bg-2014-486: "Carbon dioxide transport across the hillslope-riparian-stream continuum in a boreal headwater catchment"

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Response to Referees

We thank the Associate Editor, and the two Referees for their constructive reviews of the manuscript. We welcome the many positive comments made by the Referees and we are fully able to address all points raised in the reviews and submit a revised manuscript. Both Referees made similar comments: 1. the literature review and discussion largely focus on Sweden and other northern European examples which should be expanded to include other relevant boreal catchments, particularly those in north America and 2. more details should be included regarding the modelling approach used in this study. These two points are addressed first followed by specific points raised by each Referee. Referees' comments are given in italics with page and line numbers referring to the published discussion paper.

1. Expansion of literature review

We agree with the Referees that the manuscript largely focuses on the Krycklan catchment, with many of the comparisons made with similar catchments in Sweden and northern Europe. In order to provide a wider range of examples the literature cited has been changed in a number of places and three additional references have been added (full references are included at the end of this document).

15588 Line 27: the cited literature considering spatial and temporal variability are site specific studies conducted only in Scotland and as indicated by the Referees do not cover the breadth of research on CO_2 evasion. The literature cited here has been changed to better cover spatial variability using Wallin et al. (2014) which examined the spatial variability in CO_2 evasion from 200 headwaters across southern Sweden. The discussion on temporal variability now includes a study which made high temporal CO_2 measurements in Alaska (Crawford et al., 2013) in addition to Dinsmore et al. (2013b) which used high temporal resolution data sets from Canada, Sweden, Finland and the UK. The manuscript has been changed to "Due to the limited numbers of direct measurements of the gas transfer coefficient (KCO_2) (Raymond et al., 2013; Wallin et al., 2011) and the considerable spatial (Wallin et al., 2014) and temporal (Crawford et al., 2013; Dinsmore et al., 2013a) variability in dissolved CO_2 concentrations observed across a wide range of northern latitude catchments, evasion, and the drivers of this flux are likely to be poorly quantified."

15606 Lines 13-18: This section has been significantly modified to include a wider range of studies to investigate the importance of terrestrial inputs to CO_2 processing in streams. This includes examples from tropical (Abril et al., 2014), temperate (Butman and Raymond., 2011) and north American boreal catchments (Crawford et al., 2013). The section now reads: "Terrestrial processes have been shown to have an important role in determining CO_2 export via the aquatic pathway in a wide range of catchments (Abril et al., 2014; Butman and Raymond, 2011; Crawford et al., 2013). The results from this catchment indicate that terrestrial-aquatic export of CO_2 was controlled by riparian water table dynamics, highlighting the potential importance of riparian zones in headwater catchments."

2. Clarification of modelling approach and methods

We thank the Referees for drawing our attention to the need to clarify the methods for modelling water export. Referee #1 suggested adding a figure describing the modelling. During the production of the original manuscript a number of options for a figure were discussed but these were not felt to help in explaining the modelling approach. Instead, Section 2.3 Data processing and analysis, especially from Page 15594 Line 26, has been modified and is included below. Specific points raised by Referee #2 are covered in more detail below. We hope this clarifies the methods.

"The model was constructed by subdividing the 90 cm deep soil profile into 5 cm horizons. The daily lateral water export from each 5 cm soil layer was estimated by combining the measured volumetric water content with lateral saturated hydraulic conductivity estimated by Stähli et al. (2001). Total daily water export from the full soil profile was estimated by adding together the lateral flow from all 5 cm horizons below the daily mean water table. As CO_2 concentration was only measured at two depths (30-40 cm and 60-70 cm) these were assumed to represent the concentration above and below 45 cm depth. Daily average CO_2 concentrations below the water table, in mg CO_2-C L^{-1}, were multiplied by the water export, with CO_2 export expressed in units of mg CO_2-C m^{-2} day^{-1}. The model was run twice to estimate the export from 1. podzol hillslope soils and 2. riparian organic soils. Hillslope export was taken to represent the input of water and CO_2 into the riparian zone with riparian export representing the total terrestrial water and CO_2 export to the stream."

Additional points

Referee #1

"The hypothesis of riparian control on gas export is also evaluated for other catchments and could help frame these results. My question is how often and where would we expect riparian CO_2 controls in streams? Does this extend to the temperate zone or the tropics where soil CO_2 has been used to infer aquatic evasion?"

We comment on 15603 Lines 11-14 that the approach used in this study is suitable due to the nature of the hydrological flowpaths through the catchment, with numerous studies showing that all water exported from the catchment passes through the upper 1 m depth of the riparian zone. The validity of this approach was commented on by Referee #2. The finding of this study that the riparian zone has an important role in controlling CO_2 evasion is therefore dependent on the catchment characteristics (particularly the nature of the hydrological flowpaths and the distribution of organic rich soils within the catchment). 15603 Lines 11-14 have been altered to more clearly explain this. In summary, in areas where there are mineral soils upslope and organic soils close to the stream, the riparian zone will be a major source of CO_2. While the findings from this study could be extrapolated to other catchments, in a range of geographical areas, we feel that due to the wide variety of definitions of riparian zones and the catchment specific nature of the processes then it would be inappropriate to make an overarching statement on how all riparian zones may contribute to CO_2 export in headwaters. This aim of this study was to use a very well defined catchment to show the potential extent of riparian control, so that future studies are aware of the importance of this area and can include it in experimental or modelling exercises in a range of catchments. The final paragraph of the Section 4.3, which discusses the wider implications of the work, has been significantly modified to give a greater range of literature examples (including tropical, temperate and boreal catchments) and to further

highlight the importance of riparian zone processes in headwater catchments (15606 Lines 13-18). The new text is included in the response to 15606 Lines 13-18 above.

Referee #2

"A 4m riparian zone on each side is relatively large for many headwater systems, and it is conceivable that hill slope soil CO_2 will contribute consistently more as the riparian area decreases. This cannot be tested here, but discussed."

We agree that the lateral extent of the riparian zone in this catchment contributes to its importance for soil CO_2 export, as shown in this study and for studies to consider TOC also in this catchment (Grabs et al., 2012). The study catchment was chosen due to the consistency of the riparian extent down the stream reach allowing us to upscale from our single transect. At 15603 Lines 11-14 the discussion of the validity of using the riparian export to understand stream water CO_2 dynamics has been changed to include the potential impact of variability in the lateral extent of the riparian zone. The section now reads:

"This approach can be used as the catchment chosen for this study is relatively simple in terms of the water flowpaths (with water transported laterally through the soil at $<$1 m depth with groundwater and overland flow not significant) and the consistency of the riparian lateral extent down the stream reach. In catchments with more complex hydrology or where the riparian lateral extent is variable, riparian CO_2 export alone may not account for all variability in stream water CO_2 dynamics and additional sources would need to be considered."

"The notion that you can have a large spring pulse from snowmelt moving high volumes of water through relatively low CO_2 environments, contrasts with the episodic nature of infrequent storm events moving overall smaller volumes of water through very high CO_2 environments. This should be highlighted more, with a discussion regarding how the community should better constrain annual estimates of carbon evasion and lateral export across scales. A few sentences to this effect could broaden the work beyond the Krycklan system."

We agree that it is an interesting finding that periods of high riparian CO_2 export can occur during periods of both low and high soil CO_2 concentrations. The importance of the spring snow melt period to annual fluxes of a range of solutes has been widely shown in boreal catchments (Dyson et al., 2010; Laudon et al., 2004). Additionally, in catchments which do not experience large snow melt events, much of the research focus has been on episodic storm events. The importance of capturing hydrological extremes across seasons is now discussed in more detail at 15603 Lines 25-27 in the line "This observed pattern of peaks in CO_2 export suggests that riparian export is a function of both season and runoff. This highlights the importance of capturing hydrological extremes when quantifying annual estimates of downstream export and evasion of CO_2 across catchments and scales."

"More detail within the description on page 15595 would help resolve some confusion as to how the water was modeled, and how hill slope and riparian portions are separated. Presumably the hill slope is added to the riparian water profiles?"

The export of water and CO_2 was calculated per 1 m^{-3} area of hillslope and riparian soils with hillslope export taken to represent the input of water and CO_2 into the riparian zone and riparian export representing the total terrestrial water and CO_2 export to the stream. This distinction has been added to the manuscript at 15595 Lines 6-8.

"...some description regarding how periods when sensors were not submerged were handled within the modeling would be helpful"

The model only calculated lateral CO_2 export below the daily mean water table as only these soil horizons are connected hydrologically. CO_2 concentrations, especially at 30-40 cm depth, from when the sensor was not submerged were not included in the model. This is now made clearer at 15595 Line 5. There were periods, especially in the hillslope when the water table was below the 90 cm depth profile used in the model. During these times it was assumed that there was no lateral flow through the soil profile. As can be seen in Figure 3a, during drier months (in the summer and under snow conditions in winter) there was no flow through the upper 50 cm of the soil profile. Concentrations above the water table are only included in the time series of CO_2 concentrations given in Figure 2a.

15605 - Lines 15-20 - Finally, it is mentioned that the export of soil CO_2 and hence the evasion proportion of the total aquatic carbon flux, was not estimated during storm events however the findings from this work suggest that these could be hotmoments for carbon removal (15605 lines 15-20). I would like to see the authors comment briefly on this.

Evasion was not estimated during the largest storm events, which we assume relates to a lag in water residence times. These storms are very short lived, with the storm peak occurring in a time period of less than 24 hours. As the model calculated the daily riparian export there is a potential time lag between the discharge peak and the peak in riparian export during the largest, but short lived storm events. The results from this study show that periods of high flow, both during storm events and the spring snow melt event, are hotmoments for CO_2 export. This highlights the importance of high frequency measurements, as commented on in the manuscript, but also the study of hydrological extremes in accurately determining annual CO_2 export which is now commented on at 15603 Lines 25-27 with the line "This observed pattern of peaks in CO_2 export suggests that riparian export is a function of both season and runoff. This highlights the importance of capturing hydrological extremes when quantifying annual estimates of downstream export and evasion of CO_2 across catchments and scales."

15588-23, check this value of 205,000 Tg-C yr^{-1}. That would be HUGE!!

Agreed. The value should be 0.205 Tg C yr^{-1} and has been corrected in the manuscript. The incorrect units were taken from the original reference (Humborg et al., 2010).

15588-15589 why would these fluxes be underestimated? They could be completely overestimated!

Agreed. This line has been changed to say that the values could be both under and over represented due to the variability in gas transfer coefficient.

15593 - can you explain / cite what a dipwell is?

Dipwells allow the separation of soil water from the surrounding soil material with this explanation now included at 15593 Lines 9-11. The soil water collected in the dipwell corresponds to the water table depth within the soil profile and also allows sampling of the water for dissolved CO_2 concentration and in a separate dipwell, the water table depth and soil water temperature. The construction of the dipwell is given on 15593 Line 12 and a graphical representation given in Figure 1.

15595 - differences in soil moisture content at 60cm depths are really not significantly different SD on some of these numbers would be appreciated.

Agreed. The SD of the soil moisture values are now included.

15601 - please explain in more detail what transmissivity feedback is.

Transmissivity feedback is defined as the increase in lateral saturated hydraulic conductivity towards the ground surface, resulting in more lateral flow as water table rises into near surface soil horizons. The introduction of the concept on 15601 Line 21 has been changed from 'indicate' to 'defined' to now define the concept, with reference made to the original works to define this term at 15601 Line 20.

15606 - The conclusion points 1&2 are actually not things measured by the work presented. It is understood that these are inferred by changes in concentration and water level. No exchange with the atmosphere was actually quantified. Arrange the conclusion to better match the paper.

Agreed. The first sentence of the conclusion (15606 Lines 20-23) has been modified to highlight the section that was inferred from the results (the numbered points) from what was directly measured and now reads: "CO_2 concentrations were significantly higher in the riparian zone than hillslope soils, which we infer was due to 1. greater production of CO_2 in riparian peats compared to the hillslope pozols and 2. higher water table positions limiting the vertical CO_2 diffusion and exchange with the atmosphere."

Additional references

Abril, G., Martinez, J.-M., Artigas, L. F., Moreira-Turcq, P., Benedetti, M. F., Vidal, L., Meziane, T., Kim, J.-H., Bernardes, M. C., Savoye, N., Deborde, J., Lima Souza, E., Albéric, P., Landim de Souza, M. F., and Roland, F.: Amazon River carbon dioxide outgassing fuelled by wetlands, Nature, 505, 395398, doi:10.1038/nature12797, 2014.

Crawford, J. T., Striegl, 5 R. G., Wickland, K. P., Dornblaser, M. M., and Stanley, E. H.: Emissions of carbon dioxide and methane from a headwater stream network of interior Alaska, J Geophys Res-Biogeo, 118, 482494, doi:10.1002/jgrg.20034, 2013.

Wallin, M. B., Löfgren, S., Erlandsson, M., and Bishop, K.: Representative regional sampling of carbon dioxide and methane concentrations in hemiboreal headwater streams reveal underestimates in less systematic approaches, Global Biogeochem Cy, 28, 465479, doi:10.1002/2013GB004715, 2014.