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Carbon dioxide transport across the hillslope–riparian–stream continuum in a boreal headwater catchment

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Headwater streams export CO₂ as lateral downstream export and vertical evasion from the stream surface. CO₂ in boreal headwater streams generally originates from adjacent terrestrial areas, so determining the sources and rate of CO₂ transport along the hillslope–riparian–stream continuum could improve estimates of CO₂ export via the aquatic pathway, especially by quantifying evasion at higher temporal resolutions. Continuous measurements of dissolved CO₂ concentrations and water table were made along the hillslope–riparian–stream continuum in the Västrabäcken sub-catchment of the Krycklan Catchment, Sweden. Daily water and CO₂ export from the hillslope and riparian zone were estimated over one hydrological year (October 2012–September 2013) using a flow-concentration model and compared with measured lateral downstream CO₂ export.

Total water export over the hydrological year from the hillslope was 230 mm yr⁻¹ compared with 270 mm yr⁻¹ from the riparian zone. This corresponds well (proportional to the relative upslope contributing area) to the annual catchment runoff of 265 mm yr⁻¹. Total CO₂ export from the riparian zone to the stream was 3.0 g CO₂-C m⁻² yr⁻¹. A hotspot for riparian CO₂ export was observed at 30–50 cm depth (accounting for 71 % of total riparian export). Seasonal variability was high with export peaks during the spring flood and autumn storm events. Downstream lateral CO₂ export (determined from stream water dissolved CO₂ concentrations and discharge) was 1.2 g CO₂-C m⁻² yr⁻¹. Subtracting downstream lateral export from riparian export (3.0 g CO₂-C m⁻² yr⁻¹) gives 1.8 g CO₂-C m⁻² yr⁻¹ which can be attributed to evasion losses (accounting for 60 % of export via the aquatic pathway). The results highlight the importance of terrestrial CO₂ export, especially from the riparian zone, for determining catchment aquatic CO₂ losses and the importance of the CO₂ evasion component to carbon export via the aquatic conduit.

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1 Introduction

Boreal forests are an important ecosystem within high latitude regions containing a globally significant carbon store in both soils and vegetation (Dunn et al., 2007; Pregitzer and Euskirchen, 2004). The net ecosystem carbon balance (NECB) of individual northern latitude catchments has shown them to be net sinks for carbon (Dinsmore et al., 2010, 2013b; Koehler et al., 2011; Nilsson et al., 2008; Olefeldt et al., 2012; Roulet et al., 2007). In boreal forest catchments, carbon export via the aquatic pathway (consisting of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), particulate organic carbon (POC) plus dissolved and gaseous CO₂ and CH₄) accounted for 4–28% of carbon uptake via Net Ecosystem Exchange (NEE), representing an important, but spatially and temporally variable component of the NECB (Öquist et al., 2014; Wallin et al., 2013).

Headwater streams are generally supersaturated in CO₂ with respect to the atmosphere, resulting in export via the aquatic conduit consisting of both the downstream lateral export and vertical evasion of CO₂ from the stream surface (Kling et al., 1991). CO₂ evasion has been shown to account for 13–53% of the total aquatic flux across a range of northern latitude headwater streams (Billett et al., 2004; Öquist et al., 2009; Wallin et al., 2013), representing an important component of the catchment NECB. Low order streams have been observed to have disproportionately high evasion rates (Aufdenkampe et al., 2011; Butman and Raymond, 2011; Raymond et al., 2013). Across Sweden, CO₂ evasion from 1st order streams was estimated at 205 000 Tg C yr⁻¹ or 39% of the total from all streams, despite accounting for only 13% of the total stream area (Humborg et al., 2010). Quantifying evasion involves combining dissolved CO₂ concentrations and the gas transfer coefficient (KCO₂) (Hope et al., 2001). Due to the limited numbers of direct measurements of the gas transfer coefficient (KCO₂) (Raymond et al., 2013; Wallin et al., 2011) and the considerable spatial and temporal variability in dissolved CO₂ concentrations (Dawson et al., 2001b; Dinsmore et al., 2013a; Hope et al., 2004), evasion, and the drivers of this flux are likely

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to be underestimated. To improve understanding of both lateral downstream export and vertical evasion of CO₂ from headwater streams the concentrations and sources of dissolved CO₂ need to be better quantified.

To better understand the drivers of stream water CO₂ dynamics an increasing number of studies have made continuous, direct measurements of dissolved CO₂ concentrations in stream waters (using in situ, non-dispersive infra-red (NDIR) CO₂ sensors) giving new insights into diurnal, storm event and seasonal CO₂ dynamics (Dinsmore and Billett, 2008; Dinsmore et al., 2013a; Dyson et al., 2011; Johnson et al., 2006, 2010). Much of the excess CO₂ in temperate and boreal streams originates from terrestrial areas through lateral subsurface transport through the soil (Hope et al., 2004), confirmed by isotope studies in peatland catchments (Garnett et al., 2012; Leith et al., 2014). The concentration of CO₂ in stream water is largely dependent on the concentration in terrestrial source areas and the hydrological connectivity between source areas and the stream channel (Vidon et al., 2010). Despite the apparent importance of soil sources, most studies of stream CO₂ dynamics take the observed response in the stream and link it to terrestrial processes without direct measurements in soils. Quantifying the rate of export of carbon from soil to stream will enable better estimates of CO₂ export via the aquatic pathway and in particular contribute to higher temporal resolution estimates of evasion.

A few studies have made continuous, high frequency CO₂ concentration measurements in soils but are largely restricted to sampling at shallow depths above the water table (Dinsmore et al., 2009; Jassal et al., 2004, 2008; Tang et al., 2003). Higher soil CO₂ concentrations have been observed below the water table and in response to soil re-wetting after storms (Jassal et al., 2005; Rasilo et al., 2012). In soil, CO₂ can be derived from root respiration, soil organic matter decomposition and weathering of carbonate parent material. Mobilisation of CO₂ occurs through the displacement of high CO₂ concentrations in the soil atmosphere, combined with decreased vertical diffusivity as soil pore space becomes saturated (CO₂ diffusion is 10000 times slower in water than in air) (Šimůnek and Suarez, 1993). This

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highlights the importance of considering concentration changes over the full soil profile depth, especially in horizons which experience frequent water table fluctuations as transient saturation can increase the lateral export of water and dissolved constituents exponentially (Bishop et al., 2011).

5 The terrestrial–aquatic interface is a continuum between the wider catchment area (hillslope), riparian zone and stream. Riparian zones in headwater catchments commonly represent a 1–5 m wide area immediately adjacent to the stream (Luke et al., 2007). Common characteristics of the riparian zone are higher water table conditions (Burt et al., 2002), organic rich soils and distinct vegetation composition in comparison
10 to the surrounding hillslope (Lyon et al., 2011). Hence, the riparian zone has been widely shown to be a key area for hydrological, ecological and biochemical processes (Naiman and Décamps, 1997; Vidon et al., 2010). Subsurface hydrological flowpaths converge at the terrestrial–aquatic interface resulting in the riparian zone being the last biogeochemical environment encountered by subsurface water (Bishop et al.,
15 1990; McClain et al., 2003). The riparian zone has been shown to have a stronger hydrological connection to the stream in comparison to groundwater or soil water (Buttle et al., 2004; Stieglitz et al., 2003) and to control stream water chemistry during hydrological events (Bishop et al., 2004). Water and solute transport has been shown to be episodic with hotspots and hotmoments in export (McClain et al., 2003; Vidon et al.,
20 2010), hence the full hillslope–riparian–stream continuum needs to be considered at high temporal resolutions to quantify solute transport across the terrestrial–aquatic interface.

25 Across five different northern latitude catchments, stream water CO₂ concentrations were shown to be strongly linked to discharge, with the highest 30 % of flow having the greatest impact on lateral CO₂ export (Dinsmore et al., 2013a). DIC export via the aquatic pathway over a 13 year period in a headwater Swedish catchment (the same catchment as this study) was positively correlated with precipitation with export varying from 2.3 to 6.9 g DIC-C m⁻² yr⁻¹ (Öquist et al., 2014). In boreal systems, water and carbon cycles are highly seasonal and strongly linked to the length of the snow

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covered period in winter and the spring snow melt event. In these systems, snow melt is the major hydrological event of the year, with one example being the Krycklan catchment where 40–60% of the annual runoff occurs during only 10–15% of the year (Laudon et al., 2011). Snow melt has been shown to be an important period for carbon export via the aquatic pathway both as DOC (Laudon et al., 2004; Nilsson et al., 2008) and gaseous species (Dyson et al., 2011). Another example of the short-term variability in stream water dissolved CO₂ concentrations is the observation in some catchments of bimodal frequency distributions during storms, indicative of two distinct CO₂ sources within the catchment (Dinsmore et al., 2013a). Combining high resolution concentration measurements in both the soil and the stream is a powerful way of studying hydrological and seasonal variability in these catchments. However, previous studies which determined dissolved CO₂ concentrations in riparian soils and streams have used either a limited number of discrete measurements (Hope et al., 2004; Öquist et al., 2009) or did not determine the variability in the depth of lateral subsurface hydrological flowpaths transporting CO₂ to the stream (Rasilo et al., 2012). This is likely to under represent variability in these dynamic systems, especially for short lived hydrological events such as storms.

This study uses high temporal resolution measurements of CO₂ concentrations along a hillslope–riparian–stream continuum in a hydrologically well defined catchment with extensive previous work delineating the hydrological flowpaths along the continuum (Bishop et al., 2004; Seibert et al., 2009; Stähli et al., 2001). This allows the sources of stream water CO₂ to be investigated while estimating the export of water and CO₂ across the terrestrial–aquatic interface. Due to the position of riparian zones within the catchment and the greater potential for CO₂ production in the organic rich riparian soils we hypothesise that it is the riparian zone, rather than the wider catchment area, that is maintaining CO₂ export to streams.

2 Materials and methods

2.1 Site description

This study was conducted in the 0.13 km² forested Västrabäcken subcatchment of the 0.47 km² Svartberget catchment, which is part of the wider 68 km² Krycklan Catchment (64°14' N, 19°46' E), 50 km northwest of Umeå, Sweden (Laudon et al., 2013).

The altitude of the catchment ranges from 235 to 310 m a.s.l. (Bishop et al., 1990). Mean annual temperature (1980–2008) is 1.7 °C, with the maximum (14.6 °C) and minimum (−9.6 °C) in July and January, respectively. Mean annual precipitation (1981–2008) is 612 mm, with approximately 35 % falling as snow (Haei et al., 2010). Snow covers the ground on average for 171 days from October to May to a depth of between 43 and 113 cm (1980–2007) (Laudon et al., 2011). The largest hydrological event during the year is a 4–6 week long snow melt period in late April/early May which contributes between 40 and 60 % of annual runoff (Laudon et al., 2011). The Västrabäcken is a 1st order, low pH (range pH 4.5–5.9) with little variability in the bicarbonate equilibrium system (Wallin et al., 2010).

Drainage channels were deepened and widened in the 1920s to improve forest drainage (Bishop et al., 1990). Scots pine (*Pinus sylvestris*) is the dominant tree species in hillslope areas with some Norway spruce (*Picea abies*) nearer to the stream. Understory vegetation is predominately a mix of *Vaccinium myrtillus*, *Vaccinium vitis-idaea* and grasses (*Deschampsia flexuosa*), with mosses (*Sphagnum spp*, *Polytrichum commune*) and wood horsetail (*Equisetum sylvaticum*) in the wetter riparian areas.

The bedrock is gneiss overlain by 10–15 m of locally derived glacial till. Soils consist of well-developed iron podzols comprising a surface 5 cm humus layer overlying a 12 cm thick sandy bleached E-horizon and a 60 cm thick B-horizon (Nyberg et al., 2001). The riparian zone formed through the accumulation of organic matter in low lying areas and extends 4 m on either side of the stream channel. Riparian soils consist of ~ 70 cm thick peat transitioning to the underlying till at ~ 90 cm depth. Soil organic content is considerably higher in the riparian soil (> 80 %) compared to the hillslope

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podzols (< 5%) (Nyberg et al., 2001). Saturated hydraulic conductivity is about one order of magnitude lower in the riparian zone ($6.2 \times 10^{-6} \text{ m s}^{-1}$) than the hillslope ($5.6 \times 10^{-5} \text{ m s}^{-1}$) (Nyberg et al., 2001) decreasing with depth (Stähli et al., 2001). Porosity and water retention were higher in the riparian soil (Nyberg et al., 2001; Stähli et al., 2001). The riparian zone studied is representative of headwater till catchments across the larger Krycklan catchment (Grabs et al., 2012).

2.2 Field methods

Sampling was carried out in both the hillslope podzol soils (15 m perpendicular to the stream) and riparian zone peat soils (1.5 m from the stream) (Fig. 1). At each location there were two dipwells for CO₂ measurement with a 10 cm perforated sampling window at either 30–40 or 60–70 cm depth. Dipwells were constructed from 50 mm inner diameter (ID) pipe open at the bottom and sealed at the surface using rubber bungs (Saint Gobain Performance Plastics, France). To prevent damage to the dipwells over winter due to freezing, the short above ground section was covered in insulation foam. Each dipwell contained a Vaisala CARBOCAP GMP221 non-dispersive infrared (NDIR) CO₂ sensor (range 0–5%). Prior to deployment, sensors were enclosed in a water-tight, gas-permeable membrane (Johnson et al., 2006, 2010). At each sampling point a third dipwell, constructed from 90 mm ID pipe perforated along its entire 1 m length and open at the bottom, was used for the measurement of water table depth (Level Troll 300, In-situ, USA) and soil temperature (CS457A, Campbell Scientific, USA), with sensors suspended at 90 cm depth. All sensors were connected to a datalogger (CR1000, Campbell Scientific, USA) which recorded measurements at 30 min intervals. The system ran for three months (from 1 July 2012) to allow it to become stabilised and equilibrated before the main measurement period over one hydrological year (1 October 2012 to 30 September 2013). Soil moisture content was recorded by time domain reflectometry (TDR) probes (Laudon et al., 2013; Nyberg et al., 2001).

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Measurements were made at one point in the hillslope and riparian zone assuming, as with all transect studies, that these points are representative of the catchment overall. A single transect approach is appropriate for this catchment due to the small area (0.13 km²) and limited variability in soils and vegetation (Bishop et al., 1990; Lyon et al., 2011). Furthermore, overland flow or deeper groundwater inputs to the stream have been shown to be limited in this catchment (Laudon et al., 2004; Peralta-Tapia et al., 2014). The sampled riparian zone is consistent with the 13 riparian zones in the wider Krycklan Riparian Observatory (Grabs et al., 2012).

Stream water dissolved CO₂ concentrations (measured using the same Vaisala CO₂ sensors), plus discharge were measured continuously in a heated dam house at the catchment outlet (Laudon et al., 2013), 200 m downstream from and over the same time period as soil measurements.

2.3 Data Processing and analysis

CO₂ sensor output was corrected for temperature and pressure using the method of Tang et al. (2003) but using algorithms supplied by the manufacturer specific to the GMP221 sensors. In addition to atmospheric pressure, the correction also accounted for the head of water above the sensor, related to the water table depth at the time of sampling. Corrected concentrations are given in units of ppmv with mg CO₂-C L⁻¹ used for export calculations.

The export of water and CO₂ from each m² of hillslope and riparian zone were estimated using a flow-concentration model, a similar approach to the Riparian Integration Model concept used previously in this, and similar, hillslope–riparian systems (Grabs et al., 2012; Seibert et al., 2009). Our study used measured water table positions in the hillslope and riparian zone while previous studies have used a correlation between groundwater and runoff dynamics (Grabs et al., 2012).

The 90 cm deep soil profile was subdivided into 5 cm horizons with the daily lateral water export from each 5 cm soil layer estimated by combining the daily mean water table position with measured volumetric water content and lateral saturated hydraulic

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conductivity estimated by Stähli et al. (2001). Total daily water export from the full soil profile was estimated by adding together the flow from each 5 cm horizon below the daily mean water table. As CO_2 concentration was only measured at two depths (30–40 and 60–70 cm) these were assumed to represent the concentration above and below 45 cm depth. Daily average CO_2 concentrations in $\text{mg CO}_2\text{-C L}^{-1}$ were multiplied by the water export, with CO_2 export expressed in units of $\text{mg CO}_2\text{-C m}^{-2} \text{day}^{-1}$. The model was run twice to estimate the export from (1) podzol hillslope soils and (2) riparian organic soils.

Downstream CO_2 export was determined by multiplying daily mean stream water CO_2 concentration with discharge at the catchment outlet. Based on the assumption that all stream water carbon is derived from terrestrial inputs, evasion was estimated by subtracting the downstream lateral CO_2 export from the export of CO_2 from the riparian zone to the stream. Whilst we recognize this assumption may not be completely met and we may be underestimating total inputs and therefore evasion, in stream processing in this catchment is likely to be minimal due to the low temperatures, pH and short water residence time (Öquist et al., 2009). Our results therefore provide a useful means to consider temporal variability in a flux which is otherwise unmeasurable at high temporal resolution.

3 Results

3.1 Hillslope–riparian hydrological connectivity

Water table was significantly higher in the riparian zone compared to the hillslope, but with similar temporal variability (Fig. 2). Mean (\pm SD) hillslope water table during the hydrological year was -63 ± 16 cm compared with -37 ± 10 cm in the riparian zone (Table 1). Volumetric soil moisture content was also higher in the riparian zone (mean of 0.73 and 0.46 $\text{m}^3 \text{m}^{-3}$ at 30 and 60 cm depths respectively) compared to the hillslope (0.30 and 0.45 $\text{m}^3 \text{m}^{-3}$ at 30 and 60 cm depths respectively).

Annual mean (\pm SD) soil temperature was 4.1 ± 3.0 and 3.9 ± 3.0 °C in the hillslope and riparian zone respectively with a strong seasonal trend (Fig. 2). Soil temperature (measured at 70 cm depth) did not fall below freezing, with minimum temperatures in the hillslope (0.8 °C) and riparian (0.7 °C) (Table 1) reached at the beginning of May (Fig. 2).

Water table was above the 60 cm CO₂ measurement depth for 32 and 97 % of the time and above the 30 cm depth 7 and 59 % of the time, in the hillslope and riparian zone respectively. These values describe the relative proportion of the measurement period over which the CO₂ sensors were submerged.

3.2 Hillslope–riparian CO₂ concentrations

CO₂ concentrations were on average higher in the riparian zone than the corresponding depth in the hillslope (Table 1). Highest mean (\pm SD) CO₂ concentrations were at 60–70 cm in the riparian zone ($23\,100 \pm 4\,100$ ppmv) with lowest at 30–40 cm in the hillslope ($4\,410 \pm 2\,570$ ppmv). At both depths the hillslope and riparian zone CO₂ concentrations were significantly different (Table 1).

There was considerable temporal variability in CO₂ concentration in the hillslope, which displayed a baseline and peak pattern (Fig. 2). Baseline concentrations were generally $< 2\,000$ ppmv. In the winter period (January–March), median concentrations at 60–70 cm depth (1600 ppmv) were 24 % less than those at 30–40 cm depth (2110 ppmv). During drier periods in summer (July–September), the baseline was higher with median concentrations at 60–70 cm (1770 ppmv), 61 % less than those at 30–40 cm depth (4530 ppmv). The range was also higher in summer (7640 and 6470 ppmv at 30–40 and 60–70 cm depths) than in winter (680 and 870 ppmv).

Periodically, sharp increases in hillslope CO₂ concentrations were observed, corresponding to a rise in water table position (Fig. 2). CO₂ concentrations in the hillslope had a positive correlation with hillslope water table at 30–40 cm ($r^2 = 0.43$; $P < 0.001$) and 60–70 cm ($r^2 = 0.65$; $P < 0.001$) depths. Over the measurement period the two spikes with the highest CO₂ concentrations (14 100 and 13 160 ppmv) occurred

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when the water table was above the level of the deeper (60–70 cm depth) sensor at –41 and –51 cm, respectively.

CO₂ concentrations in the riparian zone did not display the same baseline and peak pattern as the hillslope. At 60–70 cm depth, CO₂ concentrations peaked at 31 920 ppmv in October before falling to 16 140 ppmv in April (Fig. 2). This change in concentration closely followed soil temperature which decreased over a similar period from 9.2 °C to the annual minimum of 0.7 °C on 26 April 2013 (Fig. 2), coinciding with minimum CO₂ concentrations. CO₂ concentrations had a weak positive correlation with riparian water table at 30–40 cm ($r^2 = 0.12$; $P < 0.001$) and a weak negative correlation at 60–70 cm ($r^2 = -0.21$; $P < 0.001$) depth. At 30–40 cm depth in the riparian zone there was considerably more temporal variability in CO₂ concentrations than at 60–70 cm depth with concentrations at 30–40 cm depth rising during periods of higher water table. Minimum concentrations (4430 ppmv) occurred in April before the spring snow melt event.

3.3 Hillslope–riparian water and CO₂ export

Annual water export from each m² of hillslope over the hydrological year was estimated at 230 mm yr⁻¹. Across the year, water export was consistently low with flow largely restricted to below ~ 50 cm depth. Total monthly export was highest in May (109 mm month⁻¹) accounting for 47 % of the annual hillslope water export, due to greater flow at 25–35 cm depth (37 mm month⁻¹). Hillslope CO₂ export over the hydrological year was 1144 mg CO₂-C m⁻² yr⁻¹ and followed a similar pattern to water export. CO₂ export was considerably higher in May (482 mg CO₂-C m⁻² month⁻¹), accounting for 42 % of the annual CO₂ export, largely due to considerable export (93 mg CO₂-C m⁻² month⁻¹) from 45–50 cm depth (Fig. 3).

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3.4 Riparian–stream water and CO₂ export

Annual water export from the riparian zone to the stream channel over the hydrological year was estimated at 270 mm yr⁻¹. Below 65 cm depth, although water export was relatively low (< 3 mm month⁻¹) it occurred for > 97% of the measurement period.

Water export was highest in a zone between 25 and 50 cm depth. At shallower depths (0–25 cm) flow was restricted to the wettest months. Total monthly export was highest in May (49 mm month⁻¹) due to dominant flow at 25–50 cm depth with maximum monthly flow (9 mm month⁻¹) at 35–40 cm depth.

Total annual CO₂ export from the riparian zone to the stream channel over the hydrological year was estimated at 3008 mg CO₂-C m⁻² yr⁻¹. Two monthly peaks in riparian CO₂ export to the stream occurred over the hydrological year, in December (529 mg CO₂-C m⁻² month⁻¹) and May (522 mg CO₂-C m⁻² month⁻¹). CO₂ export was highest in a narrow zone between 25 and 50 cm depth (Fig. 3). In December, water flow (5 mm month⁻¹) and CO₂ export (77 mg CO₂-C m⁻² month⁻¹) were highest from 35–40 cm depth. In May, maximum flow of both water and CO₂ was from the same depth (35–40 cm) at 9 mm month⁻¹ and 96 mg CO₂-C m⁻² month⁻¹.

3.5 Downstream CO₂ export and evasion

Total catchment runoff over the hydrological year was 265 mm yr⁻¹ (Fig. 4). Total downstream lateral CO₂ export from the catchment was estimated at 1183 mg CO₂-C m⁻² yr⁻¹. There was considerable temporal variability in the downstream lateral export of CO₂ from the catchment, related to temporal variability in discharge (Fig. 4). Median downstream lateral export was 1.2 mg CO₂-C m⁻² day⁻¹ with two large spikes (57 and 35 mg CO₂-C m⁻² day⁻¹) corresponding to sudden increases in discharge after storm events. Over the same period the input of CO₂ from the soil to the stream was 3008 mg CO₂-C m⁻² yr⁻¹. Based on the assumption that all stream water CO₂ is derived from soil input then by subtraction 1825 mg CO₂-C m⁻² yr⁻¹ is lost between the

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suggesting that the vertical exchange of CO₂ is greater than the lateral export during these periods (Dyson et al., 2011).

Temporal variability in riparian zone CO₂ concentrations was more pronounced at 30–40 cm depth which can largely be attributed to water table fluctuations (the sensor was below the water table for 59% of the measurement period). The 60–70 cm sampling depth was below the water table for 97% of the measurement period with water table variability alone unlikely to explain the observed pattern in riparian CO₂ concentrations. CO₂ concentration was linked to soil temperature, which had a strong seasonal cycle (Fig. 2) suggesting root respiration and/or organic matter decomposition, driven by changes in soil temperature, provides an additional control on CO₂ concentrations. During periods of generally high water tables in the riparian zone, such as during the spring snow melt event in May, concentrations increased (Fig. 2) again highlighting the importance of water table fluctuations on CO₂ concentrations in soils.

Overall, the large temporal variability in porewater CO₂ concentration, especially in the hillslope, can largely be attributed to water table fluctuations altering the rate of CO₂ mobilisation and vertical diffusion of CO₂ stored in soil pore space. This confirms the results of others who measured higher CO₂ concentrations during periods of water table fluctuation (Jassal et al., 2005; Rasilo et al., 2012). The importance of the water table for CO₂ concentration dynamics suggests that pore water CO₂ concentration differences between the hillslope and the riparian zone are strongly influenced by the altered diffusion gradient and surface exchange of CO₂ with the atmosphere; the riparian zone had continually higher water tables than the hillslope (Fig. 2). However, despite the importance of water table fluctuations, most of the existing studies involving continuous use of CO₂ sensors have been focused predominately above the water table, potentially missing this observation (Jassal et al., 2004, 2005; Tang et al., 2003). This highlights the importance of considering CO₂ concentration changes over the full soil profile depth, especially in horizons which experience frequent fluctuations between wet and dry conditions. In this study, CO₂ concentrations were

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only determined at two sampling depths (30–40 and 60–70 cm). In the riparian zone the shallower measurement depth was below the water table 59 % of the time giving a range of measurements under saturated and unsaturated conditions. The deeper measurement point was below the water table 97 % of the time giving concentrations under saturated conditions. These two sampling depths therefore gave a good overall representation of soil conditions, and their respective CO₂ concentrations.

4.2 Hillslope–riparian–stream water and CO₂ export

The total export of water per m² of hillslope was 230 mm yr⁻¹ and from the riparian zone 270 mm yr⁻¹. Both estimates correspond well (proportional to the relative upslope contributing area) to the annual catchment runoff of 265 mm yr⁻¹. The lateral movement of water along the hillslope–riparian–stream continuum is dependent on a number of assumptions, principally that lateral subsurface flow is the dominant hydrological pathway and that these flowpaths are perpendicular to the stream. These assumptions have been validated for the study catchment by the observed planar nature of the water table (Cory et al., 2007) and through stable isotope studies (Laudon et al., 2004; Peralta-Tapia et al., 2014). Alternative flowpaths, such as overland flow and groundwater recharge are not important at this site (Grabs et al., 2012). Downslope lateral water flow occurs in saturated soils, with minimal lateral flow occurring above the water table, in accordance with the transmissivity feedback conceptualisation of subsurface flows in shallow till catchments (Bishop et al., 2011; Rodhe, 1989).

Transmissivity feedback, which has been widely observed in this catchment, indicates that lateral saturated hydraulic conductivity increases toward the soil surface, resulting in more lateral flow as water table rises into near surface soil horizons (Bishop et al., 1990, 2004; Laudon et al., 2004). The drier hillslope podzol soils had a greater potential to store water without increasing water table (Seibert et al., 2003), limiting the time in which high water table conditions occurred; mean water position in the hillslope was –63 cm. Water table only moved into higher lateral hydraulic conductivity horizons during the spring snow melt event in May when 42 % of annual hillslope CO₂ export

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occurred, emphasising the importance of the spring snow melt event in this system. The results from this study show that maximum water export occurs where water table position and soil hydrological properties (lateral hydraulic conductivity and soil water content) combine to produce the set of conditions most conducive to water flow, in agreement with the transmissivity feedback principal.

The concept of a riparian chemosphere has been conceptualised by and shown to exist in the catchment studied here (Bishop et al., 2004; Seibert et al., 2009), with the chemistry of water flowing laterally through the catchment determined by soil interactions. The final soil encountered by subsurface waters (in this study the riparian peat soils) will determine the composition of water transported across the terrestrial–aquatic interface (Bishop et al., 2004). Over the hydrological year, total CO₂ export per m² of hillslope was 1144 mg CO₂-C m⁻² yr⁻¹ with export from the riparian zone estimated at 3008 mg CO₂-C m⁻² yr⁻¹. The organic rich peat soils of the riparian zone therefore represent a significantly greater CO₂ export source than the podzol hillslope soils, despite accounting for < 10 % of the catchment area. This can be related to the higher measured CO₂ concentrations (Fig. 2). The importance of riparian–stream CO₂ export is in agreement with the results for other catchments (Peter et al., 2014; Rasilo et al., 2012) and for TOC in this catchment (Grabs et al., 2012).

Few studies have estimated carbon export across the terrestrial aquatic interface, especially for CO₂. The total annual export of CO₂ in this study (3.0 g CO₂-C m⁻² yr⁻¹) was similar, given the large inter-annual variability, to the estimate for DIC (3.2 g DIC m⁻² yr⁻¹) produced from spot measurements (Öquist et al., 2009) and the 2.3–6.9 g DIC m⁻² yr⁻¹ estimated over a longer period (1997–2009) in the same catchment (Öquist et al., 2014). As expected, CO₂ export was lower than in peat dominated catchments in Sweden (3.1–6.0 g CO₂-C m⁻² yr⁻¹) (Nilsson et al., 2008) and Scotland (11.2–15.5 g CO₂-C m⁻² yr⁻¹) (Dinsmore et al., 2010, 2013b).

The results of this study suggest that the riparian zone, and not the wider hillslope, is the dominant source of CO₂ entering the stream but the contribution of the riparian zone to water and CO₂ transport has been shown to be episodic, resulting in hotspots

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and hotmoments when export is greatest (McClain et al., 2003; Vidon et al., 2010). CO₂ export was highest in a narrow band between 30 and 50 cm depth, which accounted for 71 % of CO₂ export. The results from this study suggest that the riparian zone contains two distinct sources of CO₂ export; high export rates at 30–50 cm depth as water table moves into more superficial horizons and a deeper (> 65 cm depth) continuous but smaller export (Fig. 3). The presence of these two water sources in this catchment has also been shown isotopically (Peralta-Tapia et al., 2014) and indicated by the observed bimodal frequency distributions in stream water CO₂ concentrations during storm events (Dinsmore et al., 2013a). Therefore, the riparian export rates of water and CO₂ measured here can be used to explain the observed changes in stream water CO₂ concentrations. The catchment chosen for this study is relatively simple in terms of the catchment characteristics and water flowpaths. Water is transported laterally through the soil at < 1 m depth with groundwater and overland flow not significant. However, this may not be the case in other catchments with more complex hydrology.

Peaks in water and CO₂ export occurred in late autumn (October–December) and May. The export of water from the riparian zone was highest during May at 49 mm month⁻¹ when the spring snow melt event occurred, accounting for 18 % of the annual water export from the riparian zone. In May, at the onset of spring snow melt, CO₂ concentrations were close to minimum values of 3840 and 14 400 ppmv at 30–40 and 60–70 cm depths in the riparian zone, resulting in relatively low CO₂ export despite large water export at this time. In October–December, despite only moderate water export, CO₂ export was high (275–529 mg CO₂-C m⁻² month⁻¹) (Fig. 3). During these months, CO₂ concentrations in the riparian soil were at or close to their maximum values (Fig. 2), coinciding with maximum soil water DOC concentrations in late summer/autumn observed in the catchment (Lyon et al., 2011). The importance of export from certain horizons in the soil profile found in this study suggests that hotspots occur both spatially throughout the soil profile and temporally.

The lateral export of riparian dissolved CO₂ is therefore the main source of stream water CO₂, with the amount of CO₂ exported related to the depth of water flow through

the riparian zone. The riparian export of CO₂ can therefore be used as an estimate of the catchment CO₂ export to partition the export of CO₂ via the aquatic conduit.

4.3 Downstream CO₂ export and evasion

Total downstream lateral CO₂ export, calculated from the CO₂ concentration and discharge at the catchment outlet, over the hydrological year was 1.2 g CO₂-C m⁻² yr⁻¹. This is within the range 0.9–1.3 g CO₂-C m⁻² yr⁻¹ of estimates for the same catchment (Öquist et al., 2009) and a peatland catchment in southern Scotland (Dinsmore et al., 2010, 2013b). Due to the greater range in discharge (0.02–15.3 L s⁻¹) than dissolved CO₂ concentrations (daily mean CO₂ concentration ranged from 1.8–7.2 mg CO₂-C L⁻¹); discharge had a greater influence on temporal variability in downstream lateral CO₂ export (Fig. 4).

By subtracting downstream lateral CO₂ export (1183 mg CO₂-C m⁻² yr⁻¹) from the estimate of soil export over the same period (3008 mg CO₂-C m⁻² yr⁻¹), an estimated 1825 mg CO₂-C m⁻² yr⁻¹ was released to the stream but not accounted for by downstream lateral export. Photosynthetic uptake by aquatic plants or in stream respiration is unlikely to be important in this catchment due to the short water residence times (typically ~ 4.5 h) and the low temperatures (Öquist et al., 2009). Hence the remaining CO₂ is likely to be evaded from the stream surface. Our evasion estimate from the stream surface (1825 mg CO₂-C m⁻² yr⁻¹) was at the lower end of evasion rates determined from direct point measurements in the same catchment (Wallin et al., 2011). However, evasion accounted for 60 % of export via the aquatic pathway supporting previous findings of the rapid CO₂ loss from the stream (Öquist et al., 2009).

Estimating evasion rate based on this approach is dependent on two assumptions: (1) all stream water CO₂ is derived from lateral soil inputs from the riparian zone and (2) a short water transport time between the riparian zone and the stream to allow rapid exchange of water and CO₂ during events. In headwater systems, in-stream productivity (through biological respiration and photo-degradation of DOC) is limited

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by the cold temperatures, low pH and short water residence times (Dawson et al., 2001a). Additionally, CO₂ evasion from headwater streams has been widely shown to be composed predominately of recently fixed, plant derived CO₂ transported from the surrounding soil (Billett et al., 2012; Leith et al., 2014). The transport time for water between the riparian zone and the stream varied with depth from < 1 h at < 15 cm depth up to ~ 25 h at > 70 cm depth. The lateral exchange of water and CO₂ between the riparian zone and the stream was rapid enough for the approach to be valid at the daily scale that was used in the model. Additionally, the total volume of water exported from the riparian zone (270 mm yr⁻¹) corresponded well with the annual runoff from the catchment (265 mm yr⁻¹) suggesting that no other inputs of water are contributing. Riparian CO₂ export to the stream is therefore sustaining the lateral downstream export and vertical evasion of CO₂.

There was considerable temporal variability in the evasion estimate (Fig. 4) related to variability in CO₂ dynamics in both the terrestrial (Fig. 2) and aquatic systems (Fig. 4). During the two largest storm events, in which discharge increased suddenly over a very short time period (< 1 day), downstream lateral export spiked but without a corresponding increase in soil export. Evasion was therefore not estimated during these periods. This also occurred during the onset of the spring flood. This suggests that during storms there may be a rapid input of overland flow or direct channel water input contributing to discharge without interacting with the soil. The model used to estimate soil CO₂ export did not include overland flow so may be underestimating the total flow of water and CO₂ into the stream during storm events. Overland flow has been shown to be a relatively minor flowpath within the Väststrabäcken catchment (Grabs et al., 2012; Peralta-Tapia et al., 2014). However, during the spring flood, up to 20 % of stream runoff was found to be derived from snow melt transported via overland flow (Laudon et al., 2004). Thus during the spring snow melt period, water and CO₂ stored within the snowpack may be an additional export source, bypassing the soil profile. In two Finnish catchments, CO₂ concentrations in the snow pack of 500–1900 ppmv were recorded (Dyson et al., 2011) with snow melt estimated to contribute 35–46 % of

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downstream lateral CO₂ export during the spring snow melt period (Dinsmore et al., 2011). Over the course of the spring snow melt event in the same Finnish catchments the isotopic signature of evaded CO₂ showed a decreasing contribution from recently fixed, plant derived CO₂ from near surface soil horizons with a corresponding increase in the atmospheric CO₂ component, likely derived from the melting snow pack (Billett et al., 2012). In some headwater catchments, the effects of melt water and overland flow would need to be accounted for in annual estimates of riparian CO₂ export.

Although the annual estimate of riparian export and evasion in the study compare well to estimates from discrete measurements (Öquist et al., 2009), the results of this study highlight the importance of high frequency, direct measurements of CO₂ concentrations given the high temporal variability in CO₂ dynamics in the terrestrial and aquatic systems. Terrestrial processes, especially riparian water table dynamics, have an important role in determining CO₂ export via the aquatic pathway. Carbon export via the aquatic pathway positively has been shown to be positively correlated with precipitation (Öquist et al., 2014). Changes in climate, especially greater variability in precipitation patterns (IPCC, 2007), have the potential to alter riparian water table dynamics and the export of CO₂ to streams impacting on the NECB of boreal headwater catchments.

5 Conclusions

CO₂ concentrations were significantly higher in the riparian zone than hillslope soils principally due to (1) greater production of CO₂ in riparian peats compared to the hillslope pozols and (2) higher water table positions limiting the vertical CO₂ diffusion and exchange with the atmosphere. The riparian zone was therefore the main source of stream water CO₂ with a hotspot for export observed at 30–50 cm depth (accounting for 71 % of total riparian export). Seasonal variability was high with peaks in export during the spring flood and autumn storm events highlighting the importance of high frequency measurements in this very dynamic system.

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Downstream CO₂ export (determined from stream water dissolved CO₂ concentrations and discharge) was 1.2 g CO₂-C m⁻² yr⁻¹. Subtracting downstream lateral export from riparian input (3.0 g CO₂-C m⁻² yr⁻¹) gives 1.8 g CO₂-C m⁻² yr⁻¹ which can be attributed to evasion losses (accounting for 60 % of export via the aquatic pathway). The results highlight the importance of terrestrial CO₂ export, especially from the riparian zone, for determining catchment aquatic CO₂ losses and especially for maintaining the high evasion fluxes from boreal headwater streams.

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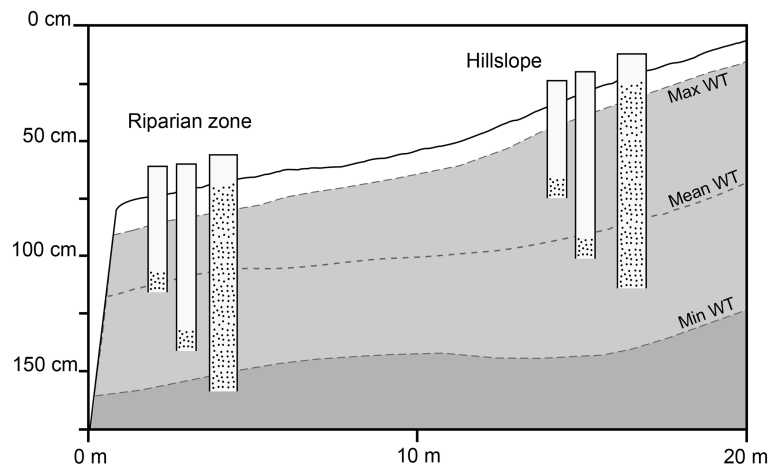


Figure 1. Schematic of the hillslope–riparian transect used in this study. CO₂ sensors were installed in dipwells with sampling windows at 30–40 and 60–70 cm depth. An additional dipwell for water table and soil temperature was perforated along the full length to 90 cm depth. Grey box indicates the zone of transient saturation (between max and min water table positions) over the hydrological year.

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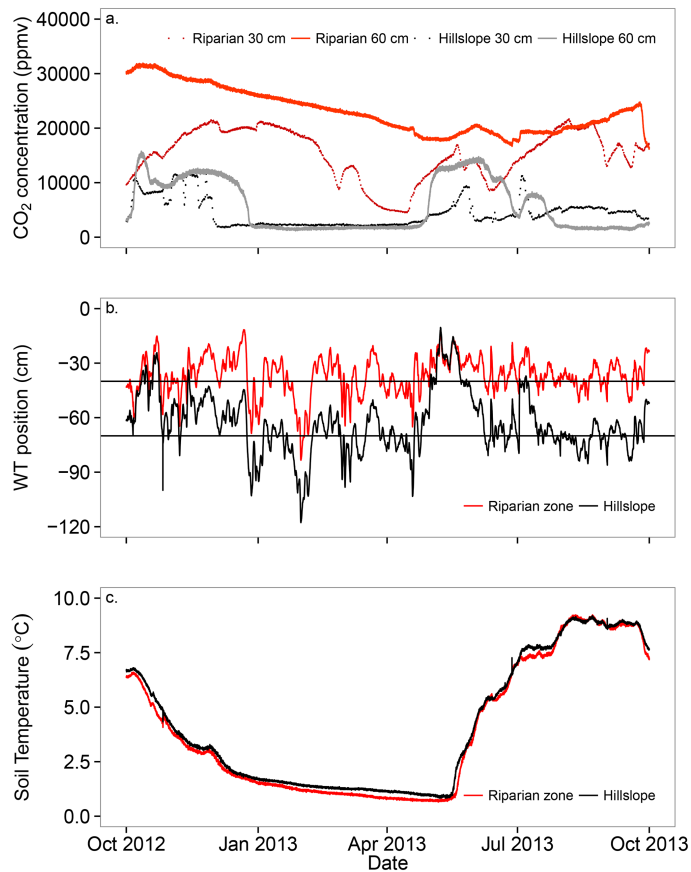


Figure 2. Time series of hillslope and riparian zone **(a)** CO₂ concentrations sampled at 30–40 and 60–70 cm depths, **(b)** water table and **(c)** soil temperature across the full measurement period. Horizontal lines in **(b)** highlight the deepest depths sampled by the 30–40 and 60–70 cm depth CO₂ sensors.

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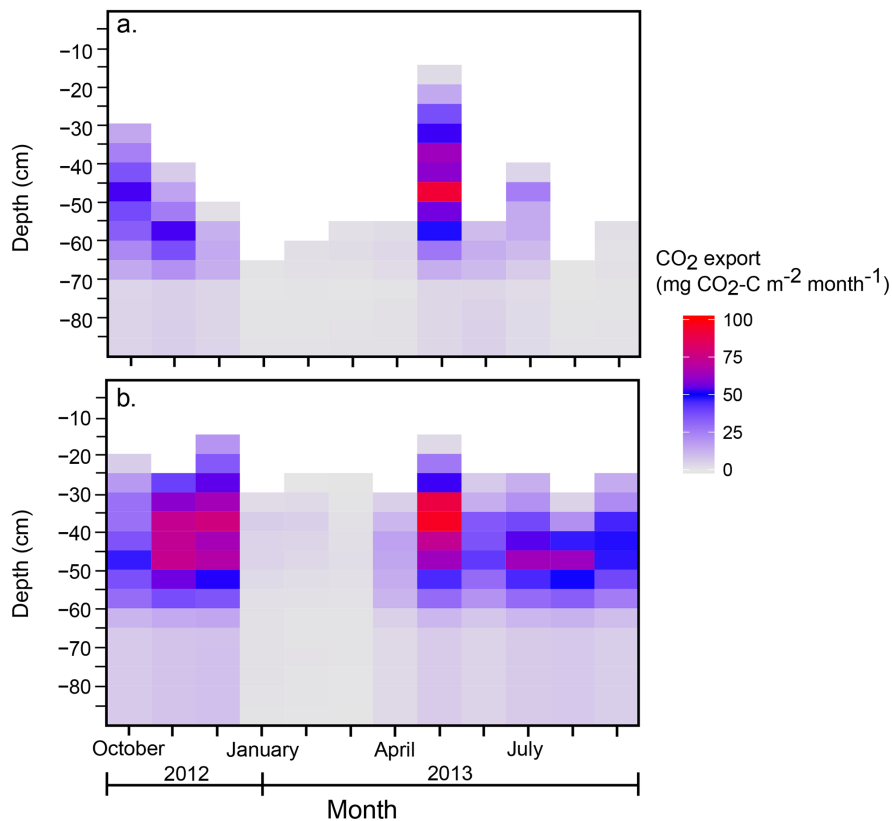


Figure 3. Total monthly export of CO₂ from the (a) hillslope and (b) riparian zone across the measurement period

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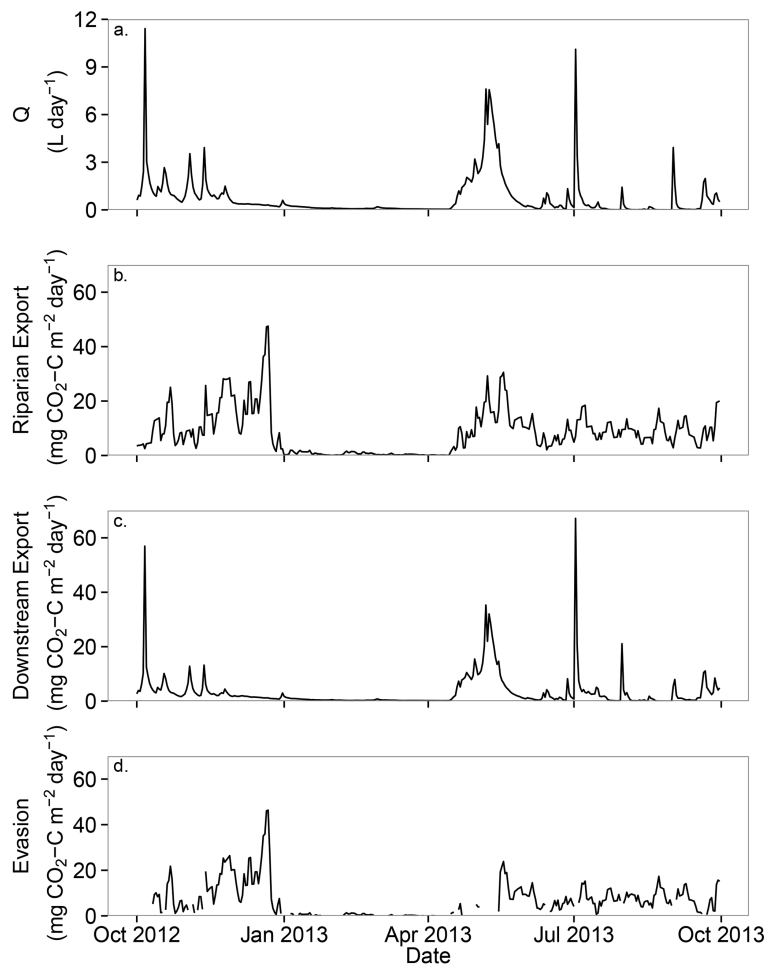


Figure 4. Mean daily (a) discharge (Q), (b) CO_2 export from the riparian zone to the stream, (c) downstream lateral CO_2 export and (d) vertical CO_2 evasion over the hydrological year.

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