Contrasting responses in dissolved organic carbon to extreme climate events from adjacent boreal landscapes in Northern Sweden

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Abstract
The ongoing pressures of climate change, as expressed by the increased intensity, duration, and frequency of temperature and precipitation events, threatens the storage of carbon in northern latitudes. One key concern is how these events will affect the production, mobilization, and export of dissolved organic carbon (DOC), the main form of aquatic carbon export in these regions. In this study, we retrospectively show contrasting effects of climate extremes over 23 years on two adjacent boreal catchments, one dominated by forest cover and the other draining a mire (wetland), despite experiencing the same extreme climate events. During the peak snowmelt, DOC concentrations ranged from 20 to 33 mg l\(^{-1}\) in the forest catchment and 10–28 mg l\(^{-1}\) in the mire catchment respectively, highlighting large inter-annual variation in the springtime hydrologic C export at both sites. We used climate and discharge variables to predict this variation, and found that DOC from the forested catchment, which is derived largely from riparian soils, had the highest concentrations following cold summers, dry autumns, and winters with high precipitation. By contrast, in the mire outlet, where DOC is primarily derived from decomposing peat, the highest DOC concentrations in the spring followed cold/dry winters and dry summers. Our results indicate that processes regulating stream DOC concentrations during spring in both catchments were dependent on both temperature and precipitation in multiple seasons. Together, these patterns suggest that DOC responses to climatic extremes are complex and generate variable patterns in springtime concentrations that are strongly dependent upon landscape context.

Introduction

Extreme climate events are among the major threats to environmental sustainability in the 21st century, as current projections predict an increase in both their frequency and severity (IPCC 2013). In northern landscapes, these changes pose a threat to the stability of large stores of soil organic carbon (SOC), including the fraction that is exported as dissolved organic carbon (DOC) (Bell et al 2018). DOC export is significant to landscape C balance (Cole et al 2007) and plays fundamental ecological and biogeochemical roles in aquatic ecosystems (Kalbitz and Wennrich 1998, Köhler et al 2002). The production and mobilization of DOC is largely dependent on temperature and moisture, which regulate decomposition processes in soils. For example, warmer seasons may support increased rates of microbial activity, which could reduce the DOC available for export through elevated respiratory losses of carbon dioxide (CO\(_2\)) (Dorrepaal et al 2009, Pries et al 2017). On the other hand, under wetter soil conditions, DOC may be more easily mobilized from soils to streams as compared to drier periods when DOC source areas become hydrologically disconnected (Tank et al 2018). Yet, the combined effects of extremes in temperature and precipitation on the processes regulating DOC production and mobilization remains poorly understood.

One challenge to predicting how aquatic DOC export will respond to extremes in temperature and precipitation in the north is resolving how the key drivers of DOC generation differ among major
contributing source areas (Eimers et al. 2008, Teuling et al. 2010, Tiwari et al. 2018). In this context, northern boreal landscapes comprise of two dominant sources: forest soils and mires (wetlands), which regulate DOC export in different ways. In forest landscapes, DOC is derived primarily from organic soils in the upper horizons of riparian zones (Ledesma et al. 2015), while in mires, deep peat deposits overlying bedrock or mineral soil are the primary sources (Fouché et al. 2017). These sources differ in the composition and quality of soil organic matter that is degraded (Davidson and Janssens 2006) and their hydrological connections to streams (Ledesma et al. 2015, Waddington et al. 2015). Therefore, a key question is whether the processes regulating DOC from these different sources will respond in similar ways to a common set of climate extremes.

A second important challenge to understanding the effects of climate extremes on spring DOC concentrations lies in identifying their occurrence (Ummenhofer and Meehl 2017). Previously, efforts aimed at detecting extreme events have employed a probabilistic approach which involves identifying extremes in time series using the extreme value theory (EVT) (Coles 2001, Ghil et al. 2011). These approaches involve identifying observations that exceed a specific threshold which can be modelled using an appropriate distribution (Northrop et al. 2017), or identifying maximums within defined blocks of the dataset (Ferreira and de Haan 2015). More recently, a common set of climate indices have been developed to predict future extreme events in climate models by using a number of different identification criteria (Donat et al. 2013). These indices capture different aspects of extremes including intensity, duration, and frequency of events. Determining such indices within a defined season (seasonal block such as summer, autumn, winter) offers a novel approach to assess antecedent climate extremes (climate extremes in the previous three seasons to spring) in a more robust way than was possible using only the maximum values identified during a particular season.

In northern landscapes, the spring season is a critical time window for detecting potential effects of climate extremes on stream DOC concentrations and variability. First, spring snowmelt represents the dominant hydrological event across northern regions and accounts for the bulk of annual runoff of water and solutes (Ågren et al. 2010, Laudon et al. 2011). Second, as melt water drains these landscapes, it flushes DOC that was either produced during the summer and/or accumulated during the colder autumn and winter seasons (Brooks et al. 1999). This also means that inter-annual variability in stream DOC concentrations during snowmelt may be related to differences in climatic conditions during previous seasons that determine the pool size available for flushing (Raymond and Saiers 2010, Frank et al. 2015, McMillan et al. 2018). While snowmelt flushes DOC accumulated in soils, it does so differently in forest- compared to mire-dominated catchments (Laudon et al. 2011). Specifically, DOC concentrations in forest streams increase during spring flood as the water table rises and intersects increasingly organic-rich riparian soils (Bishop et al. 2004). In mires, flood waters dilute stream DOC concentrations because they move along preferential flow paths and thus bypassing organic rich peat layers (Rennéralm et al. 2010). Despite these characteristic discharge/DOC relationships, variability in concentrations among years often cannot be explained by differences in water table levels alone (Mattsson et al. 2015). For example, DOC concentration have been shown to increase with trends in annual primary production (Dinsmore et al. 2013), suggesting that variation in concentrations may be attributed to year-to-year changes in OM production (Moore et al. 1998, Harrison et al. 2008). Importantly, such findings also suggest that concentrations during the spring flood period can be used as an indicator of how terrestrial biogeochemical processes respond to climate extremes in these landscapes (Creed et al. 2018). Thus, connecting long-term spring DOC concentration to antecedent climate extremes can provide new insights into how soil C losses are regulated among landscape sources.

In this study, we ask how antecedent climate extremes influence DOC concentrations during the spring flood in boreal landscapes. To answer this question, we used a variety of extremes related to air temperature, precipitation and discharge over a 23 year period in northern Sweden. We then used multivariate analysis to explore whether and how climate extremes during summer, autumn, and winter influence maximum and minimum DOC concentrations during the ensuing spring flood in a forested catchment and a mire-dominated catchment. Overall, we hypothesized that variations in the amount and spatial arrangement of SOC storage between landscape units (forests versus mires), as well as differences in how these units function hydrologically, would result in in unique relationships between stream DOC and antecedent climate extremes over the long-term.

**Methods**

**Study location, sampling and analysis**

We conducted this study in the boreal zone of northern Sweden where the long-term monitoring program from the Krycklan catchment provided data from a forest and mire dominated catchment (Laudon et al. 2013). The forest catchment (C2) is 0.12 km² and consist of Norway spruce (Picea abies), Scots pine (Pinus sylvestris), and deciduous forest which overlays till and thin soils. The 0.18 km² mire catchment (C4) has 40% peat coverage where the majority of water flows through before entering the streams. In both...
catchments, streams were sampled for DOC 3–4 times per week during snowmelt, using high-density polyethylene bottles that were acid washed prior to use. Samples were refrigerated until analysis in the lab using a Dohrmann Carbon Analyzer (in 1993) then Shimadzu 145 DOC-VPCH analyzer (1994–present) after acidification to remove inorganic compounds. All data were obtained from the Krycklan catchment database hosted by Unity Svarterget Data portal (https://franklin.vfp.slu.se/). Note that data from 2002 were unavailable.

From the 23 years of DOC concentration data available (1993–2017), we determined the maximum concentrations for the forest and minimum concentrations for the mire during the spring period for each year. The spring period was defined using a temperature-based delineation as described in the season’s definitions below. For each spring, a long-term average DOC concentration was calculated by averaging DOC concentrations every three days for each catchment. This long-term average was then used to determine how maximum and minimum concentrations in each spring varied among the years in the forest and mire catchment respectively. It should be noted that maximum and minimum DOC concentrations from the forest and mire serve as reasonable proxies for the amount of organic carbon exported during the entire spring season. For example, using seven years of data from which we have continuous high quality discharge records (2009–2016) (supplementary table 1 is available online at stacks.iop.org/ERL/14/084007/mmedia), total DOC export during snowmelt from the forest site ranged from 7.4 to 164.5 kg C, and was closely correlated with the observed maximum concentrations \( r = 0.83, p < 0.05, n = 7 \). For the mire site, springtime DOC export ranged from 33.3 to 212.1 kg C, and was positively correlated with the minimum springtime concentrations \( r = −0.64, p < 0.1, n = 7 \). However, only seven years of data for discharge were available for each catchment, and could not be used in the PLS modeling.

Temperature, precipitation and discharge data
We collected data for temperature and precipitation from the Svarterget field station, which is located <1 km² away from the study site. For daily air temperature, the average, minimum, and maximum values were used to create the following seasonal (summer, autumn, winter, and spring) metrics: (1) average air temperature \( T \), (2) minimum air temperature \( T_{\text{min}} \), (3) maximum air temperature \( T_{\text{max}} \) and (4) daily sum of precipitation. Discharge was measured from a 90° V notch in a heated weir house with a pressure transducer that connected to a Campbell Scientific data logger in a downstream catchment (C7) and scaled to the specific discharge of each catchment (C2 and C4). Four discharge variables were used to assess potential effects on spring DOC concentrations: (1) maximum discharge during spring, (2) end of winter discharge, (3) winter baseflow, and (4) difference between the end of winter and maximum spring discharge.

Season’s definition
We defined seasons according to the Swedish Meteorological and Hydrological Institute, which is based on ecological responses to air temperature changes. Winter included the period when daily mean air temperatures fell below 0 °C for more than seven consecutive days without a longer period (more than five consecutive days) of greater than 0 °C afterwards, summer started when daily mean air temperature was greater than 10 °C for more than five consecutive days without a longer period (more than five consecutive days) of less than 10 °C afterwards. We defined the end of summer as the point when daily mean air temperatures fell below 10 °C for more than five consecutive days and was not followed by a warmer period of more than 10 °C. Spring season fell between winter and summer and started at the point when air temperature was more than 0 °C for five consecutive days. We delineated the autumn season through the metrics above that mark the end of summer and onset of winter.

Extreme temperature and precipitation
We used the 27 climate change indices created by the Expert team on Climate Change Detection and Indices in the World Meteorological Organization as a consistent and traceable set of metrics to assess long-term variability of extremes over the past 23 years (http://etccdi.pacclimate.org/list_27_indices.shtml). These indices were designed to assess three aspects of temperature and precipitation events: intensity, duration, and frequency, which were originally created to evaluate global climate models efficacy in projecting future climate extremes (Donat et al 2013). There are 17 temperature based indices and 10 precipitation based (supplementary material table 2). These indices have been used to calculate monthly or annual averages where one value per year was used to assess changes in long-term trends of climate extremes (Alexander 2016).

We applied a similar extreme value analysis to our dataset, however instead of using yearly or monthly averages, we used season (as defined by the temperature based delineation mentioned above) to obtain one value for each climate index using the block maxima approach from the EVT (Ghil et al 2011). The block maxima approach is commonly applied to seasonal data such as windspeed (An and Pandey 2005), flood (Mudersbach and Jensen 2010), rainfall (Villarini et al 2011) and snowdepth (Marty and Blanchet 2012). This approach divides the observation period (23 years) into non-overlapping periods (in this study, we use seasons as blocks) and restrict the attention to the
maximum observation in each period (Ferreira and de Haan 2015). By using climate indices to explore the extremes in the temperature and precipitation datasets allows us to assess different aspects of extremes that results in the shift in the mean, as well as the change in symmetry and variability of the distributions (Ummenhofer and Meehl 2017).

Partial least square analysis (PLS)
To predict which of the seasonal climate extremes and discharge variables best explained the responses of forest and mire DOC concentrations during the spring, the PLS was used to create a multivariate model for each landscape. The analysis was carried out in SIMCA 14.0 where a model was created for one y variable (forest DOC or Mire DOC) and 85 x-variables. The 85 x-variables were created from 27 climate indices in the summer, autumn and winter and four discharge variables. Initially, all x variables and the y variable was included into the model. Then a variable selection process was done where variables that had low variable importance in the projection (a value of less than 1) and loadings weights that exceeded the 90% confidence intervals were excluded from the model (Chong and Jun 2005, Mehmood et al 2012). The x variables that exceed the Hotellings T² or had a high distance to the model (DMO) were also excluded. This process was rerun until R²X, R²Y and Q² was maximized for DOC concentrations from both the forest and mire catchments, respectively.

Results

Contrasting DOC responses in forest and mire landscapes
Analysing spring DOC concentrations from the forest and mire catchments revealed that maximum and minimum DOC concentrations did not occur on the same years for the two catchments. We found the highest concentration in the forest catchment in 2017 (34 mg l⁻¹) and at the mire outlet in 1996 (28 mg l⁻¹) (figure 1(a)). The lowest concentration in the forest stream occurred in 1994 (19 mg l⁻¹) while the lowest concentrations in the mire outlet were in 2012 (10 mg l⁻¹) (figure 1(a)). For the forest catchment, the long-term average DOC spring concentration was 24 mg l⁻¹ which was 9 mg l⁻¹ below the highest concentration and 5 mg l⁻¹ above the lowest concentration (figure 1(a)). In the mire catchment, the long-term average DOC spring concentration was 15.6 mg l⁻¹, which was approximately 12 mg l⁻¹ below the highest concentration and 6 mg l⁻¹ above the lowest concentration (figure 1(b)).

PLS prediction of forest and mire DOC using climate extremes and discharge variables
The most important variables for explaining DOC spring concentrations in the forest stream were winter runoff variables (consecutive wet and dry days), summer temperatures (coldest maximum temperature (Min Tmax), cool nights) and autumn runoff (heavy precipitation) (figures 2(a), 3(a) and (b)). A two component model (r²X = 0.56, r²Y = 0.66, q² = 0.46) showed gradients between the highest DOC concentrations
Figure 2. Partial least squared analysis of 85 climate change indices throughout the summer, autumn and winter and discharge indices used to predict forest (A) and mire DOC (B) during the spring. The forest concentrations were best predicted by (i) summer temperatures where a low to high gradient in DOC corresponds to warm–cool summers (upper left to lower right), (ii) winter precipitation where another gradient can be seen from left (low DOC) to right (high DOC) as the number of consecutive wet days increases (A), and (iii) autumn heavy precipitation was also an important variable for explaining the years with low DOC in the forest although the level of importance was low. The mire on the other hand showed low DOC responses to warm winter and high DOC in years with cold winters as the gradient moved from upper right to lower left (B). Winter precipitation (wet and dry days) were also important showing a gradient of low to high DOC from lower right to upper left as winter consecutive wet days decreased. Summer heavy precipitation and winter baseflow were also important variable for explaining low DOC although their importance were lower than winter heavy precipitation and consecutive wet days (B). The colour ramp shows the variation in DOC concentrations across the years in both catchments with highest concentrations gradient from red to lowest concentrations blue.

Figure 3. Loadings plot and regression models of the significant climate indices and discharge variables used to model spring DOC concentrations in the forest (A) and (B) and mire catchment (C) and (D). Winter consecutive dry days (W con dry days) and summer cool nights (S cool nights) were positively correlated to the highest forest spring DOC concentrations while autumn heavy precipitation (A Heavy precipitation), winter consecutive wet days (W con wet days) and summer coldest average maximum temperature (S min T max) were negatively correlated with forest spring DOC highest concentrations. The minimum concentrations from the mire were positively correlated to winter cool night and day (W cool nights and W cool days), and negatively correlated with winter baseflow (W baseflow), accumulated freeze degree days in the winter (W AFDD), winter warmest average minimum temperature (W max Tmin), and winter heavy precipitation (W heavy precipitation), winter consecutive from wet days (W con wet days), summer heavy precipitation (S heavy precipitation) and summer consecutive from wet days (S con wet days). The variables are colour coded according to seasons where light blue represents autumn, green represents winter, red represents spring and dark blue represents DOC concentrations from the respective catchments.
concentrations in years dominated by low autumn precipitation, wet winters and cold summers to lowest DOC concentrations dominated by high autumn precipitation, dry winters and warm summers (figure 3(b), supplementary table 3). In contrast, the most important variables for explaining mire spring DOC concentrations were related to winter temperatures (accumulated degree day below zero, maximum minimum temperatures (Max Tmin), cool days/ nights), winter runoff (contribution from very wet days, heavy precipitation, baseflow) and summer runoff (contribution from wet days, heavy precipitation) (figures 2(b), 3(c) and (d)). The two component model \((r^2x = 0.64, r^2y = 0.65, q^2 = 0.48)\) showed gradients between the years with highest DOC in cold/dry winters with low baseflow and dry summers to low DOC concentrations in years following warm/wet winters with wet antecedent summers (figure 3(d), supplementary table 3).

It should be highlighted that, although both autumn and summer precipitation were significant variables in predicting DOC from the forest and mire catchments respectively, they had low variables of importance.

**Discussion**

DOC flushing during snowmelt is an important component of the boreal landscape C balance (Cole et al 2007), and also has a major influence on pulses of springtime acidity in streams and lakes in this region (Kohler et al 2009). Using long-term records from adjacent forest- and a mire-dominated catchment, we show that springtime DOC concentrations, and seasonal organic C flux, are variable from year-to-year. Interestingly, this inter-annual variability was driven by different sets of antecedent climate extremes for the two catchments, even though they experience the same intensity, duration, and frequency of events during summer, autumn, and winter. These different sets of predictors highlight important heterogeneity in how the primary DOC sources in the boreal landscape respond to climate conditions. Overall, our approach leverages on the connection between springtime concentrations and total seasonal DOC exports which provides a way to explore how climate in previous seasons regulates a key component of gross annual soil C loss via streams using relatively simple and widely available descriptors.

Our results suggest that multiple antecedent drivers interact to influence DOC concentrations during snowmelt. For example, in the forest-dominated catchment, spring DOC concentrations were best predicted by temperature extremes in summer and autumn/winter runoff. In contrast, the mire catchment DOC concentrations during spring was best predicted following temperature extremes in the summer/winter and winter runoff. While these results highlighted that DOC in different catchments responded to seasonal extremes in different ways, the combination of both temperature and precipitation events in successive seasons indicate that the mechanisms regulating DOC production, mobilization and export are more complex than previously thought.

Previous studies exploring the effects of extreme temperature and moisture on DOC in isolation have documented a variety of processes and mechanisms that influence production. For example, warmer temperatures have been linked to DOC production through the increase decomposition of SOC (Christ and David 1996, Freeman et al 2001a). Soil freezing may also promote DOC losses (Haei et al 2010, Hagemann et al 2016) by physically disrupting soil aggregates (Kalbitz and Kaiser 2008), damaging plant roots (Cleavitt et al 2008), and lysing microbial cells (Yanai et al 2004). Similarly, drought has been linked to increased aeration of otherwise waterlogged soils, facilitating the decomposition of soil carbon and eventual DOC release (Freeman et al 2001b, Sippel et al 2018), while increased precipitation has been shown to enhance the mobilization of organic carbon from soils to streams (Ågren et al 2010, de Wit et al 2016). Although these studies have shed important light on our understanding of soil carbon responses to individual drivers, they have not addressed the combined, interactive, and potentially lagged and legacy effects (Smith et al 2009) of climate extremes that typify seasonal transitions in ecosystems.

While observational rather than experimental, the strength of our approach is that it addresses the long-term, co-variability in the occurrence of climate extremes. For instance, PLS results suggest that cool summers, dry autumns and wet winters promoted higher spring DOC concentrations in the forest catchment. A potential explanation for this is that cool summers leave behind larger pools of DOC available for export because lower temperatures reduce rates of decomposition in contrast to warmer summers that deplete organic pools due to more active microbial activity (Huang and Hall 2017, Melillo et al 2017). Furthermore, accumulation of DOC in riparian soils is supported by dry autumns, when low streamflow likely reduces the possibility of flushing from the upper organic horizons (Hinton et al 1998, Cooper et al 2007). When dry autumns are followed by winters with large snowpack, we assume that this causes higher water table levels that connect to more surficial sources of DOC and results in elevated spring DOC concentrations (McMillan et al 2018).

A different set of interacting drivers appear to influence the accumulation and flushing of DOC from the mire-outlet during spring. Here, PLS modelling indicated that dry summers followed by cold/dry winters promoted higher DOC spring concentrations. These results suggest that dry summers could contribute to larger pools of carbon available for export in the following spring, supporting the enzyme latch...
mechanism, where droughts have been linked to higher DOC concentrations in the long-term following rewetting (Freeman et al 2001b, Worrall et al 2006). When dry summers are combined with dry/cold winters, greater DOC concentrations may arise either because of reduced dilution from a smaller snowpack during melt (Pastor et al 2003), or an increased freezing effects on peat due to a lower water table (Freeman et al 2001b) and a cold season (Haei et al 2010). These results are consistent with Frolking et al (2001) who found highest rates of peat accumulation under warm/wetter conditions and lowest under cold/dry conditions.

Multiple, successive extremes that explained variation in DOC concentrations for both forest and peatland catchments provide insights into the controversy of whether DOC increase will respond to warmer (Freeman et al 2001a, Dorrepaal et al 2009), colder (Haei et al 2010), wetter (Bianchi et al 2013) or drier conditions (Freeman et al 2001a). These studies were short-term lab or field experiments aimed at understanding the DOC responses to single drivers, yet it is unlikely that a particular climate extreme will occur in consecutive summer, autumn and winter seasons. Additionally, we have found that if any one seasonal extreme was eliminated, the explanatory power would be reduced by 50% ($r^2$) and the prediction power by 32% ($q^2$) in the forest and by 10% for both the explanatory ($r^2$) and predictive ($q^2$) power of the mire model. This further indicates that subjecting SOC to an isolated extreme across all season is likely unrealistic and may not be representative of future climate change impacts. Overall, the hypotheses that emerged from our PLS modelling provide a guide for future experiments that could test more complex interactions between climate extremes across seasons.

Based on the climate predictions of the IPCC (2013), we cannot only expect an increase in mean annual air temperature within this century, but also a change of precipitation patterns. In this context, our results indicate that warming can affect DOC variability during the spring, but this depends on whether it is accompanied by increases or decreases in precipitation. Thus, the overall variation is related to hydrology, primary productivity (carbon production), and how productivity is balanced by decomposition (Tranvik and Jansson 2002). Future climate projection in the Krycklan catchment suggests earlier springs, with shorter winters, where flow regimes are projected to change from very low winter flow and a dominant spring peak, to regimes with an earlier snow melt initiation and low peak flow (Teutschbein et al 2015). Low spring discharge peaks in the future will likely be translated into lower spring DOC concentrations in the forest and higher concentrations from the mire with significant consequences for the carbon cycle in the boreal zone.

**Conclusion**

Using a range of climate indices that reflect the natural variability of climate extremes across seasonal, we have shown that DOC concentrations during the spring in northern landscapes are regulated by more complex processes than has been previously alluded to using single manipulation experiments. We found that the impact of these extreme climate events are likely to affect the biogeochemical processes that influence the production of DOC, as well as hydrological processes that influences the mobility and export of DOC from both forest and mire catchments. However, the findings from this study further suggest that these processes will likely respond differently to climate extremes depending on whether the sources of DOC are from forest or mire catchments.

**Acknowledgments**

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