrestrial carbon balances in the studied watersheds, and the role of aquatic organic carbon cycling at the whole catchment scale largely remains an open question.

Material and methods

Study area

The Öreälven catchment (Fig. 1) is situated in the county of Västerbotten in northern Sweden (64°N, 19°E), in a landscape that was deglaciated approximately 10000 years ago. The catchment area is 3025 km^2; the basin is dominated by coniferous forests consisting mainly of Norwegian spruce (*Picea abies* L. Karst.) and Scots pine (*Pinus sylvestris* L.). Approximately 1% of the area is clear-cut annually (National Board of Forestry, http://www.svo.se). Mires cover large areas, while agricultural areas are very small. There is some minor use of the running waters for hydroelectric power generation, even though the main stream (Öreälven) is not regulated. The catchment basin has further been described by Ivarsson and Karlsson (1992, 1994a). Lakes and streams are typically unproductive humic waters containing concentrations of total organic carbon (TOC) between approximately 5 and 30 mg/L with a mean concentration of approximately 10 mg/L.

Calculations

We separated the watershed C budget into the following components:

- Content of organic carbon in forested areas, clear-cut areas, and mires in the terrestrial system
- NEE of forested areas, clear-cut areas, and mires in the terrestrial system
- Loss of terrestrially fixed carbon to the aquatic environment
- Volume of water, and content of TOC and dissolved inorganic carbon (DIC) in streams and lakes
- Loss of TOC and DIC (CO_2) by means of the sedimentation and mineralization/evasion in streams and lakes
- Stream transport of TOC and DIC to the sea

We used these components to calculate the loss of terrestrial carbon to aquatic systems. We also calculated the accumulation of organic carbon in terrestrial systems (NEE

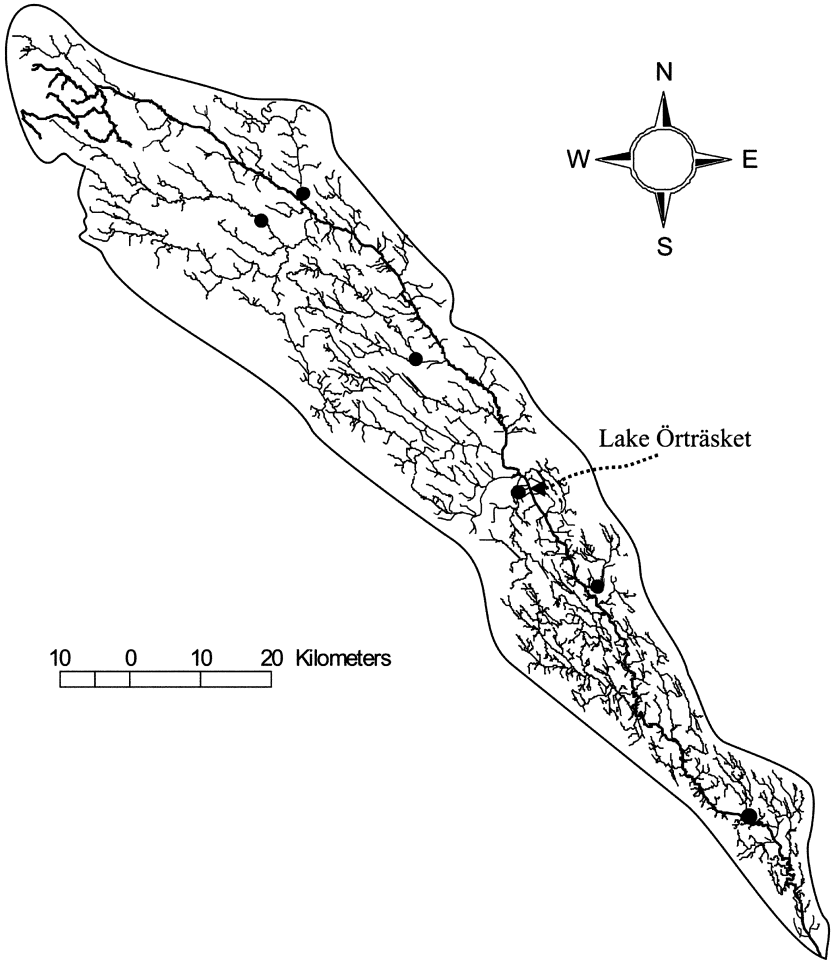

Figure 1 The Öreälven catchment: the main stream (Öreälven) is indicated by a bold line, and the six tributaries studied by Ivarsson and Jansson (1994a) by black circles. The position of Lake Örträsket is indicated by a dotted arrow.

of terrestrial systems minus the terrestrial export of organic carbon and DIC to aquatic systems) and the fate of terrestrially exported organic carbon in aquatic systems (sedimentation, mineralization/CO_2 escape to the atmosphere, and transport to sea). We considered the DIC transport as an additional loss factor of organic carbon from terrestrial systems. The reasons are that the catchment bedrock is composed of non-carbonate minerals (Ivarsson and Karlsson (1992)) and that DIC is depleted in ^{13}C ($\delta^{13}C$ is between $-20‰$ and $-13‰$, cf. Jonsson et al., 2001) compared to in carbonate bedrock (a typical $\delta^{13}C$ value is approximately $0‰$, Craig, 1957). These characteristics strongly support the supposition that most of the HCO_3^- emanates from soil respiration and not from the weathering of carbonate bedrock. We therefore considered that all DIC transport represented a loss of organic carbon from the terrestrial systems.

Terrestrial organic carbon pools and the NEE of CO_2

We estimated carbon pools and NEE in the major terrestrial compartments of the river basin, i.e., the forests, the mires, and the clear-cut areas, from published data. The area of arable land is only approximately 0.5% of the catchment (Ivarsson and Jansson, 1994a) and was treated as forest; mires cover approximately 20% of the catchment (Ivarsson and Jansson, 1994a). Subtracting the area covered by lakes (3.5% of the catchment), streams, the river (see below), and mires, results in a forest cover of 77%. Clear-cut areas have been reported to change from being a net carbon source to a net sink within approximately 10 years of planting (Rannik et al., 2002; Kolari et al., 2004). We therefore subtracted all clear-cut areas less than 10 years old from the total forested area, and treated clear-cut areas and forested areas as functionally different units in our balance. In this area of Sweden, approximately 10% of the catchment area is clear-cut in 10 years (approximately 1% per year, National Board of Forestry, http://www.svo.se). Thus, 67% of the catchment area was treated as forested and 10% as clear-cut. Published data were selected to represent habitats similar to those in the Öreälven catchment area, i.e., data pertaining to boreal landscapes from Sweden/Finland or, when possible, from the Öreälven catchment. The carbon pool in mires was derived from a study of peatlands and forests in boreal Finland (Kauppi et al., 1997), and represents the organic carbon content in peatlands deeper than 30 cm. The carbon pool of forests and clear-cut areas was estimated using data from northern Finland, with the carbon pool including vegetation, litter, and soil carbon (Karjalainen and Kellomäki, 1995). These modeled values are close to what was reported for forests in Finland by Kauppi

Table 1 Area, water content of the aquatic environment, and the carbon pools of different terrestrial and aquatic compartments of the Öreälven catchment

Compartment	Area km^2	Water volume m^3 10^6	Carbon pool	
			Compartment specific, kg C/m^2	Catchment area specific, kg C/m^2
Forest	2010	–	14	9.5
Mire	596	–	72	14.2
Clear-cut	303	–	7.5	0.7
Öreälven	7	6.9	<0.1	<0.1
Small streams[a]	3	1.0	<0.1	<0.1
L. Örträsket	7	167.9	0.3	<0.1
Small lakes	99	315.4	<0.1	<0.1
Lake sediment	(106)	–	48	1.7
Whole catchment	3025	491.2		26.1

Catchment-area-specific values are normalized to the total catchment area (3025 km^2).
[a] 1st order streams represent 50% of the area.

et al. (1997). However, their estimate excluded the litter, and was somewhat lower than the estimates we have used, as given by Karjalainen and Kellomäki (1995). The compartment-specific pools used in the calculations are given in Table 1.

The NEE for the forest was estimated using eddy covariance data from the SMEAR II site in Finland (Markkanen et al., 2001). The site (61°N, 24°E) is dominated by a 34-years old Scots pine (*Pinus Sylvestris* L.) forest. The measured NEE is close to those found by other studies of boreal forests using the eddy covariance technique (Rayment and Jarvis, 1999; Cienciala et al., 1998). For clear-cut areas we used an annual NEE value obtained using the eddy covariance technique in a 5-year-old clear-cut area of a Scots pine forest in the SMEAR II study site in southern Finland (61°N, 24°E) (Kowalski et al., 2004). The site lost CO_2 to the atmosphere, in line with findings pertaining to other clear-cut areas (Kowalski et al., 2004).

The NEE of mires was based on a study at Degerö Stormyr (64°N, 19°E) using the eddy covariance technique (Sagerfors, unpublished, 2006). The study site is close to our study area. The compartment-specific NEE of 55 g C/m^2/yr is higher than the six years average NEE measured for a subarctic fen in Finland (69°N) of 22 g C/m^2/yr (Aurela et al., 2004) and that reported for a subartic mire in northern Sweden (68°N) of 28 g C/m^2/yr (Johansson et al., 2006).

Water volume and area of streams and lakes

The volume of water in Öreälven and its tributaries was estimated from the morphometry (length, width, and depth) of all streams. We digitized the whole drainage network of the Öreälven system (excluding the lakes) from maps (scale 1:50 000 or 1:100 000) using ArcView GIS 3.0 (ESRI) and a digitizing table. The stream lengths were then measured and the widths and depths estimated. The Öreälven drainage network was divided into one main stream (Öreälven) and small streams (all others). The average width and depth of the main stream were set to be 25 m and 1 m, respectively, based on measurements made along the river course and on map data. To estimate the volume of water of small streams, we determined the stream order of each stream in the whole drainage network. The length of each stream order was calculated using the spatial analysis extensions in ArcView. Stream order 1 was assumed to be 1 m wide with an average depth of 0.1 m; stream order 2 was assumed to be 2 m wide and 0.2 m deep, stream order 3, 4 m wide and 0.3 m deep, stream order 4, 8 m wide and 0.4 m deep, while stream order 5 streams were assumed to be 16 m wide and 0.5 m deep. These assumptions were partly based on actual measurements of the width and average depth of six different streams (stream orders 3 and 4), draining into Öreälven (Ivarsson and Jansson, 1994a) (Fig. 1). Assuming that there are additional small streams in the area not covered by the maps, we considered our estimates of the importance of streams to be conservative. It would, however, require a very large number of these small streams to have a significant impact on the carbon balance, and their possible effect is therefore not considered.

Lakes cover approximately 3.5% of the Öreälven basin area (Ivarsson and Jansson, 1994a). The large Lake Örträsket (7.3 km^2) was treated separately, since data specific to the lake exists. Lake Örträsket is also morphologically different from other lakes in the river basin, having a maximum depth of 64 m and a mean depth of 23 m. The average mean depth of all other lakes was set to 3.2 m, which is the average mean depth of 103 lakes in the county of Västerbotten (data from the County Administrative Board of Västerbotten). The area covered by lakes was calculated from map data.

TOC and DIC content of streams and lakes

TOC was obtained from our own measurements or from published data. DIC was calculated as the sum of HCO_3^- (estimated from alkalinity) and CO_2.

For lakes, CO_2 was calculated as described by Algesten et al. (2004a) using the TOC–pCO_2 relationship from lakes in northern Sweden given by Sobek et al. (2003). CO_2 concentration was then calculated using Henry's law and assuming a mean annual water temperature of 3 °C. For Lake Örträsket we have our own measurements of the CO_2 concentration (Åberg et al., 2004).

We used an average CO_2 concentration of 3400 ppmv for small streams (1st to 5th-order streams), which is the average from four studies of 27 small streams from the north-eastern Scotland and from the Appalachian mountains in the US (Dawson et al., 1995; Jones and Mulholland, 1998a; Jones and Mulholland, 1998b; Hope et al., 2001). This value is conservative compared to observations of very high concentrations of CO_2 in some small headwater streams in the area (Temnerud, 2005), but clearly higher than the mean concentration (1000 ppmv at 3 °C) in small streams in the Öreälven catchment estimated from pH and alkalinity data (see below) from the years 1995 and 2000. The pCO_2 for Öreälven was calculated using the same TOC–pCO_2 correlation as for the lakes.

The TOC concentration in Lake Örträsket was set to 10.6 mg/L, the mean of 83 analyses made during the years 1993–1995 (Jonsson and Jansson, 1997), while the average alkalinity was set to 0.116 meq/L, the mean of 41 analyses made between 1990 and 1992 at the outlet of the lake (Ivarsson, unpublished data 1994). The TOC and alkalinity in small streams and lakes in the Öreälven basin were taken from national surface water surveys carried out in 1995 and 2000 (SLU, Department of Environmental Assessment, Uppsala, Sweden, http://www.ma.slu.se/). Each location was sampled once each year, with most (76%) samples taken in October. All sampling stations were located in the county of Västerbotten, at a similar longitude and latitude as the Öreälven catchment. Using the mean data from these surveys of 44 streams (11.4 mg TOC/L, alkalinity 0.140 meq/L) and 193 lakes (10.9 mg TOC/L, alkalinity 0.121 meq/L), we found the average pH of the small streams to be 6.6 and of the small lakes to be 5.9.

TOC and alkalinity in the main stream, Öreälven, were sampled close to its outlet to the marine environment, and data were obtained from the Department of Environmental Assessment (SLU, Uppsala, Sweden, http://www.ma.slu.se/). TOC was sampled monthly between 1987 and 2003 (annual average 9.8 mg/L ± 1.3, ±one standard deviation (SD)) and alkalinity was sampled monthly between 1966 and 2003 (annual average 0.152 meq/L ± 0.021, ±SD).

A time series analysis of the Öreälven stream data showed that data for the years 1995 and 2000 (the years for which we have data for small lakes and streams) gave reasonable long-term averages for the alkalinity and TOC of the Öreälven stream, and there were no statistically significant differences between the averages of the 1995 and 2000 samplings compared to the long-term annual means ($p = 0.879$ for TOC and $p = 0.802$ for alkalinity, t-test, Sigmastat 3.0).

Sampling in the autumn reflected the annual average reasonably well, and there was no significant ($p = 0.098$, t-test Sigmastat 3.0) difference in TOC, with an annual average (±SD) of 9.8 ± 1.3 mg/L compared to the concentration in October of 11.3 ± 2.9 mg/L in the Öreälven stream. In the Öreälven stream, the annual average (±SD) alkalinity was 0.152 ± 0.021 meq/L, while the alkalinity in October was 0.111 ± 0.036 meq/L. The October data significantly ($p < 0.001$, t-test Sigmastat 3.0) differed from the annual average.

The time series analysis thus indicated that we could use data for small streams and small lakes from the years 1995 and 2000 as the long-term average. However, we likely underestimated inorganic carbon content in the small streams and the small lakes by using data sampled in the autumn.

The TOC and DIC concentrations in streams and lakes were used to calculate the content of carbon in the different aquatic compartments of the catchment (small streams, Öreälven, small lakes, and Lake Örträsket) by multiplying the concentrations by the water volumes of the different compartments.

Emission of CO_2 from streams and lakes

Estimates of the aquatic losses of organic carbon from streams and lakes were made for transport to the sea, permanent incorporation into lake sediments, and mineralization/emission of CO_2 to the atmosphere. Emission to the atmosphere was calculated assuming an ice-free period of 180 days, no emission through the ice, and no enhanced emission upon ice break-up. Since there may be considerable build-up of CO_2 under ice during the winter (Striegl et al., 2001), we consider the estimated emission to be conservative.

Flux data recorded using the eddy covariance technique do not exist for lakes, except for a few short data series. Moreover, the large variation in CO_2 emission between lakes (Sobek et al., 2003) makes this method unsuitable for use in regional studies. Fluxes of CO_2 across lake surfaces were therefore estimated from the CO_2 saturation measured in lakes (Cole et al., 1994). Emission of CO_2 (F_{CO_2}) to the atmosphere from Lake Örträsket has previously been estimated in a separate study (Åberg et al., 2004). Emission of CO_2 from other lakes was calculated using the equation presented by Cole and Caraco (1998) for estimating the gas transfer velocity of CO_2 (k) in small lakes. This was applied to the equation $F_{CO_2} = k((CO_{2water}) - (CO_{2eq}))$, where ($CO_{2water}$) is the concentration of CO_2 in the water and (CO_{2eq}) is the equilibrium concentration of CO_2 between water and air. Concentrations of CO_2 in the water were calculated from Henry's law (Weiss, 1974). For these calculations we set the wind speed to 2.5 m/s, pCO_{2air} to 360 μatm (Åberg et al., 2004), and the mean surface water temperature during the ice-free season to 10 °C. Varying the temperature within credible limits (5–15 °C) had a minor effect on the emission from lakes (±7%).

Emission from streams was calculated by applying the estimated gas transfer velocity of O_2 in various stream environments (Wannikhof et al., 1990). Data was selected based on water flow and stream depth. Gas transfer velocities were corrected to $CO_2$and a temperature of 10 °C, using the equation reported by Crusius and Wannikhof (2003) and the calculated Schmidt numbers reported by Wannikhof (1992). This gave an average gas transfer velocity of 16 cm/h for small streams and 4.6 cm/h for the main stream, Öreälven. The emission from streams estimated using this method gave a compartment-specific evasion of CO_2 from small streams (1st to 5th-order streams) of 7686 mg C/m^2/d, which is within the range (upper half) reported in other studies as summarized by Hope et al. (2001).

Incorporation of organic carbon in lake sediments

The accumulation of organic carbon in lake sediments was estimated using the compartment-specific accumulation

rate for Finnish lakes smaller than 1 km^2 (5.72 g $C/m^2/yr$; Pajunen, 2000) and that for Lake Örträsket (34 g $C/m^2/yr$; Jonsson and Jansson, 1997). The Finnish value is lower than those reported by Boville et al. (1983) for 21 lakes across Canada. However, the accumulation reported by Pajunen (2000) is likely more similar to lakes in the Öreälven catchment. More lakes were also cored in that study, and several of those lakes were cored more intensively than in the study of Boville et al. (1983). We regard the high figure obtained for Lake Örträsket as a special case caused by the high sedimentation (approximately 50% of the annual sedimentation) of organic carbon on suspended mineral particles during the high spring flood event (Jonsson and Jansson, 1997). The pool of organic carbon in lake sediments was also calculated using data from Pajunen (2000) using the value for lakes smaller than 1 km^2.

Stream transport of organic carbon and DIC to the sea

The transport of carbon from the catchment to the sea by Öreälven was calculated by applying the mean concentration of TOC of 9.8 mg/L and the mean concentration of DIC of 2.6 mg/L, calculated as described above. The transport was then calculated by assuming an average annual water flow of 35 m^3/s, which is equivalent to a runoff of 365 mm/yr (Ivarsson and Jansson, 1994b).

Export of terrestrially fixed carbon to streams and lakes

The export of terrestrially fixed carbon to the aquatic compartment of the catchment was calculated as the sum of the aquatic net fluxes of DIC and TOC, as follows:

Terrestrial export = TOC and DIC transport to the sea + sedimentation of organic carbon in lakes + net emission of CO_2 from streams and lakes.

This calculation gives the sum of the export from all different terrestrial habitats.

Error estimates

Several of the estimates in this study have a large degree of uncertainty due to the use of different data sources where different methods have been used to measure carbon fluxes. It is almost impossible to provide fully accurate error estimates for the comparison of different compartment fluxes. However, the most critical uncertainty for this study emanate from the data on carbon dioxide fluxes from different terrestrial and aquatic compartments of the catchment. These fluxes were estimated by multiplying the annual net ecosystem exchange of carbon dioxide from forest, mires, clear-cut areas, lakes and streams (obtained using different methods) with the areal distribution of these compartments. Areal distributions were taken from map material, which is quite accurate at the landscape scale. The largest degree of uncertainty is, therefore, the spatial and temporal variation of the carbon fluxes within the different compartments. The ranges of values given by the different authors from the specific data sources were taken as an estimate of the uncertainty in each of the specific carbon flux. Thus, for the forest, and the mires, ranges given for multiannual measurements were taken as an uncertainty of the NEE from these compartments. For clear-cut areas no such data exists, and a general uncertainty of 10% of measured compartment-specific flux was assumed, see Baldocchi (2003) for a discussion on this matter.

No uncertainty for the accumulation of carbon in lake sediments could be calculated, since the data source did not give any error estimates. This will not have a major impact on the results since the long-term accumulation is very small compared to other fluxes.

We estimated the emission of CO_2 from lakes by calculating a gas transfer velocity from wind speed using the equation given by Cole and Caraco (1998). This equation could explain approximately 60% of the variation in gas transfer velocity (Cole and Caraco, 1998). We therefore varied the gas transfer velocity within 0.6 and 1.4 times the calculated value using the equation given by Cole and Caraco (1998).

The uncertainty of the emission of CO_2 from streams is even more difficult to assess due to the large variation in stream properties. We made an uncertainty estimate of the emission of CO_2 from small streams based on the uncertainty of the gas transfer velocity by adding or subtracting one SD (13 cm/h) from the mean (16 cm/h) (Wannikhof et al., 1990).

Uncertainty of the stream transport of carbon to the marine environment was calculated based on the uncertainty of the measured concentration of organic and inorganic carbon in Öreälven. We used one SD of the data obtained from the Department of Environmental Assessment (SLU, Uppsala, Sweden, http://www.ma.slu.se/) comprising 17 years of TOC and 36 years of alkalinity measurements (see above). The calculated SD was added or subtracted from the mean concentration of TOC. Uncertainty in the concentration of HCO_3^- was estimated by adding or subtracting the SD of the alkalinity from the mean alkalinity. Uncertainty in the concentration of CO_2 was estimated using the equation for the relationship between pCO_2 and DOC (Sobek et al., 2003), assuming an average water temperature of 3 °C, and varying the DOC concentration as described above. Uncertainty in the DIC concentration was then obtained by adding the HCO_3^- and the CO_2 data.

However, even if these ranges are considered, the relative importance of different compartments for the total catchment NEE is obvious, especially when considering the areal extent of different compartments. For example, the high net areal flux from running water has very little total impact due to that running waters have a small total area, and constitute a very small share of the total catchment. We therefore consider, that even if we cannot provide exact error estimates, it is possible to use the calculated compartment fluxes for a discussion of the net exchange of carbon dioxide with the atmosphere in this typical boreal catchment and how different terrestrial and aquatic compartments take part in this exchange.

Results and discussion

Mires and forested areas contained the largest stores of organic carbon in the Öreälven catchment (Table 1). Even though the area of mires is considerably less than the area

of forests, the large deposits of peat in the mires result in most (54%) of the total catchment organic carbon pool being found in mires. Lake sediments contribute another 5%. This is a low estimate compared to those presented in other studies (Mulholland and Elwood, 1982; Molot and Dillon, 1996), which is mainly an effect of different accumulation rates (see Methods). At the catchment scale, mires and lake sediments are the most relevant long-term carbon sinks in the boreal landscape. The amount of carbon in stream and lake water is negligible at the catchment scale. Other pools are dynamic and constantly contribute to the flux of carbon.

The NEE of the terrestrial compartments is highest in growing forest and lowest in clear-cut areas (Table 2). When related to the areal extension of different habitats, forested areas dominate the NEE of the terrestrial environment (Table 2). The catchment-area-specific net gain of CO_2 of the forest was thus approximately 152 g C/m^2/yr, while the corresponding figure for mires was only 11 g C/m^2/yr. The net release of CO_2 from clear-cut areas was 24 g C/m^2 of catchment area per year (Table 2). The terrestrial loss of organic carbon to the aquatic environment was 8.6 g C/m^2/yr. Thus, the total accumulation of organic carbon by the terrestrial part of the catchment can be estimated to be 131 g C/m^2/yr. This figure is lower than other estimates for forested areas (Rayment and Jarvis, 1999; Markkanen et al., 2001), which is largely explained by the inclusion of clear-cut areas that are net sources of CO_2, the large area of mires which have a low NEE, and the losses to the aquatic system.

The aquatic flux of carbon was dominated by the stream transport of organic carbon to the sea, and the lake mineralization of allochthonous TOC and the subsequent emission of CO_2 to the atmosphere. The stream transport to the sea was almost twice as high as the escape of CO_2 (Table 2). Most of the emission from aquatic systems took place in lakes (Table 2), which is reasonable considering that the total volume and surface area of streams were negligible compared to those of lakes (Table 1). The calculated specific evasion rate of CO_2 from all lakes (Table 2) was similar to those previously reported for lakes in northern Sweden (Algesten et al., 2004a) which is between estimated emissions for more barren Arctic lakes in Alaska (Kling et al., 1992) and lower-latitude bog lakes in Wisconsin (USA) (Riera et al., 1999). The combined net release from lakes and streams, normalized to the total catchment area, was 3.8 g C/m^2/yr, which is a small flux compared to the large terrestrial fluxes. Although the emission of CO_2 from streams is uncertain, the minor extent of streams in the catchment implies that even large errors in this respect would have no large effect on the total aquatic system carbon balance and even less on the catchment carbon balance. Similarly, catchment export of DIC via stream transport to the sea was low (Table 2, approximately 25% of TOC export). Therefore, this transport accounted for rather little of the terrestrial loss of organic carbon. Permanent incorporation of organic carbon in lake sediments made up only 3% of the aquatic flux, and is thus insignificant compared to mineralization and stream transport. The input of organic carbon by means of aquatic primary production was previously estimated to account for approximately 0.5% of the total organic carbon input to the aquatic environment in the Öreälven catchment (Algesten et al., 2004a). We can therefore conclude that the carbon flux of surface waters in the Öreälven catchment was dominated by the export of organic carbon from terrestrial systems and the mineralization and subsequent evasion to the atmosphere of this carbon in lake ecosystems.

Approximately 45% of the terrestrial losses were mineralized in lakes and streams, while approximately 50% were transported to the sea. The degree of mineralization in

Table 2 The net carbon flux of different compartments of the Öreälven catchment

Compartment/process	Area, km^2	Net carbon flux	
		Compartment specific,[a] g C/m^2/yr	Catchment area specific, g C/m^2/yr
Forest NEE	2010	229 (191–262)	152 (127–174)
Mire NEE	596	55 (48–61)	11 (9.4–12)
Clear-cut area NEE	303	−239 (−215 to −263)	−24 (−21 to −26)
Total terrestrial NEE			139 (115–160)
Terrestrial export to aquatic environment			−8.6 (−6.0 to −12)
TOC accumulation in lake sediment	106	8	0.3
Aquatic NEE			
Lakes	106	−63 (−38 to −105)	−2.2 (−1.3 to −3.7)
Streams	10	−471 (−142 to −800)	−1.6 (−0.5 to −2.6)
Stream transport to the sea			
TOC	10		−3.6 (−3.1 to −4.1)
DIC	10		−0.9 (−0.8 to −1.1)
Net accumulation of carbon in the whole catchment	3025		131 (109–148)

Catchment-area-specific values are normalized to the total catchment area (3025 km^2). Negative values indicate a loss of carbon. Values within parenthesis in the column for catchment specific data give the uncertainty calculated in the error analysis.

[a] Numbers in parentheses give the ranges used in the uncertainty calculation as described in the Material and methods section.

freshwaters of the Öreälven catchment was lower than in other catchments in northern Sweden. This is in accordance with what can be predicted from the short residence time (Algesten et al., 2004a) of water in this catchment (ca. 0.4 years). The portion of allochthonous carbon that is not mineralized in freshwater systems is drained downstream to the sea. Since mineralization proceeds in the marine environment (del Giorgio and Duarte, 2002; Algesten et al., 2004b), the major part of the terrestrial loss is returned to the atmosphere as CO_2 by mineralization in different aquatic systems. The proportions of allochthonous carbon that are mineralized in freshwater and marine systems are largely influenced by the residence time of water in the freshwater environment.

Since most of the terrestrial export of carbon to aquatic systems is returned to the atmosphere within a few years, this export must be subtracted from terrestrial NEE to obtain the net accumulation of organic carbon in both the terrestrial compartment and in the whole catchment. In the Öreälven catchment, this means that terrestrial NEE (139 g C/m^2/yr) is fairly similar to the whole catchment accumulation (131 g C/m^2/yr, Table 2). Thus, accounting for the return flux via lakes and streams does not decrease the net accumulation of organic carbon in the Öreälven catchment to any great extent compared to an estimate based on the NEE of the terrestrial system only (approximately 6%). However, the importance (or unimportance) of the aquatic losses should depend on time scales and on land use. The largest flux in the catchment carbon balance is the net accumulation in forested areas. We used a value for a growing forest with 34-year-old trees, which corresponds reasonably well to the mean age of trees in regions with intensive forestry in northern Sweden. A major part of the NEE in such a forest comprises accumulation of carbon due to the imbalance created during clearfelling of the forest, resulting in a large accumulation of carbon both in soil and growing trees (Kolari et al., 2004).

Compared to the NEE we have used, mature–natural forests–should have a considerably lower NEE, since the build-up of tree biomass and degradation of plant biomass should be close to balanced, even if there are large variations in the NEE between years and habitats (Goulden et al., 1998; Lloyd et al., 2002; Milyukova et al., 2002). NEE is here controlled mainly by the net accumulation of organic carbon in forest soil (Lloyd et al., 2002). In such systems the terrestrial export of organic carbon to aquatic systems and its subsequent mineralization can have a considerable influence on the catchment net accumulation of organic carbon. One example is from the undisturbed temperate forest system in Hubbard Brook, N.H, USA, where most of the accumulation of carbon occurred in the soil and the terrestrial loss of dissolved organic carbon to aquatic systems was greater than the net carbon accumulation in the terrestrial system (Cole and Caraco, 2001). This is likely a general property of mature forest ecosystems that are in equilibrium with the climate. In the tropical ecosystem of the Amazon basin, emission and transport in the aquatic system was also found to be highly important for the whole landscape carbon budget, bringing the whole ecosystem carbon balance close to equilibrium (Richey et al., 2002).

The relevance of calculating the NEE and net accumulation of organic carbon from growing forests in areas with intensive forestry can also be questioned if these figures are to be used in large-scale calculations of carbon fluxes. Such forests are managed in order to optimize production of tree biomass. Trees are cut down and used for products, such as paper and building material, or burned directly to produce heat or electricity. From a longer-term perspective, most of these wood products are eventually burned and their carbon content is released as CO_2, and returned to the atmosphere. It is therefore interesting to compare biomass accumulation in a forest over a rotation period with the amount of carbon withdrawn by clearfelling. By modeling the accumulation of C during the rotation period of a coniferous forest in Dalarna in mid Sweden, Ericsson et al. (2002) calculated an average carbon accumulation of approximately 21 g C/m^2/yr. This figure can be compared with the withdrawal of biomass during clearfelling in the county of Västerbotten of approximately 16 g C/m^2/yr (average for the years 1990–1999, data from the Swedish Forest Agency, http://www.skogsstyrelsen.se/). These data indicate that most (approximately 80 % in this example) of the C accumulation over a rotation period is removed by clearfelling. From a 50 to 100-year perspective, it is therefore likely that organic carbon export to aquatic systems is highly significant for the net accumulation of organic carbon in boreal forest landscapes, independent of whether they are preserved as natural forests or used for intensive forestry.

Based on these calculations of the carbon balance of the Öreälven catchment, we conclude that aquatic fluxes and metabolism play a relatively small role in boreal areas subject to intensive forestry. However, we suggest that the importance of aquatic carbon metabolism increases with the age of the forest, and can be significant at the catchment scale in natural landscapes but also if the final fate of forestry products are considered in a longer time perspective.

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