Dear Editor,

Thank you for your efforts and those of the Reviewers in evaluating and handling our manuscript bg-2019-486, “Carbon dioxide dynamics in an agricultural headwater stream driven by hydrology and primary production.”. We have changed the manuscript in response to the reviewer’s comments, and a detailed breakdown of our responses and revisions to the manuscript follows. In the revised manuscript we feel that we have dealt fully with the points raised and as a result the manuscript has been significantly improved.

Best regards / Marcus Wallin (corresponding author)

Reviewer (R#1) comments and author responses to ms bg-2019-486

Reviewer comments are given in normal style and with author responses in *italic*

Headwater streams are known hotspots for CO2 emissions, although studies of headwater streams draining agricultural catchments, and specially studies that includes a temporal dimension, are sparse. In this study, a headwater stream draining an agricultural catchment was continuously monitored during for approximately one year, and the responses in CO2 concentrations to hydrological variations were studied.

General comments

This study provides important insights of CO2 and discharge dynamics in a headwater stream draining a catchment impacted by agriculture. We need more studies like this in order to better understand the exchange of greenhouse gases between inland waters and the atmosphere. Overall, I think the manuscript is very good. The study is well designed and presented in a well-structured way. I have only a few, although important, remarks that I think would improve the manuscript.

Response: We thank reviewer #1 for their overall positive evaluation of our manuscript and appreciate that it is found “very good” and “well designed and presented in a well-structured way”. We believe that the revised manuscript has been significantly improved following the comments given by reviewer #1.

Firstly, this paper would benefit from the authors emphasizing the relevance of their study better. For instance, this study points out potential effects of stream intermittency for streams draining agricultural catchments. This finding is highly important with respect to climate change. Despite this, the authors do no mention this neither in the abstract nor in the conclusions of the paper.

Response: We agree that this is an important finding that we do not well enough lift up as one of the main messages. We do not have enough years of measurements for saying how common the intermittency of this specific stream is. The spring and summer of 2018 was unusually dry, but this kind of conditions are expected to occur more frequently in the future. We have in the revised version included this finding in the abstract (ln 22-25) and also more explicitly in the conclusions of the study (ln339-343).

Secondly, the manuscript would benefit from a more extensive discussion, for example how this stream compares to other agricultural influenced streams, if the type or insensitivity of the agriculture matters, land use change etc.

Response: We have in the revised version tried to improve the discussion on the spatial representativeness of our findings. However, this is not easy as there are not many relevant studies existing, while the current study contributes to fill this knowledge gap. We have further included references concerning DOC-discharge responses in agricultural areas. Ln285-291

Lastly, the readability of the manuscript could be greatly improved by simple sentence adjustments, such as shortening sentences and inserting more commas. Also, the figures could be designed in a more intuitive way.

Response: We have in the revised version tried to improve the readability of the text where appropriate, and we agree that some of the figures needed a quality lift up, although no suggestions on how were given by the reviewer. We have improved the quality of the figures (mostly improved font sizes) and believe that they are now clear and informative for the reader.

Specific comments

Abstract

L15: It is unclear what "one year of open-water season" means. It would be helpful to add the dates and/or number of monitored days.

Response: We agree that this was a bit unclear, in the revised version we have removed "open-water season" and also added "(in total 339 days excluding periods of ice and snow cover)" at the end of the sentence. Ln16

L22: I recommend the authors to add a sentence about the effects of indeterminacy of streams draining agricultural catchments here, since this is an important finding of the paper.

Response: We agree that this was missing. In the revised version we have added two sentences on this topic in the abstract. Ln22-25

Introduction

L41-42: This sentence is unclear. What do you mean with positive and negative responses? Please clarify.

Response: We mean that variations in stream CO2 concentration have been found to be both positively and negatively related to variations in stream discharge, i.e. either that CO2 concentrations increase when discharge does, or that CO2 concentrations decrease when discharge increase (dilution). This is now clarified in ln47-48

L44: "...dominant CO2 source areas of catchment soils"? Please rephrase this sentence.

Response: This is now clarified. Ln50-51

L45: Please specify what kind of other catchments.

Response: There is no consensus (partly due to few existing studies) in which catchments CO2 are mainly controlled by hydrology or biology so it is hard to specify them more than catchments where the hydrological influence is low or non-existing. Hence, we keep the original formulation.

L48: New paragraph needed.

Response: Now added

L50: Please specify what "relevant" time-scales are.

Response: "(<hourly resolution)" is now added in ln58.

L69: Please specify what you mean with high-resolution. Also, as mentioned before, it is unclear what "one year of open-water season" actually means.

Response: Both "(hourly)" and "(in total 339 days excluding periods of ice and snow cover)" are now added to this sentence. Ln77-78.

Methods

L76: Please rephrase this sentence. Is it unclear if you mean the annual mean temperature or the January and July temperatures. This is especially important since you do not mention the precipitation in January or July - perhaps this could be added.

Response: This is now clarified in ln85-86.

L82: Stream pH ranging between 7.4 and 8.4. Also, this sentence would be much more readable if you would add a comma. In general, I would recommend using commas more frequently.

Response: This is now clarified in ln93.

L83-84: How much lower? Please provide a reference percentage.

Response: It is hard to give exact percentages as the variables included in "nutrients" are many. We have instead added, as a general approximation, that the studied stream is within the 25th percentile of the monitored agricultural streams in Sweden when it comes to DOC and nutrient levels. Ln94

L86-87: This sentence could be moved to the beginning of the paragraph.

Response: We agree and in the revised version have moved it to the start of the paragraph in ln84-85.

L90: influences

Response: Correct, now changed in ln100.

L91: Table S1; Figure S2

Response: Correct, now changed in ln101.

L93: Would it be possible to add here the percentage that were snow/ice-free (and included in your study) as well as the percentage when the stream was falling dry?

Response: We have again added the total number of measurement days in ln103-104. Concerning the number of days of the dry periods, this is more of a result and is already given in the text.

L100: This is quite confusing for the reader, especially since you have not mentioned before that the stream is falling dry during some periods of the year. In general, I would recommend you to highlight the stream intermittency better, including adding some sentences in the introduction about this.

Response: Again, the dry periods are here seen as result rather than description the methods. Still we needed to explain that analysis of the CO2 data was only made when runoff was generated. It would therefore not be logical to introduce the stream intermittency already in the introduction as this was not included in the aims of the study. However, as it became evident during the study that stream intermittency occurred and also was highly influential for the CO2 dynamics of the studied stream, this is something that needs to be discussed in a more extended way. See response to the first general comment.

L108-109: Please clarify. What is the temporal resolution of your data?

Response: As for many sensor-based systems averaging high-frequency data reduces the noise of the measurements and makes them more reliable. The given averaging time needs to account for relevant time-scales for the processes you want to study but also consider practical limitations as power consumption, data storage etc. In this case we measured at a 1 min interval and stored average values based on these 1 min measurements every 30 min (in 2017) or 60 min (in 2018). This is now clarified in ln118-119.

L112-114: Please rephrase. Also, how many replicates?

Response: We have clarified that one sample was taken at each sampling occasion in ln122-123.

L117: Please clarify. When was the phosphoric acid added?

Response: The phosphoric acid was pre-injected in the vial before the sample was injected. This is already stated and so no change has been made.

L121: Did you run any standards?

Response: Yes, certified standards were analysed. This is needed as the DIC-values are given in relation to the PDB standard. This is clarified in ln132.

L129: Add reference to Figure S2 here.

Response: Correct, that is now added in ln 141.

L140: It would probably be easier to follow if you move this paragraph to the beginning of the methods section.

Response: It is not clear how that this would clarify the text and make the methods more logical to follow. We prefer to keep this section where it is.

L145: Another example of a sentence where the overall readability could be greatly improved if more commas are added.

Response: We agree, and a comma has been added-

Results

L155: This sentence is confusing. Precipitation is usually in mm/year however the period is for a bit more than a year. I assume that the "total precipitation" represent the precipitation for the whole period. Thus, it would be easier to read if the sentence would first state the mean air temperature (XXX) and then the total precipitation (XXX).

Response: We write that "The mean air temperature and total precipitation for the entire period (Sep 26, 2017-Dec 12, 2018)". We believe this is already clear and have not made any changes.

L205: It would be good to also add the corresponding pCO2 here for reference.

Response: We have chosen to present the CO2 data as a concentration in the unit of mg C/L as this normalizes for solubility and makes it directly comparable with for example DOC/TOC concentrations if total aquatic C export would be of interest. We give corresponding pCO2 values in ln ?? as an example for how they compare. But we don't think it is reasonable to give pCO2 values to all given CO2 concentrations in the manuscript while no addition has been made.

L212: Same as above, the corresponding pCO2 values would be helpful as reference values.

Response: Same as above

Discussion

L231: "highly dynamic pattern in streamwater CO2 concentration".

Response: Yes, we have added "concentration" for clarity in ln245.

L250: Please add references.

Response: Two suitable references for this statement are added in ln264.

L256: could

Response: We agree, is now changed in ln272.

L258-260: Please rephrase.

Response: We have removed one piece of this sentence that might have been unclear. Ln274

L266-270: Great paragraph. Would it be possible to develop more on this?

Response: We have extended this paragraph to further develop the discussion about similarities/dissimilarities in carbon dynamics observed for agricultural streams. Ln285-291.

L271-272: Please rephrase.

Response: The sentence is now rephrased in order to clarify in ln 294-295.

L309-311: Another great paragraph. This could also be further developed and better highlighted.

Response: We thank the reviewer for this positive comment. We have in the revised version developed this section further in ln333-334, and also highlighted this finding in the abstract (ln 22-25) and the conclusions (ln339-343).

Tables

Table 1: Throughout the manuscript, you write either "land-use" or "land use". In the table it is obviously a spelling mistake; however, please be consistent with the terminology throughout the whole manuscript.

Response: Thank you for noting, we have now used a consistent spelling "land use" throughout the ms.

Table 2: Would be good to add the name of the catchment and not only the abbreviation.

Response: The name is now fully spelled out.

Figures

Figures: I recommend the authors to redo all figures. They are not intuitively designed or appealing for the reader.

Response: Although the comment is very un-specific concerning what to improve, we agree that some of the figures needed polishing, especially concerning font sizes etc. We have updated many of the figures in order to make them easier to read.

Figure 7: Add regression line?

Response: Here we have used Spearman's Rank (which assumes a monotonic, non-linear, relationship), not regression, so fitting a line would not be appropriate. The given statistics in the figure refer to the Spearman rank test.

Figure 10: In the text it is written that d13C-DIC was NOT a function of Q?

Response: Yes, we write "Although there was a tendency towards more negative δ^{13}C-DIC values at higher discharge, no significant relationship was found (Figure 10)". Although not significant from a statistical point of view, we still think it is useful information provided by the figure. One can imagine that the relationship might have been significant if the number of observations would have been more.

Reviewer (R#2) comments and author responses to ms bg-2019-486

Reviewer comments are given in normal style and with author responses in *italic*

Inland waters and specifically headwaters emit significant amounts of CO2 to the atmosphere; however, studies focusing in agricultural streams and including continuously measured in-situ CO2 from are rather rare. In this MS, the authors continuously monitored CO2 with cost-effective Co2 sensors during one year and explored the spatio-temporal variations of CO2 throughout the year as a function of hydrology and metabolism.

General comments

The MS bg-2019-486 provides an interesting study about CO2 dynamics in one stream draining a catchment largely dominated by agriculture. An important finding is that stream intermittency can cause rapid pulses of CO2 even in catchment with no pronounced dry and wet seasons. I think this is an important matter to better understand carbon emissions from streams at the global scale, in the context of climate change (change in hydrology). In line with this result, it could be useful to add somewhere in the discussion the spatial representativeness at the global scale of the stream studied here. In addition, it could be nice to add discussion/comparison of this agricultural stream with other agricultural streams worldwide, because the hydrology should be very different. To increase there adability, I suggest to better define some terms used in this study, particularly, open-water season, and the different periods, and also define better the time-intervals of these seasons throughout the text. Indeed, to my opinion, those terms are specific to boreal systems, and sometimes it is difficult to follow for a reader who is novice with boreal landscapes. A second important finding is the strong biologic control (aquatic primary production) of the CO2 dynamics during baseflow that should decrease CO2 emissions during this period. Indeed, during base flow it is common to observed higher CO2 concentration in streams because deeper levels of groundwater are involved. Perhaps the authors could further developed this. Overall, I found the dataset very interesting; it is rare to have such continuous measurements for CO2 in streams. In addition, I found the paper well written. Perhaps the quality of some figures could be improved. Overall, I support publication of this manuscript and below are some more detailed comments.

Response: We thank reviewer #2 for their overall positive evaluation of our manuscript and are happy that publication in Biogeosciences is recommended after a revision. We believe that we in the revised manuscript have better discussed the spatial representativeness of our findings and also elaborated more on the primary production part. We further improved the quality of the figures (also in line with comments from R#1).

Specific comments

Abstract

L. 15-16: It would be nice for the reader adding the size of the catchment, the date of open-water season, and the time-step of CO2 measurements.

Response: We agree and have in the revised version of the abstract added catchment size and total number of days of measurements. We have further replaced "continuous" with "hourly" to clarify the temporal resolution of the measurements.

Introduction

L.31-33: The authors can check this reference that suit with their study (Deirmendjian et al, 2019. Importance of the vegetation-groundwater-stream continuum to understand transformation of biogenic carbon in aquatic systems – a case study based on a pine maize comparison in a lowland sandy watershed), where the concentration of CO2 in agricultural and forested streams (and in groundwater) in a temperate catchment was compared. They found no differences between both streams because degassing in agricultural streams was prevented.

Response: We agree that this reference is very suitable and have added two sentences using information from it in ln40-44.

L. 43-45: Please clarify this sentence. You mean that different level of soils are exported in function of the change in hydrology?

Response: Yes, we mean that dependent on hydrological conditions different source areas in the catchment soils are hydrologically connected and contribute differently to the stream CO2. The variability in source areas are both vertically and laterally distributed in the soils and are hence activated differently dependent on groundwater position and dominating pathways. This pattern is further dependent on the catchment characteristics and land use. We have in the revised version tried to clarify the lateral and vertical consideration of source areas in ln49-51.

L-40-55: To my opinion, there is a lightly lack of spatial references in this paragraph. Indeed, I guess that agricultural streams in tropical or boreal areas are very different in terms of hydrology and carbon dynamics. Could you mention spatial references?

Response: We agree that the spatial coverage among the given references might look limited. We base this section solely on studies that have used high-frequency CO2 sensor data. This is now clarified in ln46. Also, the two references originally given (Dinsmore et al. 2013 and Crawford et al. 2017) both include data from multiple sites including boreal, temperate, alpine and subtropical areas. They further represent a large variety of forest, wetland and mountainous coverage. Hence, we believe that we already have a relatively good spatial coverage, but to further support the tropical side we have added the very suitable Johnson et al. 2007 paper and adjusted the text according to this in ln46-49..

L. 69: High-resolution: what is the time-step of measurements?

Response: We have in the revised version added "(hourly)" after "high-resolution"(ln77). Although we used 30 min resolution in 2017 and 60 min resolution in 2018 (in order to save power) "hourly" is likely the best option here. Further details on the different temporal resolutions are given in the method section.

Methods

L.78: What kind of cropland it is? This is important for the d13C-DIC

Response: The land is mainly used for cereal production and pasture. This clarification is now added in ln88.

L. 83: Lower end: how much lower?

Response: It is hard to give exact percentages as the variables including in "nutrients" are so many. We have instead added, as a general approximation, that the studied stream is within the 25th percentile of the monitored agricultural streams in Sweden when it comes to DOC and nutrient levels. Ln93-95.

L. 85: Growing season: what is the time interval?

Response: The length of the growing season is on average ca 210 days starting in mid-April and ending in early November. This information is now included in ln86-87.

L. 97: what was the concentration of gas standards?

Response: Four standards were used (400, 1000 and 5000 ppm as well as 2%). This is now added in ln107.

L.100: discharge rates lower than 0 L/s: so you mean when the stream was dry or when the stream was frozen? Or both? It is a bit confusing.

Response: This mean that CO2 data was just analyzed if runoff was generated over the V-notch dam i.e. excluding standing water or completely dry conditions. The instrument was never measuring during ice or snow conditions. This is now clarified in 103-104.

L.101: Figure S1

Response: Yes, this figure reference is now given in ln111.

L109: You wrote one measurements each minute but then a temporal resolution of 30. It is a bit confusing what is the meaning of temporal resolution here?

Response: As for many sensor-based systems averaging high-frequency data reduce the noise of the measurements and make them more reliable. The given averaging time needs to account for relevant time-scales for the processes you want to study but also consider practical limitations as power consumption, data storage etc. In this case we measured at a 1 min interval and stored average values based on these 1 min measurements every 30 min (in 2017) or 60 min (in 2018). This is now clarified in ln118-119.

L.120: What is the volume of the injections?

Response: The volume of the injections was 100 µL i.e. 7 × 100 µL per sample. This info is now added in ln130.

L.129: Please specify that these streams were not located in your catchment and add the reference to the figure S2

Response: This is now clarified in ln141.

L. 145: Please define better your four periods. What are the time intervals?

Response: We have now added number of days per period in ln158-162. We have also added a new table (Table S2) to the supplementary information that gives the full period description.

Results

L.157: Please refer to figure 3

Response: Figure 3 is now referred to in ln172.

L.168-172: Please add corresponding pCO2 for reference, as you did

Response: We have chosen to present the CO2 data as a concentration in the unit of mg C/L as this normalize for solubility and makes it directly comparable with for example DOC/TOC concentrations if total aquatic C export would be of interest. We give corresponding pCO2 values as an example for how they compare. But we don't think it is reasonable to give pCO2 values to all given CO2 concentrations in the manuscript while no addition has been made.

L.166. To my opinion, I suggest to do that for the remainder of the text because pCO2 in ppmv is more "understandable" that CO2 in mg/L.

Response: See comment above. We think this is also very much a matter of personal taste and as stated above we see clear advantages of presenting the CO2 data as concentrations rather than a volume fraction i.e. ppmv.

Discussion:

L.225: I would not rush on conclusion about zero/limited tree cover along agricultural streams, at the global scale. I am agree considering your figure S2 that this is the case in your catchment. However, in temperate climate it is very common to observe riparian forest along agricultural streams.

Response: We agree that the statement was maybe too strong and have revised it in ln239. We still believe that canopy cover is important and that agricultural streams to a larger extent than for example forest streams are exposed to direct sun-light, even at the global scale.

Figures

Figure 1: In the left part, I suggest to add a map of Europe rather than just Sweden. Please add a scale in the left part too.

Response: We have updated the figure for the revised version.

Figure 2: I suggest to separate the different periods (autumn, snowmelt, spring, dry period) with dotted lines, as you did in the next figure.

Response: Good idea, this is now added

Figure 4: It is not very intuitive what the time interval is for A, B, C and D.

Response: The figure is now updated with appropriate font sizes

Figure 5: Same remark

Response: The figure is now updated with appropriate font sizes

Figure 7: Perhaps add regression line with slope

Response: Here we have used Spearman's Rank (which assumes a monotonic, non-linear, relationship), not regression, so fitting a line would not be appropriate.

Carbon dioxide dynamics in an agricultural headwater stream driven by hydrology and primary production

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Abstract. Headwater streams are known to be hotspots for carbon dioxide (CO_2) emissions to the atmosphere and are hence important components in landscape carbon balances. However, surprisingly little is known about stream CO_2 dynamics and emissions in agricultural settings, a ~~land-use~~land use type that globally cover ca 40% of the continental area. Here we present ~~continuously~~ hourly measured in-situ stream CO_2 concentration data from a 11.3 km^2 temperate agricultural headwater ~~stream~~ catchment covering more than one year ~~of open-water season~~ (in total 339 days excluding periods of ice and snow cover). The stream CO_2 concentrations during the entire study period were generally high (median 3.44 mg C L^{-1}, corresponding to partial pressures ($p$$CO_2$) of 4778 µatm) but were also highly variable (IQR = 3.26 mg C L^{-1}). The CO_2 concentration dynamics covered a variety of different time-scales from seasonal to hourly, and with an interplay of hydrological and biological controls. The hydrological control was strong (although with both positive as well as negative influences dependent on season) and CO_2 concentrations changed rapidly in response to rainfall and snowmelt events. However, during growing-season baseflow and receding flow conditions, aquatic primary production seemed to control the stream CO_2 dynamics resulting in elevated diel patterns. During the dry summer period, rapid rewetting following precipitation events generated high CO_2 pulses exceeding the overall median level of stream CO_2 (up to 3 times higher) observed during the whole study period. This finding highlights the importance of stream intermittency and its effect on stream CO_2 dynamics. Given the observed high levels of CO_2 and its temporally variable nature, agricultural streams clearly need more attention in order to understand and incorporate these considerable dynamics in large scale extrapolations.

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1. Introduction

Fluvial systems (streams and rivers) are estimated to dominate the inland water CO_2 source globally, surpassing CO_2 emissions by lakes and reservoirs by a factor of six (Raymond et al. 2013). However, this estimate relies on a number of assumptions and the scarcity of empirical data makes it uncertain. One of the critical gaps in the global upscaling is the lack of direct measurements from agriculture dominated areas (Osborne et al. 2010). Globally, agricultural land covers about 40% of the total continental area (Ramankutty et al., 2008) but there are few studies specifically focusing on the magnitude and dynamics of CO_2 emissions from agricultural streams. The few studies that do exist have shown ~~conclud~~e that agricultural stream CO_2 concentrations ~~in such streams~~ are generally high and up to ~~five~~ 5 times greater than those in streams draining forested areas which are more extensively studied (Borges et al. 2018; Bodmer et al. 2016; Wallin et al. 2018). For example, Bodmer et al. (2016) measured partial pressure of CO_2 (pCO_2) in German and Polish streams and examined differences between forested and agricultural catchments. They found that pCO_2 was generally 2-3 ~~higher~~ times higher in agricultural streams compared to streams draining forested areas. Similarly, Borges et al. (2018) found high CO_2 concentrations in streams and rivers dominated by agriculture in the river system Meuse, Belgium. They linked the higher pCO_2 in agricultural streams ~~(up to 5 times higher than in forested areas)~~ to elevated levels of dissolved organic carbon (DOC), particulate organic carbon (POC) and inorganic nitrogen. On the other hand, Deirmendjian et al. (2019) showed that there was no difference in pCO_2 between forest and cropland streams in south-west France despite higher pCO_2 in forest groundwater compared to cropland groundwater. They explained the similar stream pCO_2 by ~~less~~more efficient gas exchange in the forest streams compared to the low-gradient cropland streams.

There are numerous factors influencing CO_2 patterns in stream systems and ~~often~~ site-specific controls often dominate. Hence, large scale generalizations are difficult to make (Crawford et al. 2017). Based on high-frequency data, ~~Although the hydrology of agricultural streams will differ across climate zones (and this in turn will have an effect on C dynamics), climate itself has not directly been observed to act as a control on fluvial CO2 concentrations (Raymond et al. 2013).~~ CO_2 concentrations in streams draining nutrient-poor forest and peatlands, as well as tropical forests, ~~streams are~~ are often found~~often~~ related to variations in stream discharge but with site-specific response patterns, with CO_2 found either positively or negatively related

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to stream discharge ~~both positive and negative~~ (Crawford et al. 2017; Dinsmore et al. 2013; Johnson et al. 2007). ~~).~~ These response patterns have often been connected to the catchment characteristics and changes in hydrological pathways, which in turn control the dominant ~~CO_2~~ source areas (both from a vertical and lateral point of view) of CO_2 in the catchment soils (Campeau et al. 2018; Leith et al. 2015; Dinsmore and Billett 2008). In contrast, other catchments lack a strong hydrological control and instead display clear diel cycles in ~~the~~ stream CO_2 concentration indicating a metabolic control (Crawford et al. 2017). Here the interplay of photosynthesis and respiration (in-stream or terrestrial) could result in large day to night time differences in stream CO_2.

These recent findings concerning dynamics and controls on stream CO_2 concentrations have been possible due to the development of cost-effective CO_2 sensors (e.g. Johnson et al. 2010; Bastviken et al. 2015) which have enabled continuous data collection covering relevant time-scales (<hourly resolution). However, very little information about stream CO_2 dynamics exists from agricultural areas, a ~~land-use~~land use type that is heavily managed by humans from multiple aspects including hydrological drainage, nutrient additions, soil cultivation etc. As a consequence, CO_2 patterns in agricultural streams could potentially be very different than in other ~~land-use~~land use types with amplified diel CO_2 dynamics due to high metabolism and/or quicker response to hydrological events due to effective drainage systems.

In addition to the concentration gradient between the stream water and the above air, gas exchange is also highly dependent on the physical conditions at the air-water interface. For stream systems, the gas transfer velocity (often the variable given to describe the efficiency of the air-water gas exchange) is related to a combination of hydrological and morphological conditions of the stream channel, often including slope, velocity and water depth (Raymond et al. 2012; Wallin et al. 2011). All these variables are proxies for describing the ~~water~~ turbulence of the stream water, which controls the gas exchange but that is rarely directly measured (Kokic et al. 2018). Agricultural areas are often located in flat landscapes resulting in drainage systems that are low-gradient and slow-flowing (Rhoads et al. 2003; Hughes et al. 2010), conditions that prevent effective air-water gas exchange (Hall & Ulseth, 2019). However, whether the elevated pCO_2 observed in agricultural streams is an effect of ~~land-~~

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useland use specific hydro-morphological stream conditions preventing efficient gas exchange or an effect of high internal (aquatic) or external (terrestrial) CO_2 production is currently unknown.

Although recent studies have shown the potential importance ofidentified agricultural streams as high pCO_2 systems, there are still large knowledge gaps to be filled in order to improve our understanding concerning the influence of these waterbodies in landscape C cycling. Here we present high-resolution (hourly) CO_2 concentration measurements in a Swedish agricultural headwater stream during more than a year of open water season (in total 339 days excluding periods of ice and snow cover). The study aimed to 1) quantify CO_2 concentration levels in an agricultural stream and explore its temporal dynamics, 2) identify the main drivers causing temporal variability in stream CO_2 concentration and how they might vary with season.

2. Methods

2.1. Study area

The study was conducted within the 11.3 km^2 Sundbromark (SBM) catchment (59°55′N, 17°32′E), located 5 km NW of the city of Uppsala, Sweden (Figure 1B). The catchment is a part of the hydro-meteorological observatory Marsta that was established in the late 1940s (Halldin et al. 1999). The 30 year (1960-1991) mean annual temperature for the area is 5.3°C (mean January and July temperatures are -4.5 and 16.0°C, respectively) and with a mean annual precipitation of 535 mm The 30 year (1960-1991) mean annual, January and July temperatures for the area are 5.3°C, -4.5 and 16.0 and with a mean annual precipitation of 535 mm (SMHI). The length of the growing season is on average ca 210 days from early April to the end of October (SMHI). The catchment is dominated by agricultural land (86%) mainly used for cereal production and pasture, and with minor influence of forest (8%) and urban areas (6%). The area is flat with only 28 m elevation difference from 41 m.a.s.l. at the highest point to 13 m.a.s.l. at the catchment outlet (Table 1). The bedrock consists of gneissic granites and the soils are dominated by post glacial clay at lower elevations and with some influence of glacial clay and silt at higher elevations. Although the bedrock does not contain any known carbonates, the soils are alkaline due to glacial carbonate containing deposits resulting in a stream pH ranging between 7.4- and 8.4 (Table 2), and with high electrical conductivity (EC, ranging 791-1908 µS cm^{-1}) (Osterman 2018). The nutrient and DOC levels of the stream water (Table 1) are at the lower end (within the 25th percentile) of monitored agricultural catchments in Sweden (Linefur et al. 2018; Kyllmar et al. 2014). The oxygen conditions

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To explore how representative the SBM catchment is for streams draining agricultural areas in the region, a snapshot sampling survey was performed across 10 streams (denoted region UPP 2 in the study by Audet et al. (2019)) of various sizes (catchment area 8.5-740 km^2) and agricultural influences (30-86%) distributed within a radius of 10 km from the city center of Uppsala (Table S1Figure 1A, Table S1).

2.2. Field sampling and analysis

The measurements were conducted during the open-water season from September 26, 2017 to December 12, 2018 (in total 339 days of measurements excluding periods of ice, and snow cover and drought). Stream CO_2 concentration was monitored using an EosGP sensor (Eosense, Dartmouth, Canada). The sensor was covered by copper tape in order to avoid biofouling. Sensor accuracy is <1% of the calibrated range (0-2% CO_2) + 1% of the reading corresponding to a maximum error of ca 0.3 mg C L^{-1} based on the maximum CO_2 measured in the current study. The CO_2 sensor was calibrated against known gas standards (400, 1000, 5000 and 20,000 ppm) before and after deployment. No significant drift (exceeding the above given uncertainty) in the instrument was observed during the period. Volume fraction outputs from the sensor were corrected for variations in temperature and pressure (atmospheric and water depth) using the method described in Johnson et al. (2010) and expressed in the unit of mg C L^{-1}. Only CO_2 data measured at discharge rates > 0 L s^{-1} (i.e excluding standing water or completely dry conditions) were used in the analysis of the stream CO_2 data (Figure S1)..

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Water level, water temperature and EC were measured together with CO_2 concentration at a V-notch weir (Figure S1). Water level was measured using a pressure transducer (1400, MJK Automation, Sweden) mounted in a stilling well representing the stream water level at the V-notch weir. Discharge was calculated from a stage-discharge rating curve based on a series of manual measurements and according to a rating curve presented in Holmqvist (1998). Water temperature and EC were monitored using a thermocouple (Type T) and a CS547A-L conductivity sensor (Campbell, UK), respectively. The sensors (except for the pressure transducer) were deployed under the water surface attached to a wooden rod in the center of the stream just upstream of the weir. All sensors were connected to a CR1000X data logger (Campbell, UK) measuring at a 1 min interval and storing average values at a temporal resolution of 30 (in 2017) or 60 (in 2018) minutes.~~which stored average data (measurements every 1 minute) at a temporal resolution of 30 (in 2017) or 60 (in 2018) minutes.~~

Stable isotopic analysis of the dissolved inorganic carbon (DIC) (δ^{13}C-DIC) was performed on six occasions during the falling limb of the snowmelt discharge peak in 2018 in order to explore the temporal variability in DIC source. At each sampling occasion a ~~S~~sample~~s~~ for analysis of δ^{13}C-DIC was~~ere~~ taken in a 60 ~~ml~~ mL glass vial completely filled with stream water and closed airtight with a rubber septum below the water surface. In order to preserve the sample, 1 ~~ml~~ mL of highly concentrated $ZnCl_2$ solution was injected in each sample (with subsequent release of 1 ml of sample in order to keep atmospheric pressure) directly after sample collection. Samples were kept cold and dark until analysis. Prior to analysis, 2 ~~ml~~ mL of sample was injected into 12 ~~ml~~ mL septum-sealed pre-combusted glass vials (Labco Limited) pre-filled with He~~N_2~~ gas, and pre-injected with 0.1 ~~ml~~ mL of concentrated phosphoric acid in order to convert all DIC species to CO_2(g) (Campeau et al. 2017a). The samples were analyzed using an isotope ratio mass spectrometer (DeltaV Plus,Thermo Fisher Scientific, Bremen, Germany) Gasbench II (Thermo Fisher Scientific, Bremen, Germany) measuring the CO_2 in the headspace. Each sample was analyzed seven times (sample volume; 100 µL per sample) and the first two injections for each sample were discarded to avoid memory effects, and the mean was taken of the other five to give the final result. The δ^{13}C-DIC values are given in terms of deviation from ~~the~~known carbonate standards ~~Pee-Dee Belemnite (PDB)~~ in per mille where R is the isotopic ratio of [^{13}C]/[^{12}C]:

$$\delta^{13}\text{C–DIC (‰)} = (R_{sample}/R_{standard} - 1) \times 1000$$

Precipitation, air temperature and incoming shortwave (global) radiation data (Figure 2) were obtained from the Marsta meteorological observatory located within the catchment ca 2.5 km from the stream sampling station (Halldin et al. 1999). In the absence of direct measurements of photosynthetically active radiation (PAR) shortwave incoming radiation was used as a proxy for available photosynthetic light.

A spatial sampling campaign for CO_2 concentration, pH, EC and water temperature was conducted on June 21, 2018 across ten agricultural streams (including the SBM stream) located in different catchments around the city of Uppsala (Figure 1A). The sampling was performed between 10.00 and 14.00 during the day. Samples for CO_2 analysis were collected using the headspace method (Hope et al., 2004; Kokic et al. 2015). Briefly, 30 mL bubble-free water were collected in 60 mL polypropylene syringes and equilibrated with a known volume of ambient air by shaking vigorously for 1 min. The equilibrated headspace (15-20 mL) was recovered and analysed on an Ultraportable Greenhouse Gas Analyzer (UGGA) (Los Gatos Research, USA) equipped with a soda lime filter and manual injection port. In situ CO_2 concentration was calculated from the UGGA-determined ppm values using Henry's law considering stream temperature (Weiss 1974), atmospheric pressure, the added ambient air, as well as the water-air volume ratio in the syringe. pH, EC and water temperature were measured in-situ in the streams with handheld instruments, for pH with a pH110 pH-meter (VWR, USA), and for EC and temperature with a HI 99300 (Hanna Instr., USA).

2.3. Delineation of the stream network and catchment characteristics

Catchment area and characteristics were calculated in QGIS 3.8 based on a high resolution (2×2 m) digital elevation model (DEM) derived from LIDAR data (GSD Elevation data, grid 2+, Swedish Land Survey). Land use distribution within the catchment was derived from the CORINE Land Cover 2018 product (European Environment Agency), and soil and bedrock characteristics were based on digital versions of the Quaternary deposits (1:25,000 – 1:100,000) and bedrock (1:50,000 – 1:250,000) maps (Swedish Geological Survey).

2.4. Data analysis

Out of the total data set (339 days) from the SBM catchment, only data measured at discharge rates > 0 L s^{-1} (i.e excluding standing water or completely dry conditions) were used in the analysis of the stream CO_2 data (Figure S1). For further evaluation of the control on stream CO_2 concentration, ~~The continuous~~the data set ~~data from~~ ~~the SBM catchment~~ was divided into four periods (Autumn (49 days), Snowmelt (17 days), Spring (91 days) and Dry period (138 days)) according to distinct phases in the hydrograph ~~in order to further analyze the control on stream CO_2 concentration~~ (Figure 3, Table S2). The stream CO_2 dynamics observed among the different periods were examined visually and any hydrological controls on the CO_2 were identified by the presence and direction of CO_2-discharge hysteresis loops (Evans and Davies, 1998). Similar hysteresis analysis was used to investigate diel patterns in the CO_2 concentration data. Spearman's rank correlation coefficient was used to test for monotonic relationships between the diel amplitude in stream CO_2 concentration and potential drivers. Correlations were considered significant if $p < 0.05$. The software JMP 14.2.0 (SAS Institute Inc., Cary, NC, USA) was used for all statistical calculations.

3. Results

The mean air temperature and total precipitation for the entire period (September 26, 2017-December 12, 2018) were 6.8 °C and 704 mm, respectively. The summer and autumn of 2018 were dry with generally low precipitation, the exception was on July 29 with 82 mm rain within 24 hours (Figure 2). Mean and median stream discharge for ~~the open-water~~study period were 30.6 and 0.9 L s^{-1}, respectively, and with a total range from 0 to 668 L s^{-1} (corresponding to a range from 0 to 5.0 mm day^{-1}) (Figure 3). However, due to high water table exceeding the range of the pressure transducer the absolute peak discharge occurring during April 5 to April 7 was missed in the measurements. The large skewness between mean and median discharge was an effect of the large number of days without waterflow over the weir during the summer and autumn 2018, 128 days (38%) out of the ~~open-water~~study period. According to frequency analysis, 67% of the days had a mean daily discharge <5 L s^{-1}. Despite the few days with discharge >100 L s^{-1} (7% of the entire period), those days accounted for 69% of the accumulated discharge. The majority (84%) of these high discharge days occurred during the snowmelt in April.

3.1. General CO_2 patterns

The stream CO_2 concentrations during the entire study period (median and mean 3.44 mg C L^{-1} and 3.94 mg C L^{-1}, respectively, corresponding to a pCO_2 of 4778 µatm and 5324 µatm) were highly variable (IQR = 3.26 mg C L^{-1}) (Figure 3) and displayed a bimodal distribution with frequency peaks at ~2.7 mg C L^{-1} and ~6.1 mg C L^{-1} (Figure ~~S3~~S2). The lower peak was associated with the snowmelt and spring period, whereas the higher peak was attributed to the autumn period 2017 and to rain events during the dry period of summer/autumn 2018. In addition to the bimodal shape a very distinct peak in frequently measured concentrations was observed at ~1.6 mg C L^{-1}. This peak was attributed to the minimum concentrations values for the diel cycles observed during the spring period.

3.2. Controls on stream CO_2 concentration

The autumn period started dry with low discharge (<3 L s^{-1}) for the initial month of measurements. The CO_2 concentrations were at the same time highly dynamic but unrelated to variations in discharge. The CO_2 concentration reached the maximum for the autumn (10.89 mg C L^{-1}, which was also the maximum for the entire study period) during late October followed by a decline in CO_2 to ca 2 mg C L^{-1} in early November. During November and December four main rain events were identified which all displayed an increasing stream CO_2 concentration with increasing discharge. In three of these events a positive clockwise hysteresis loop was observed (Figure 4) where the CO_2 concentration reached its maximum before the discharge did. At the last event during the autumn 2017, the relationship between CO_2 concentration and discharge was close to linear, but still positive. During the snowmelt period the hydrograph was characterized by a diel cycle with melting during day-time resulting in daily discharge peaks which were suppressed during night-time freezing. In contrast to the autumn events the daily discharge peaks were negatively related to the stream CO_2 concentration, and with an anti-clockwise hysteresis loop where the minimum CO_2 concentration was reached before the highest discharge of the event (Figure 5). After the snowmelt discharge peak the spring and early summer periods (late April to early July) were dry with limited precipitation and with a steady decline in runoff (Figure 3). During this period the CO_2 concentration displayed a pronounced diel cycle with daily maximum and minimum CO_2 concentrations reached during early mornings (06:00) and late afternoons (18:00), respectively (Figure 6). The medium amplitude of the diel CO_2 cycle for this period was 2.03 mg C L^{-1}, corresponding to pCO_2 = 2974 µatm (IQR = 1.23 mg C L^{-1}, corresponding to pCO_2 = 2212 µatm), and with the size of the diel CO_2 concentration amplitude being related to both the daily mean water temperature and the shortwave radiation (Figure 7). The diel pattern displayed a clear negative anti-clockwise CO_2-streamwater temperature hysteresis loop, where the median CO_2 concentration could differ up to 75% between day and night-time although being measured at the same stream water temperature (Figure 8).

From early July the stream dried out and hence no runoff over the V-notch weir was generated. During this period the CO_2 sensor was mostly recording an atmospheric signal. However, for five rain events during the summer and early autumn runoff was generated which allowed stream CO_2 determination for shorter periods (Figure 9). During these runoff events (< 2 days long) high CO_2 concentration pulses were recorded (up to 11 mg C L^{-1}). At all events CO_2 was recorded for a longer period than the discharge as the small dam above the v-notch weir was still water-filled for some time after runoff over the weir ceased. Also, common for all events was that the stream CO_2 concentration continued to increase although the discharge peak had passed. During July 29 a heavy rain storm occurred with 82 mm precipitation ~~during~~ in 24 hours. Although more than 15% of the long-term annual mean precipitation fell during one day, low discharge was generated (maximum discharge 6.1 L s^{-1}) due to high evapotranspiration and dry soils (Figures 3 and 9). However, the rainstorm event resulted in close to the highest stream CO_2 concentration (10.81 mg C L^{-1}) being observed during the studied period. As soon as the stream was more permanently refilled in early December and with discharge generated over the weir, the stream CO_2 concentration was back to similarly high levels (typically 5-8 mg C L^{-1}) as observed in the autumn of 2017.

3.3. Sources of DIC

The δ^{13}C-DIC data collected during the falling limb of the spring discharge peak (discharge range 130-9.6 L s^{-1}) were ranging from -13.8 to -12.2‰. This narrow range suggests a relatively constant source of inorganic C during the spring period. Although there was a tendency towards more negative δ^{13}C-DIC values at higher discharge, no significant relationship was found (Figure 10). δ^{13}C-DIC was also unrelated to the stream CO_2 concentration (data not shown).

3.4. Spatial representativeness

The ten streams manually sampled around Uppsala displayed a wide range in CO_2 concentrations (1.8-4.6 mg C L^{-1}) on the day of sampling (June-21 2018), and with the SBM stream (site 3 in T~~t~~able S1) being close to the overall median (SBM, 2.7 mg C L^{-1}; overall median, 3.0 mg C L^{-1}) (Table S1). Furthermore, the CO_2 concentration manually sampled at SBM was close to the sensor recorded CO_2 (2.59 mg C L^{-1}) at the hour of sampling. The SBM stream was also close to the spatial median DOC concentration but slightly elevated in NO_3 and PO_4. The CO_2 concentration was on a spatial scale related to pH but unrelated to catchment area or ~~land-use~~land use distribution within the catchment. Furthermore, the CO_2 concentration was on a spatial scale unrelated to ~~open-water~~ mean ~~values~~ stream concentrations of DOC, PO_4 and NO_3, although these variables were sampled during a different period than the CO_2.

4. Discussion

In order to produce large scale estimates of the exchange of GHGs between inland surface waters and the atmosphere, a basic requirement is to know the aqueous concentrations of the gases of interest and how they might vary over time. Headwater streams have been identified as "hotspots" for CO_2 emissions (Raymond et al. 2013; Wallin et al. 2018), but there is limited data capturing the temporal resolution, specifically from streams draining agricultural regions, making large scale generalizations uncertain. Due to effective drainage, high nutrient conditions and often high sun-light exposure (due to zero/limited tree cover), agricultural streams could potentially be very different in their CO_2 dynamics compared with streams draining other environments. Here we continuously measured stream CO_2 concentration in a headwater catchment dominated by agricultural land-useland use (86%) covering more than one year of the snow-free period. In line with findings from similar studies from other environments (arctic tundra, boreal forest, temperate peatlands, alpine) (e.g. Rocher-Ros et al. 2019; Riml et al. 2019; Crawford et al. 2017; Peter et al. 2014; Dinsmore et al. 2013) we found a mixture of controls on stream CO_2 operating at different time-scales generating a highly dynamic stream CO_2 concentration pattern. These time-scales covers seasonal patterns to diel cycles, or even shorter scales associated to with discharge events. Both the magnitude of CO_2 concentrations, and their associated temporal dynamics were found to be high in the current agricultural stream when compared with the literature. The mean CO_2 concentration (3.94 mg C L^{-1} corresponding to a pCO_2 of 5324 µatm) is at the high end when compared with other high-frequency CO_2 data sets covering low-order (<3rd stream order) catchments draining multiple environments, including arctic tundra, boreal forest, hemi-boreal forest, temperate forest, temperate peatlands and alpine areas (typically ranging from ca 0.2 to 6 mg C L^{-1}) (Crawford et al. 2017; Natchimuthu et al. 2017; Peter et al. 2014; Dinsmore et al. 2013). Still, CO_2 concentrations in SBM do not seem to be exceptionally high compared to snapshot-based data from other agricultural streams.

The spatial variability seen in this study, although only based on snapshot samples, and previous studies indicate that CO_2 concentrations in agricultural streams are comparably high (Borges et al. 2018; Bodmer et al., 2016; Sand-Jensen & Staehr, 2012). In addition, the observed temporal dynamics presented here are, to our knowledge, among the most pronounced in the literature, although the number of high-frequency stream CO_2 data sets are limited. For example, the rapid decrease in stream

CO_2 during the autumn of 2017, the strong diel cycle (diel amplitude up to almost ~~<~~5.0 mg C L^{-1}) during the spring/early summer period, or the rapid and high CO_2 pulses (up to ~~<~~11.0 mg C L^{-1}) occurring in accordance to rain events during the dry late summer/autumn period. These high CO_2 dynamics clearly illustrate the need for continuous high frequency CO_2 concentration measurements in streams in general, and in agricultural streams more specifically. Without such high-frequency data, representative estimates of agricultural stream CO_2 will be associated with high uncertainty. Although based on measurements from a single stream, these findings in turn indicate that current large-scale stream CO_2 emission estimates (e.g. Raymond et al. 2013; Humborg et al. 2010), which are largely based on snapshot concentration data with low (or no) resolution in time, might be specifically uncertain for agricultural regions.

According to our continuous data the highly dynamic pattern in stream CO_2 concentration is driven by a complex interplay of hydrology and biology. The high autumn concentrations observed both in 2017 and 2018 are likely an effect of high respiration of organic matter in the stream channel and/or in the adjacent soil water (Figure ~~3c~~3D). This is supported by efficient aquatic microbial DOC degradation (<800 µg C L^{-1} d^{-1}) observed during the autumn period across the ten streams (agricultural ~~land-use~~land use, 30-86%) included in the spatial sampling campaign (Peacock et al. unpublished ~~2019~~2020). This ~~sh~~could be compared with organic C degradation rates determined in boreal forest and mire streams displaying typically lower rates (<300 µg C L^{-1} d^{-1}, Berggren et al. 2009). The positive CO_2-discharge relationships indicated that event flow pathways~~, whether those are more surficial or different spatially,~~ were in contact with soils with higher concentrations of CO_2 compared to flow pathways during base flow (Evans & Davies, 1998; Seibert et al., 2009). Also, the clock-wise shape of the hysteresis loop suggests that there is a buildup of CO_2 in the catchment that is flushed out during rain events (Figure 4). The CO_2 pool seems to be limited as the CO_2 concentration drops before the maximum discharge peak occurs, or that vertical patterns in the CO_2 soil profile control the stream CO_2 dependent on dominating flow paths (Evans and Davies, 1998; Öquist et al. 2009). This could explain that the stream CO_2 increase did not reach any source limitation at rain events of lower magnitude (Figure ~~4d~~4D). Similar positive CO_2 concentration-discharge patterns have been observed across different low-order streams (e.g. Crawford et al. 2017; Dinsmore et al. 2013), but the absolute patterns are often concluded to be highly site-specific and even event-specific. Here we suggest, by exploring the hysteresis loops, that such positive relationships are influenced by the size of the available catchment CO_2 pool or the hydrological connectivity to it. In a highly drained low-elevation agricultural landscape where much of the stream runoff is generated through drainage pipes (Castellano et al. 2019), the extent and spatial distribution of these terrestrial source areas and connections between ground- and surface water are central for the CO_2 patterns observed in the stream. ~~Similar results~~Strong hydrological control has~~ve~~ been found for DOC in agricultural streams in USA and France, where high discharge events flush allochthonous DOC, via subsurface drainage pipes, into streams (Morel et al. 2009; Royer & David, 2005). In contrast to the seasonally variable CO_2-discharge response patterns observed in the current study, Morel et al. (2009) suggested that ~~. Furthermore, fluvial CO_2 concentrations have previously been found to positively correlate with DOC concentrations (Campeau & del Giorgio, 2014). We therefore suggest that, in agricultural catchments that also feature wetland soils, CO2 delivery into the~~ stream DOC is ~~would be~~ non-limited ~~(Morel et al. 2009),~~ and would continue to rise until the maximum discharge peak is reached. Whether this discrepancy in source limitation between CO_2 and DOC (although based on different studies and environments) indicate differences in the source areas of the different carbon components require further investigation.~~Whether this discrepancy in source limitation between CO_2 and DOC (although based on different studies and environments) indicate differences in the source areas require further investigation.~~

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In contrast to the patterns observed during the autumn, during the snow melt period the stream CO_2 was diluted ~~at~~ when discharge increased~~s~~ following a diel pattern (Figure 5). The melting and freezing between day and night-time suggests that melt-water from the surface snowpack during day time to a larger extent reached the stream without picking up an elevated CO_2 signal. Similar dilution patterns in conjunction with snowmelt have been observed in catchments of various ~~land-use~~land use but specifically in peatland catchments with limited forest cover (e.g. Wallin et al. 2013). The similarity between this agricultural catchment and open peatlands could potentially be the effect of an efficient melting of the snowpack. Both non-forested peatlands and agricultural fields are open areas subject to direct sunlight, and wind and rain exposure, while the soil under the snow remains frozen. As a result, a large share of the melt-water will never infiltrate the soil but instead reach the surface drainage system as overland flow (Laudon et al. 2007). This is further accompanied by the low hydraulic conductivity of clay soils, which are dominating the catchment of the current study. Although we did not capture the 2-3 days of peak spring flood (due to a water level out of the range of the pressure transducer) it was evident that the stream CO_2 concentration was diluted from ca 6.0 mg C L^{-1} to ca 2.0 mg C L^{-1} during these days, something that is further supported by the similar drop in EC during the peak spring flood from ca 900 to ca 150 µS cm^{-1}. However, as soon as the absolute discharge peak passed, the stream CO_2 concentration recovered rapidly to the pre-peak levels suggesting a shift to hydrological pathways that mobilize a high CO_2 pool, again supported by the concurrent increase in EC. April and May 2018 were characterized by warm and clear weather with an average 4.2°C higher air temperature and 255 more sun hours than the 30-year mean (1961-1990, SMHI). Altogether, this stimulates a kick-start of the aquatic primary production upon snowmelt, which likely explains the steady decline in CO_2 that occurred during late April/early May. During the spring and early summer, a strong diel pattern in CO_2 concentration further developed, likely driven by aquatic primary production consuming CO_2 during day-time. Such diel CO_2 patterns are commonly observed in stream CO_2 time series at base-flow or during receding flow conditions (e.g. Riml et al. 2019; Peter et al. 2014) and are especially pronounced in amplitude in nutrient-rich streams or in streams without canopy shading (Alberts et al. 2017; Crawford et al. 2017; Rocher-Ros et al. 2019). Initial evaluation of the δ^{13}C-DIC data collected during the spring period suggests a relatively steady mixture of geogenic and biogenic DIC although somehow related to variations in discharge (Figure 1110). However, given the suppressed stream CO_2 during the spring period, together with the strong diel cycle caused by aquatic primary production, fractionation of a strict biogenic DIC pool (with a δ^{13}C-DIC from -28 to -20‰) could theoretically push the δ^{13}C-DIC towards the less negative values observed in the current study (from -13.8 to -12.2‰) (Campeau et al. 2017b). Combined studies on aquatic metabolism, C dynamics and stable isotopic composition would further be recommended to disentangle the dynamic CO_2 source patterns in this type of agricultural system.

The spring and early summer of 2018 were generally dry leading to the stream channel drying out during long periods. The rapid rewetting periods (< 2 days) that occurred following larger precipitation events resulted in high CO_2 pulses (3-11 mg C L^{-1}) generally exceeding the overall median level of stream CO_2 (3.44 mg C L^{-1}) observed during the study period. The intermittent nature of streams, with distinct drying and rewetting episodes, is known to generate high CO_2 concentration pulses and subsequent emissions (Marcé et al. 2019). Such rapid pulses are generally suggested to be a result of intense respiration in the stream bed sediments upon rewetting, or due to a rapid mobilization of terrestrial C, both organic (DOC) and inorganic (CO_2) in connection to precipitation events. However, the findings of high CO_2 pulses upon rewetting have mostly been done in areas that display pronounced dry and wet seasons e.g. Mediterranean areas or Australia (e.g. Gomez-Gener et al. 2015; Looman et al. 2017). Here we show that such stream intermittency can also cause high and rapid CO_2 pulses in a Swedish agricultural setting, highlighting the need for expanding the geographical coverage of studies that investigate stream intermittency in relation to GHG dynamics and emissions. Areas that display stream intermittency will likely also increase in the future given the predicted changes in temperature and precipitation patterns. An obvious tool in this work is the use of continuous sensor-based measurements which allow capturing the episodic and unpredictable nature of these phenomena.

5. Conclusions

It is evident from the current study that the stream CO_2 dynamics in an agricultural headwater catchment are highly variable across a variety of different time-scales and with an interplay of hydrological and biological controls. The hydrological control was strong (although with both positive as well as negative influences dependent on season) and rapid in response to rainfall and snowmelt events. However, during growing-season baseflow and receding flow conditions, the aquatic primary production seems to control the stream CO_2 dynamics, which in turn sets the basis for atmospheric emissions. During the dry summer period, rapid rewetting following precipitation events generated high CO_2 pulses exceeding the overall median level of stream CO_2 (up to 3 times higher). This finding thus highlights the importance of stream intermittency in agricultural areas and its effect on stream CO_2 dynamics. Given the observed high levels of CO_2 and its temporally variable nature, agricultural streams clearly need more attention in order to understand and incorporate these considerable dynamics in large scale extrapolations.

6. Data availability

Data is available from the Uppsala University data repository, LINK WILL BE ADDED

7. Author contribution

MBW and MW brought the idea and designed the study. MBW funded and instrumented the catchment and analysed the data. MW conducted the GIS analysis. JA, MP and ES provided ideas and data. MBW wrote the manuscript with great support from all co-authors.

8. Competing interests

The authors declare that they have no conflict of interest

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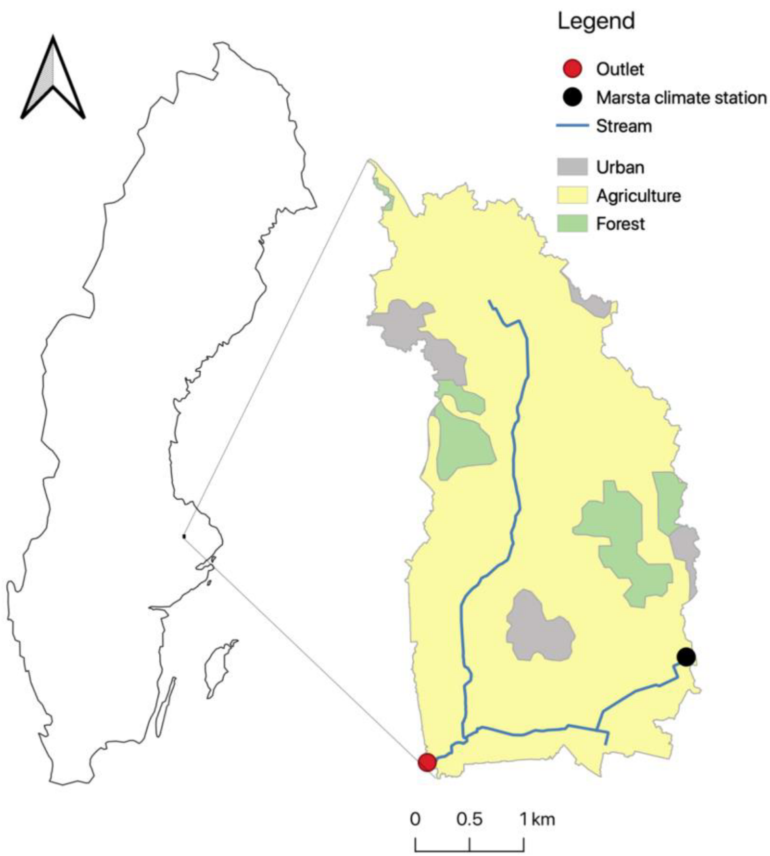
Table 1. Catchment characteristics of the Sundbromark (SBM) catchment

Catchment area (km^2)	11.3
Elevation range (masl)	13-41
Land use distribution (%)	
Agricultural land	86
Forest	8
Urban	6
Main Soil type distribution (%)	
Post glacial clay	48
Glacial silt	22
Glacial clay	14
Sandy till	12
Main bedrock distribution (%)	
Granodorite granite	89
Tonalite granodiorite	6
Dacite rhyolite	3
Granite	2

Table 2. Water chemistry at the outlet of the SBM catchment collected during June-November 2017 (n = 8) (Osterman 2018).

	Median	Mean	Min-Max
pH	7.7	7.8	7.4-8.4
EC (µS cm^{-1})	1082	1273	791-1908
NH_4-N (mg L^{-1})	0.10	0.08	0.01-0.1
NO_3-N (mg L^{-1})	0.7	1.9	0.09-6.5
PO_4-P (mg L^{-1})	0.07	0.09	0.01-0.2
DOC (mg L^{-1})	10.0	9.6	4.2-13.1
D.O. (%)	53	62	31-119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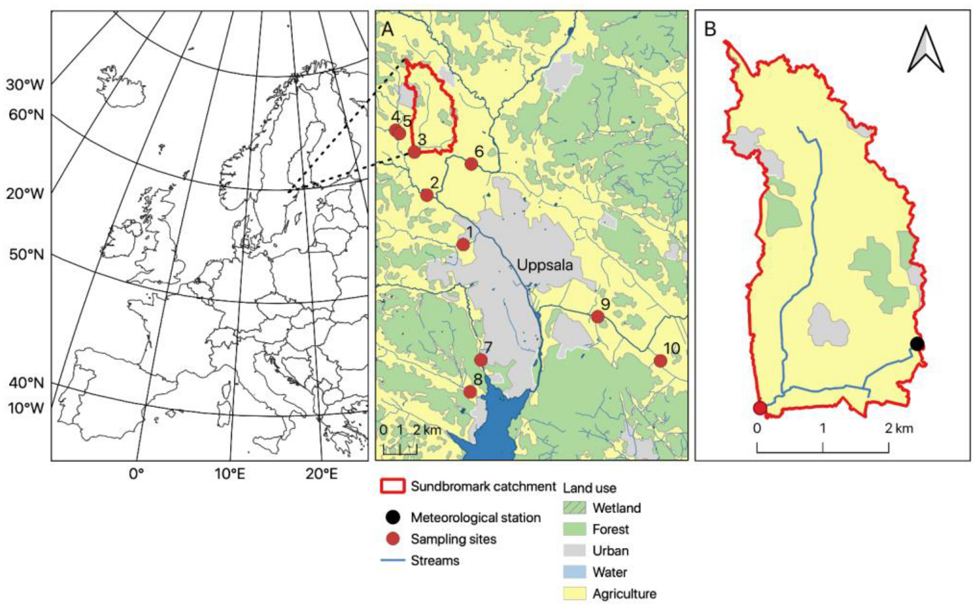

Figure 1. Location of the study with A) sampled sites of the spatial survey, and B) The Sundbromark (SBM) catchment. Catchment delineation and L.land use distributions within the SBM catchmentare given according to (GSD elevation data, grid 2+ (, ©Swedish Land Survey) and; CORINE Land Cover 2018, (European Environment)). The stream-based measurements were conducted at the catchment outlet (red dot) whereas the meteorological data derived from the Marsta Observatory (black dot).

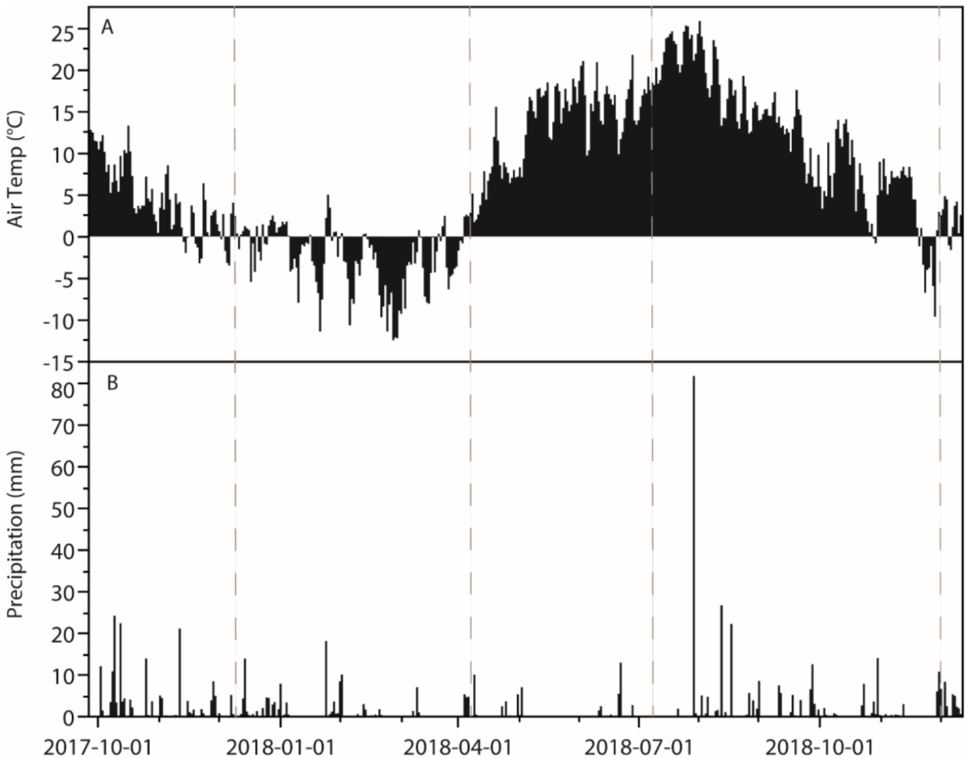

Figure 2. (A) Daily mean air temperature, and (B) daily precipitation during the study period (Sep 26, 2017-Dec 12, 2018) at the Marsta Observatory. Due to malfunctioning sensor the precipitation data for July 29 2018 is collected from the nearby (3 km) SMHI station, Ärna. The dotted lines refer to the hydrological periods displayed in figure 3.

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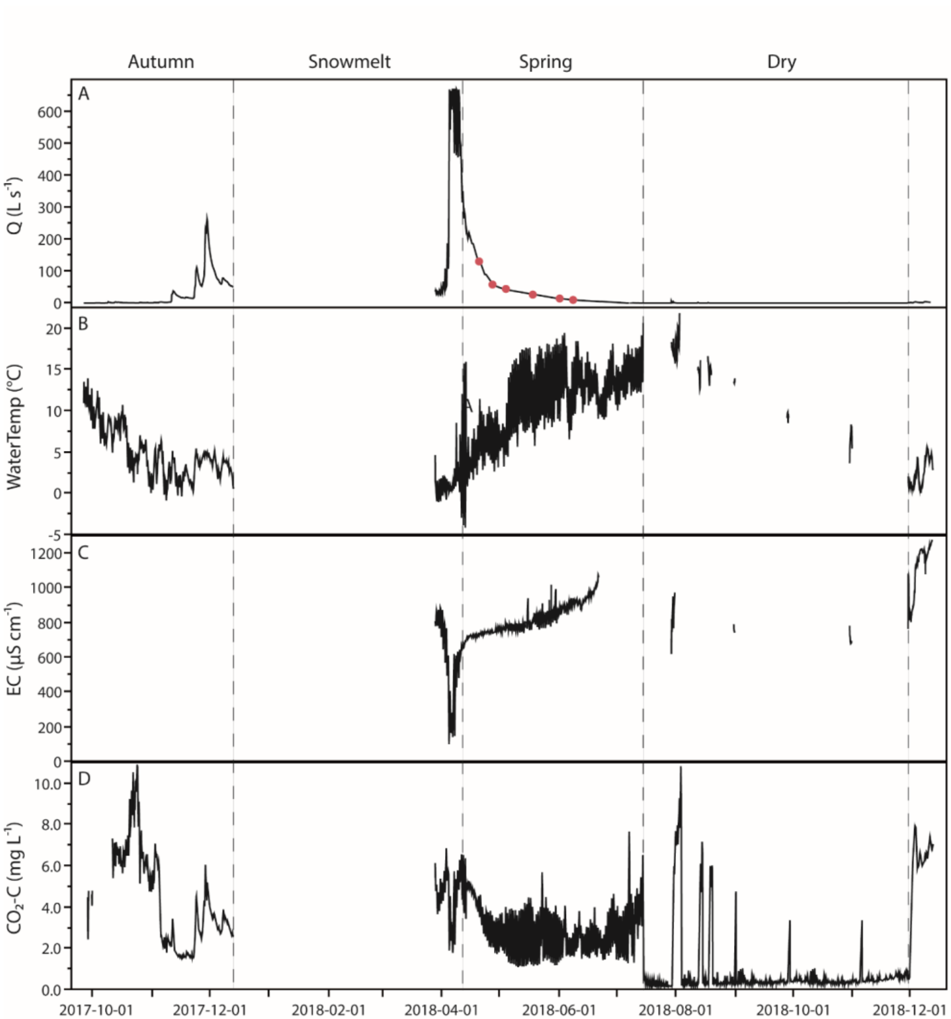

Figure 3. Time series of A) stream discharge (Q) with sampling days for δ^{13}C-DIC highlighted by red dots, B) stream water temperature, C) electrical conductivity (EC), and D) CO_2 concentration for the study period September 26, 2017-December 12, 2018, with break for the ice- and snow-covered period December-March. The CO_2 data include periods when the sensor was above the water surface during dry periods in summer/autumn of 2018.

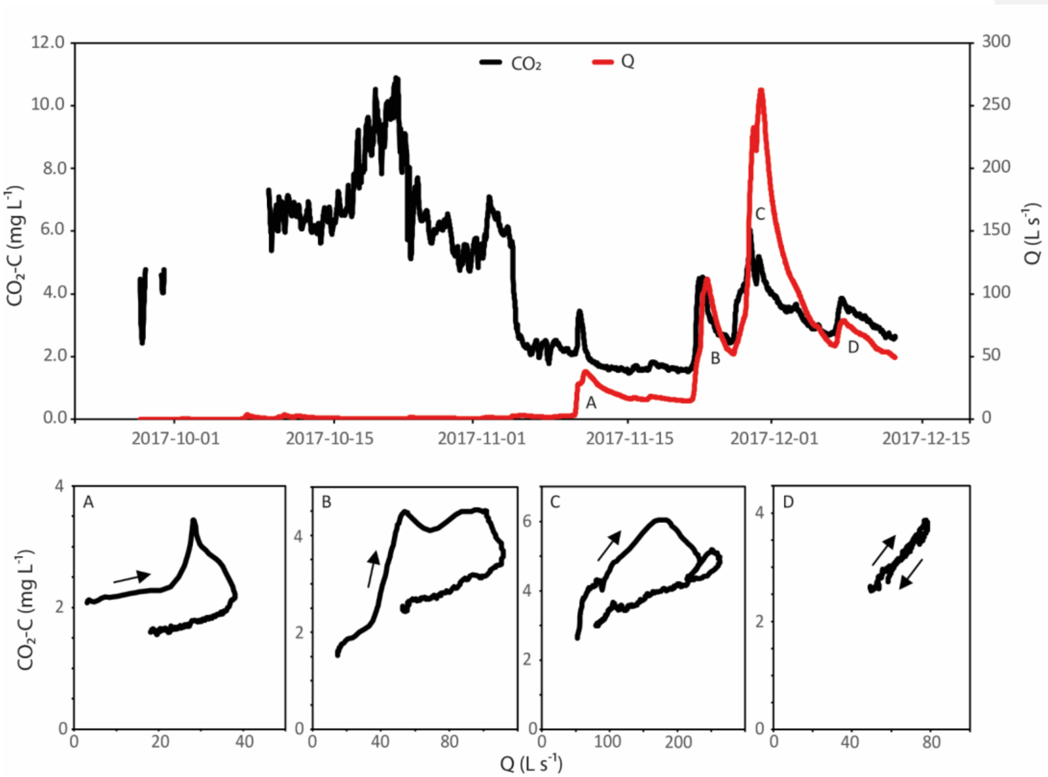

Figure 4. Stream CO_2 concentration (black) and discharge (red) for the autumn 2017 period with CO_2-Q hysteresis plots for four rain events.

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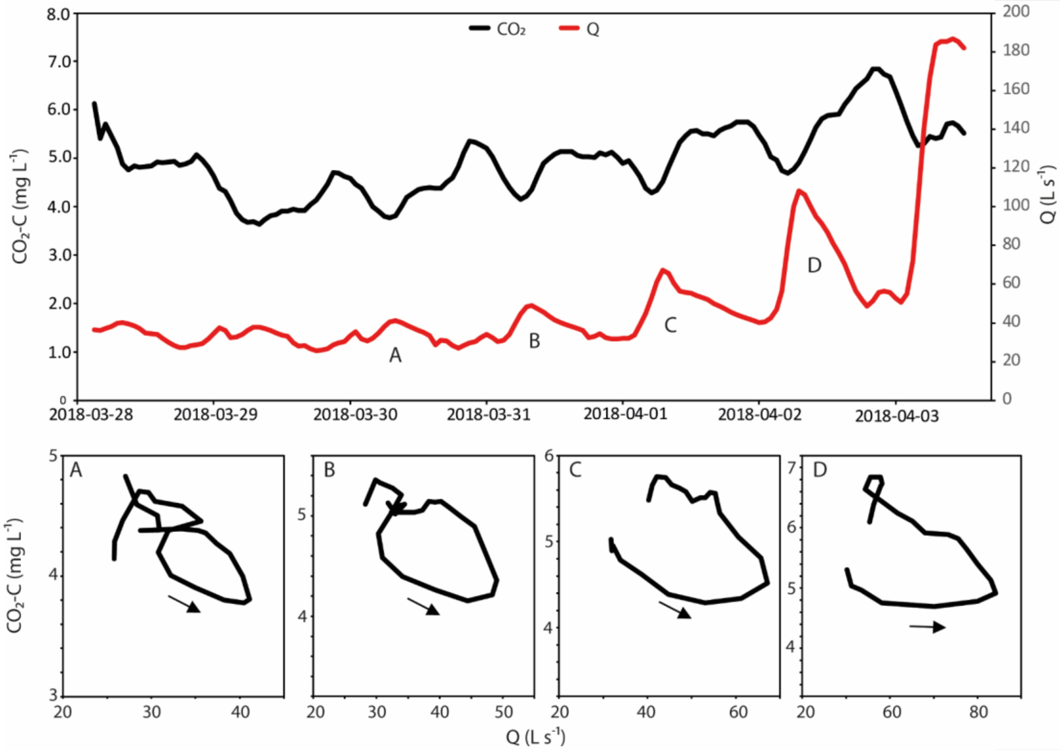

Figure 5. Stream CO_2 concentration (black) and discharge (red) for the snowmelt period 2018 with CO_2-Q hysteresis plots for four discharge events.

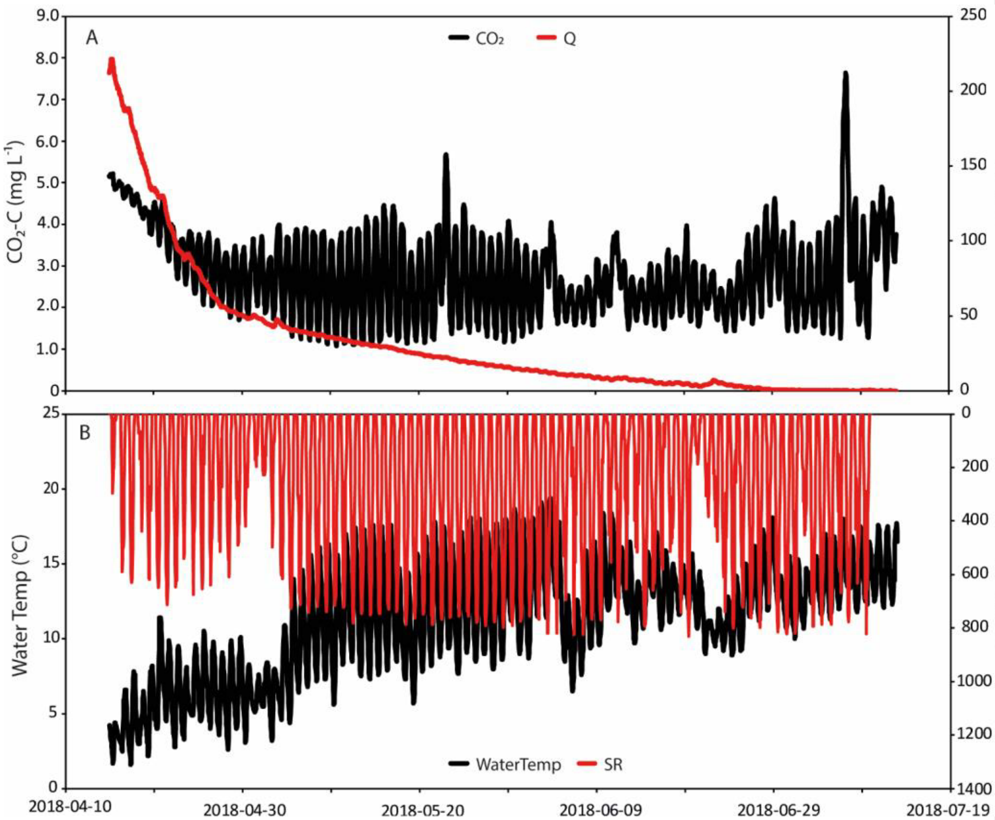

Figure 6. Time series of (A) Stream CO_2 concentration (black) and discharge (red), and (B) water temperature (black) and shortwave incoming radiation (SR, red) covering the period April-July 2018. Note the reverse axis for shortwave incoming radiation.

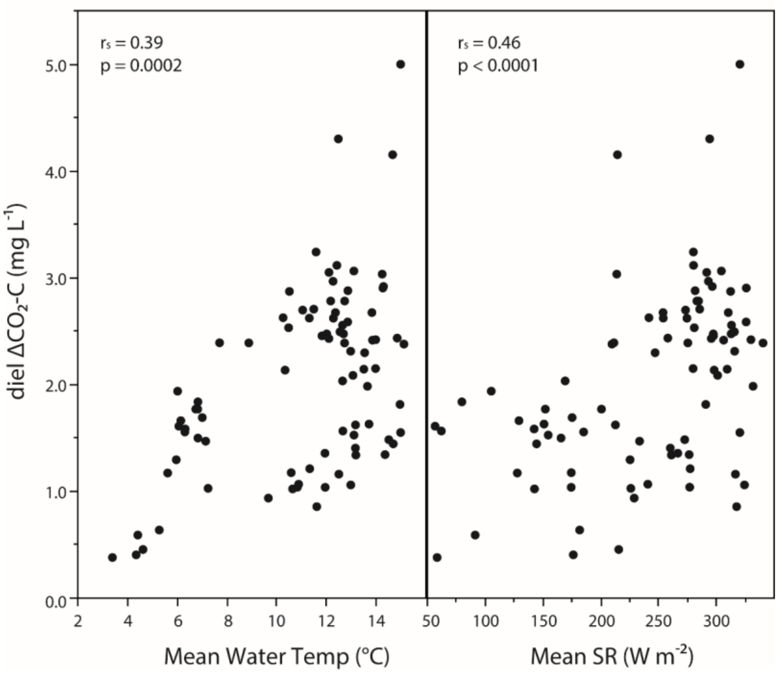

Figure 7. Diel amplitude in stream CO_2 concentration in relation to A) daily mean stream water temperature, and B) daily mean shortwave radiation (SR), covering the period April-July 2018. Statistics are given according to Spearman's rank correlation.

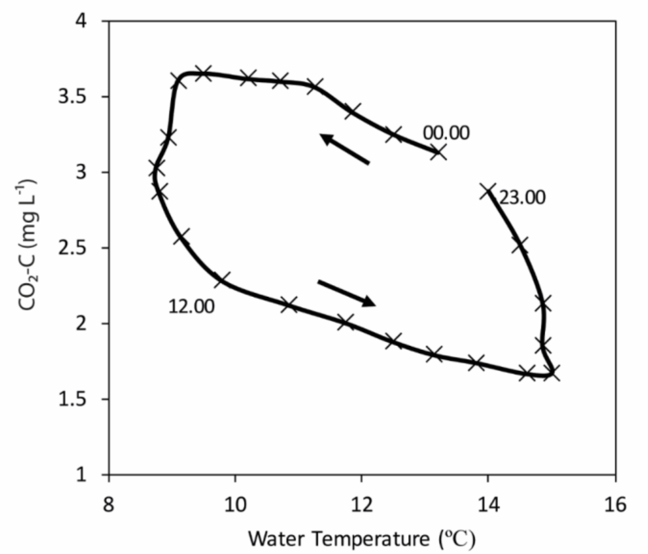

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Figure 8. CO_2-Water temperature hysteresis loop based on the median daily values presented in figure 7 covering the period April-July 2018.

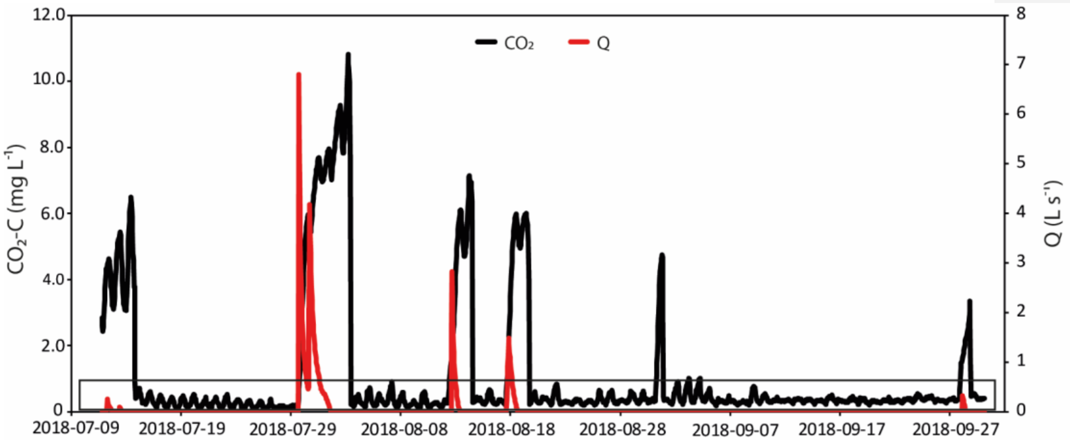

Figure 9. Stream CO_2 concentration (black) and discharge (red) for the dry period (July-September 2018). Periods when the CO_2 sensor was above the water table capturing an atmospheric signal (i.e. with concentrations <0.5 mg C L^{-1}) are highlighted by the lower box.

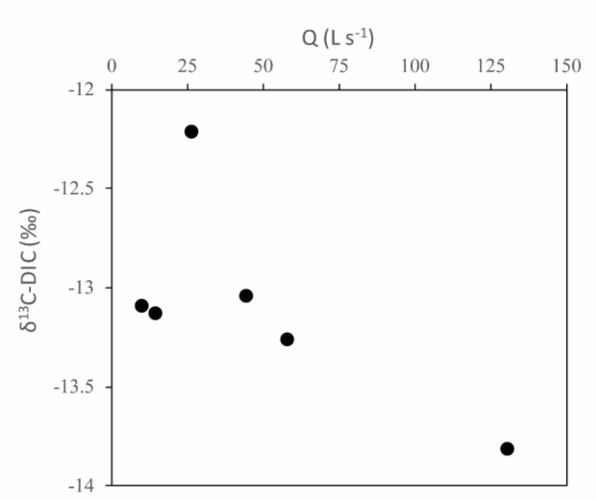

Figure 10. δ^{13}C-DIC as a function of stream discharge. The six sampling occasions covered the falling limb of the snowmelt peak April-June 2018.