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Key Points:

- Peatlands contribute 91 ± 54 Tg dissolved organic carbon (DOC) to surface waters and from 12% to 20% of the global organic carbon transferred to oceans
- Air temperature explains the variability in DOC fluxes for undisturbed sites when it is discharge for disturbed sites
- Major peatland areas are lacking from this synthesis, emphasizing the urgent need for fluvial carbon export evaluation from peatlands

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Peatland Dissolved Organic Carbon Export to Surface Waters: Global Significance and Effects of Anthropogenic Disturbance

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Abstract Peatlands are key components of the global carbon cycle. We compiled peatland dissolved organic carbon (DOC) export from 62 sites to provide a global estimate of the contribution of these ecosystems to fluvial organic carbon fluxes. Despite their modest coverage on land (less than 3%), peatlands contribute at least 91 ± 54 Tg DOC to surface waters, and could represent from 12% to 20% of the DOC ultimately transferred to oceans. Boreal peatlands are the main contributors, with 58% of peatland inputs. Tropical peatlands contribute 37% of global peatland fluxes although representing only 13% of global peatland areas. Temperature is the leading factor explaining the variability in DOC fluxes for natural sites, when it is discharge for sites impacted by direct anthropogenic activities. This suggests different trajectories under climate change pressure for non-disturbed and disturbed sites and reinforces the need for hydrological restoration of disturbed peatland sites worldwide.

Plain Language Summary Peatlands are a special type of wetland, storing large amounts of organic carbon. Since these ecosystems are organic-rich and hydrologically connected to surface water, they are expected to contribute substantially to the organic transfer to surface water, a major but poorly constrained compartment of the global carbon cycle. Here we have synthesized all the available studies reporting organic carbon fluxes from peatlands. This synthesis confirms the leading role of peatlands in organic carbon transfer from terrestrial to aquatic ecosystems. Worldwide, peatlands are threatened by human activities. Our analysis of the environment drivers of organic carbon transfer reveals that temperature drives fluxes in natural sites, whereas it is discharge in the case of disturbed sites. This result suggests that natural and disturbed sites will evolve differently under climate change pressure.

1. Introduction

Peatlands were recently recognized by the United Nations as a major soil carbon pool of great interest for atmospheric carbon sequestration and mitigation of the ongoing climate change (UNEP Assembly, 2019). They have accumulated carbon for millennia (Holden, 2005; J. E. Nichols & Peteet, 2019; Ruwaimana et al., 2020; Yu et al., 2011), but climate change as well as local anthropogenic activities disturb their carbon balance, potentially switching them from carbon sinks to carbon sources (Gallego-Sala et al., 2018; Loisel et al., 2021). Establishing peatland carbon balance requires the quantification of carbon exchanges with the atmosphere (CO_2 , CH_4) as well as transfer to surface water (in the form of dissolved [DOC] and particulate [POC] organic carbon, CO_2 and CH_4). These fluvial carbon fluxes can represent up to 48% of the net ecosystem carbon balance (Dinsmore et al., 2013; Evans et al., 2014, 2016; Nilsson et al., 2008; N. T. Roulet et al., 2007). DOC is the dominant form of carbon, constituting up to 90% of fluvial organic carbon exports from peatlands (M. Billett et al., 2010; Dinsmore et al., 2010; Leach et al., 2016; Rosset et al., 2019). Organic carbon transferred from peatlands to surface water feeds downstream food web chains (Carpenter & Pace, 1997) and can also constitute a source of greenhouse gas (GHG) emissions when mineralized by microbial oxidation and photooxidation (Dawson et al., 2004; Dean et al., 2019). In addition, it may convey potentially harmful elements to biota (Broder & Biester, 2017; Gandois et al., 2020; Tipping et al., 2003), and affect drinking water treatment processes (Ritson et al., 2014).

Peatlands have been recognized as important sources of organic carbon transfer to surface water at the watershed scale (Laudon et al., 2011; Rosset et al., 2019; Sebestyen et al., 2021). Despite this, their global contribution to fresh waters and oceans is still speculative. So far, the only regional estimation is the contribution of Indonesian tropical peatlands that has been evaluated at 10% of the global tDOC (terrestrial DOC) inputs to the oceans

(Baum et al., 2007; Moore et al., 2011). In Scandinavia, northern Europe and America, DOC concentrations in surface waters have increased in the last decade, a phenomenon called “water browning” (Monteith et al., 2007; N. Roulet & Moore, 2006). Peatlands, among other soil types are the main contributor to this phenomenon. The combined effects of land use change, climate change and reduction of SO₄ atmospheric inputs explain this phenomenon (Kritzberg et al., 2020). Worldwide, peatlands suffer from direct anthropogenic pressure, including ditching, forest clearing and land burning and are impacted by long distance atmospheric deposition and climate change. In watersheds where anthropogenic activities impact peatlands, changes in the quality and quantity of DOC have been reported (Brown et al., 2015; Clutterbuck & Yallop, 2010; Cook et al., 2018; Moore et al., 2013; Nieminen et al., 2017). Indeed, disruptions of peatland natural functioning, including modification of water flows and water table levels, may modify both the quantities and origin (modern or old carbon) of DOC exported from peatlands, with the potential of remobilizing century to millennia old carbon into the active carbon cycle (Clay et al., 2012; Dean et al., 2019; Moore et al., 2013).

The objectives of this study were to: (a) provide an up-to-date synthesis of fluvial organic carbon export from peatlands and its contribution to global DOC transfer to surface waters and oceans, and (b) identify drivers of DOC specific fluxes from peatlands both in natural and disturbed states.

2. Materials and Methods

2.1. Database Compilation

A literature review was conducted to compile DOC exports from peatland at the plot and catchment scale. The Web of Science database was queried using the following search strings: “DOC,” “export,” and “peatland.” Publications were selected only if they reported annual DOC exports (gC m⁻² yr⁻¹) or provided enough data to calculate them. Additional publications were added to the database based on the authors' knowledge and/or if they were mentioned as references in the first pool of selected publications.

At each peatland site, mean annual air temperature (°C) (hereafter air temperature), total annual precipitation (L m⁻² yr⁻¹) (hereafter precipitation), total annual specific discharge (L m⁻² yr⁻¹) (hereafter specific discharge), surface proportion of peatland in the watershed (%) and direct anthropogenic disturbances (when reported in the publications) were compiled to describe the context in which DOC export takes place. When available, these data were collected in the articles reporting DOC exports and if not in companion papers. At a given site, when an article reported multi annual fluxes, average values were calculated. When several publications reported fluxes at the same site, the latest calculations were selected.

The climate of each peatland was defined according to the present Köppen–Geiger climate classification map edited by Beck et al. (2018). Following the methodology of (Leifeld & Menichetti, 2018), polar or cold climate peatlands were grouped under boreal climate. Direct anthropogenic disturbance was coded as either disturbed (TRUE) or undisturbed (FALSE) with the disturbed category accounting for any draining, burning, logging, and grazing activities that had been reported in the studied watershed in the past 20 years before DOC exports were measured.

2.2. Statistical Analysis

Eighty-nine DOC export values from peaty watersheds were gathered from the literature. Twenty-seven DOC export values were excluded from the study since they originated from watersheds with less than 50% peatland coverage. In total, only 62 sites were included in our analyses (boreal $n = 34$, temperate $n = 17$, and tropical $n = 11$).

As the different sections of the data set (climatic and anthropogenic) are strongly unbalanced, a two-way crossed ANOVA was not conceivable for the analysis of our data. Instead, nonparametric statistical tests such as the Wilcoxon–Mann–Whitney (WMWt) and the Kruskal–Wallis (KWt) tests were used to test the differences in DOC export between the different climatic areas (KWt) and to test the effect of the anthropogenic disturbances regardless of climatic areas and within each climatic area (WMWt).

Ordinary least squares multiple regression analyses (MLR) were performed on the data set to test whether the variables “anthropogenic disturbance,” “air temperature,” “precipitation,” and “specific discharge” could explain

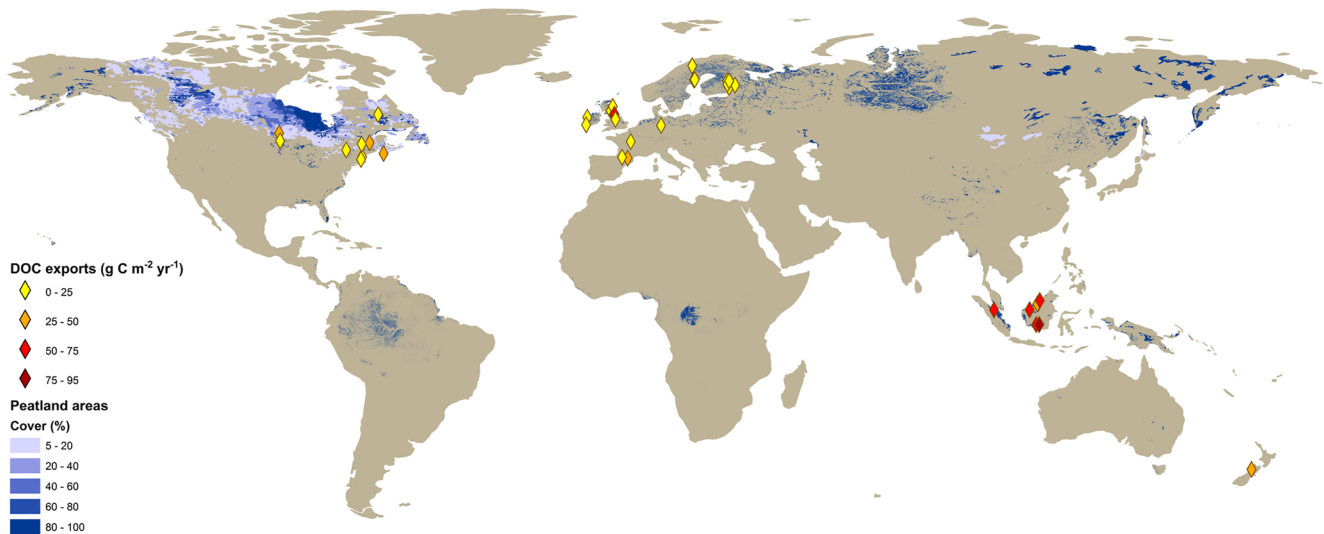


Figure 1. Peatland areas (blue areas) and localization of the 62 sites (diamonds) where dissolved organic carbon (DOC) exports have been reported (watersheds with >50% peatland coverage). The map was compiled based on the global peatland distribution derived from PEATMAP data (Xu et al., 2018). Antarctica is not represented on this figure since no peatland area has been reported on this continent.

DOC exports. Prior to the analyses, the variables “DOC exports,” “precipitation,” and “specific discharge” were log-transformed to approximate normality. Before conducting the MLR analyses, cross-Pearson's correlations among explanatory variables were examined to assess multicollinearity (Dormann et al., 2013). Precipitation was excluded from the analyses as it was collinear with air temperature (Pearson's correlation $r = 0.82$) and specific discharge ($r = 0.84$). The relative contribution of each variable in the MLR was assessed using hierarchical variance partitioning (Chevan & Sutherland, 1991). MLR were performed for the entire data set as a first step, and then specifically for the nondisturbed and disturbed groups. To facilitate the interpretation of the MLR outputs, we constructed the prediction plot for a given explanatory variable whilst maintaining all other explanatory variables in the model either at their minimum or maximum values observed in the 62 reviewed peatland sites. This allowed us to visualize the predicted change in DOC exports along one factor over the range of observable values of the remaining factor(s) at peatland sites (Figure 3). Predicted values of DOC export were back transformed into their original scale using exponential.

3. Results and Discussion

3.1. Global Significance of Peatland DOC Export

Ninety percent of the 62 examined sites are located in the northern Hemisphere, especially in the northern boreal belt (Figure 1). This is in line with the most recent global peatland maps compiled by Xu et al. (2018), showing both the dramatic proportion of northern peatland at the earth's surface (Figure 2b) and also the poor number of studies in tropical sites (11 on the 62 previously listed). When considering all climatic contexts, almost half (48%) of the sites selected in this review are disturbed peatlands (Figure 2a). In the case of tropical peatlands, eight of the eleven studied sites are disturbed areas.

Globally, annual DOC exports from peatlands range from 1.4 to 94.8 g C m⁻² yr⁻¹ with an average of 24.4 ± 21.9 g C m⁻² yr⁻¹. DOC exports increase from cold to tropical climates (Figures 1 and 2). When considering both disturbed and undisturbed sites, boreal (mean 13.7 g C m⁻² yr⁻¹), temperate (mean 24.2 g C m⁻² yr⁻¹), and tropical (mean 57.9 g C m⁻² yr⁻¹) peatlands show significantly different DOC export distributions (Figure 2a KWT p -values <0.01).

Combining DOC export means from the three climatic areas with peatland areas from (Leifeld & Menichetti, 2018), the yearly global input from peatlands to surface water reaches 91 ± 54 Gg C. This is expected to be a conservative estimate, as exports from watersheds where peatlands are not dominant are not included. Although showing

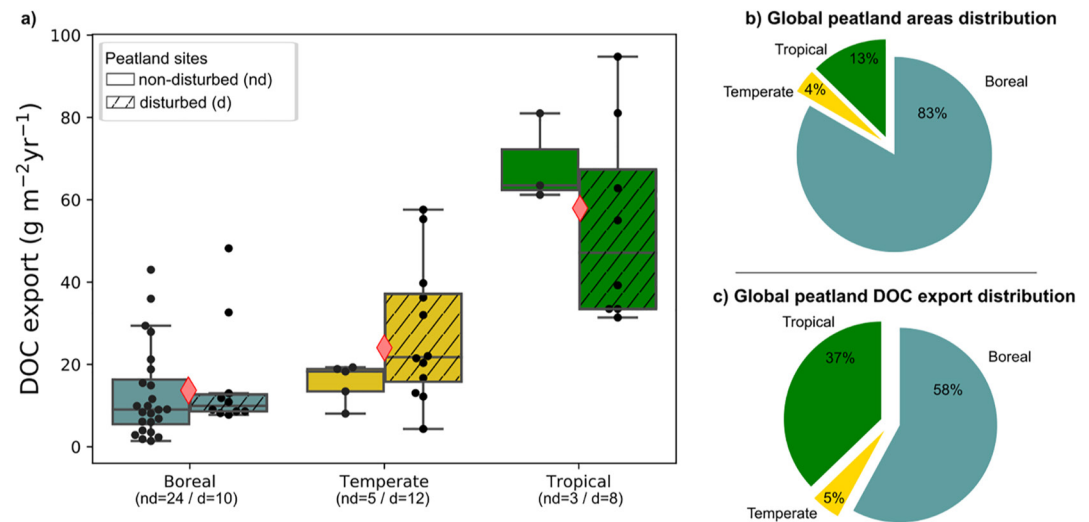


Figure 2. (a) Distribution of dissolved organic carbon (DOC) export estimates by climate for nondisturbed (nd) and disturbed (d) sites. The numbers of observations are reported under each boxplot. For each climate, a red diamond represents the DOC export average. The box plots display the median (middle line), the first and third quartiles (black box). The whiskers are the minimum and maximum values of DOC exports within the 1.5 interquartile range values. Outliers are values outside the 1.5 interquartile range values and are marked as diamonds. Jittered raw data points of DOC exports were superimposed as black dots. (b) Global peatland areas distribution according to the climatic definition of Leifeld and Menichetti, 2018. (c) Estimated global peatland DOC export distributions by climate.

the lowest specific fluxes, extended boreal peatlands are globally the main contributors of DOC to surface waters. Tropical peatlands, on the other hand, present the highest specific DOC fluxes and contribute disproportionately to fluvial export of organic carbon, with regards to their surface (Figure 2c).

The global carbon export from terrestrial to aquatic ecosystems is estimated from 1.9 to 5.1 Pg C yr⁻¹ (Abril & Borges, 2019; Cole et al., 2007; Drake et al., 2018). This includes both dissolved and particulate organic carbon, as well as inorganic carbon and dissolved gas. As the DOC fraction in this flux is unknown so far, it is impossible to evaluate the peatland contribution to this global flux. The global tDOC fluxes from lands to oceans have been estimated to be from 0.21 Pg for DOC (Ludwig et al., 1996; Meybeck, 1982) to 0.24 Pg C (Li et al., 2017). Comparing DOC export from peatlands to surface water to global tDOC export to the oceans requires estimating how much of the DOC exported from peatlands is mineralized or immobilized in sediments before reaching the ocean. This is mainly dependent on the water residence time and distance between the peatland and the ocean (Moody et al., 2013). These processes could be negligible in the case of coastal peatlands (Krachler et al., 2016; Martin et al., 2018) but much more important when peatlands are located far from the coasts. In Indonesia, Wit et al. (2015) estimated that $53.3 \pm 6.5\%$ of DOC was lost from peatlands to the ocean. More conservatively, Moody et al. (2013) quantified for the Tee river in England, that 48%–69% of DOC is mineralized or buried in sediment before reaching the coast. Applying these latter proportions to our global DOC export figure, we can estimate that from 28 to 47 TgC originating from peatlands as DOC could reach the ocean. This would represent 12%–20% of the global DOC fluxes reaching the oceans according to Li et al. (2017), for 2.84% of land surface (Xu et al., 2018). This estimate is certainly conservative. Recent publications have highlighted the limited biodegradability of DOC originating from peatlands, in different contexts, from boreal peatlands (Shirokova et al., 2019) to tropical peatlands (R. S. Nichols and Martin, 2021).

3.2. Impact of Anthropogenic Disturbances on Peatland DOC Exports

Among the 62 peatland DOC exports considered in this review, almost half of them ($n = 30$) are reported from disturbed sites. No significant difference in DOC exports is observed between disturbed and undisturbed sites within each climatic zone (Figure 2a). However, considering the complete data set, DOC exports from disturbed

Table 1
MLR Models Explaining DOC Exports From Peatlands

Response variable	Data set	Number of observations	Multiple R ² (adjusted R ²)	Reduced models			
				Coefficients	Predictors	p-value	R ² contribution
DOC exports (logarithm)	Complete data set	47 (Boreal = 25, Temperate = 11, Tropical = 11)	0.80 (0.79)	0.67 ± 0.09	Air temperature	<0.001	0.48
				0.25 ± 0.09	Specific discharge (logarithm)	0.004	0.25
				0.10 ± 0.07	Anthropogenic disturbance (Boolean)	0.166	0.07
	Nondisturbed	22 (Boreal = 17, Temperate = 2, Tropical = 3)	0.81 (0.79)	0.10 ± 0.01	Temperature	<0.001	0.66
				0.05 ± 0.12	Specific Discharge (logarithm)	0.668	0.15
	Disturbed	25 (Boreal = 8, Temperate = 9, Tropical = 8)	0.89 (0.88)	0.03 ± 0.01	Temperature	<0.001	0.37
0.77 ± 0.11				Specific Discharge (logarithm)	<0.001	0.52	

Note. Adjusted R² of each model are given as the predictors and their associated coefficients, p-values and R² contribution.

sites are significantly higher (WMWt p-value = 0.005) than those from undisturbed sites, showing means of 30.7 ± 23.1 and 18.5 ± 19.3 g C m⁻² yr⁻¹ respectively.

Multiple linear regression analysis was performed for the 47 sites (disturbed = 25 vs. non-disturbed = 22) where all the descriptors (air temperature, precipitation, discharge, and anthropogenic disturbance) were available. Considering the complete data set available (disturbed and non-disturbed), both air temperature and specific discharge appeared as significant predictors of peatland DOC export ($R^2 = 0.78$) (Table 1). First, DOC export variability is mainly controlled by air temperature (~66%), in agreement with the climatic gradient evidenced by Evans et al. (2016). Our MLR shows that we can include specific discharge as a significant predictor of DOC export variability, skipping auto correlation biases for precipitation. Moreover, while precipitation is a purely climatic descriptor, specific discharge is a descriptor influenced by both climatic variability and DOC transfer processes within peatland sites. This agrees with several plot scale studies showing that the temporal variability of peatland DOC export could be explained by discharge variability (Köhler et al., 2008; Leach et al., 2016; Rosset et al., 2019). Then, for a given specific discharge, higher DOC exports are associated to higher air temperature. Air temperature has been widely identified as a driver of higher DOC concentrations in peatlands, in relation to enhanced vegetation and microbial activities (M. F. Billett et al., 2006; Clark et al., 2009; Pastor et al., 2003). Restricting the data set to nondisturbed sites does not change the model behavior. Air temperature still explains most of DOC export variability between sites ($R^2 = 0.7$) (Table 1).

Considering only the disturbed sites in the statistical model shifts the main driver to the outlet discharge. In this review, 60% of the disturbed sites had experienced drainage alterations. Human activities influence DOC exports from peatlands mainly by modifying their hydrological regime (Evans et al., 2016; Holden, 2005; Moore et al., 2013). Specific discharge measured at the outlet of peatland integrates much of the anthropogenic impact on peatland functioning and consequently appears to be a powerful predictor of the DOC export variability (R^2 contribution 0.52) at disturbed peatland sites, while this is not the case for nondisturbed sites. Nondisturbed peatlands are dominated by saturation excess overland flows occurring at the peat surface (Holden & Burt, 2003) with limited contact with the DOC productive layer. In disturbed peatland, subsidence and alteration of the peat structure induce higher DOC concentrations as well as water draining deeper peat layers (Strack et al., 2008; Wallage et al., 2006; Zhong et al., 2020). Then specific discharge and DOC export are more closely related in disturbed sites.

This shift in variable importance between disturbed and nondisturbed peatlands highlights the fact that global change may affect peatlands differently in terms of DOC exports (Figure 3). For a given air temperature (Figure 3a), the DOC export increase with discharge is likely to increase more strongly in disturbed peatlands compared to nondisturbed peatlands. The opposite behavior is foreseen for a given specific discharge, that is, DOC export increase with air temperature will be lower at disturbed sites compared to non-disturbed sites.

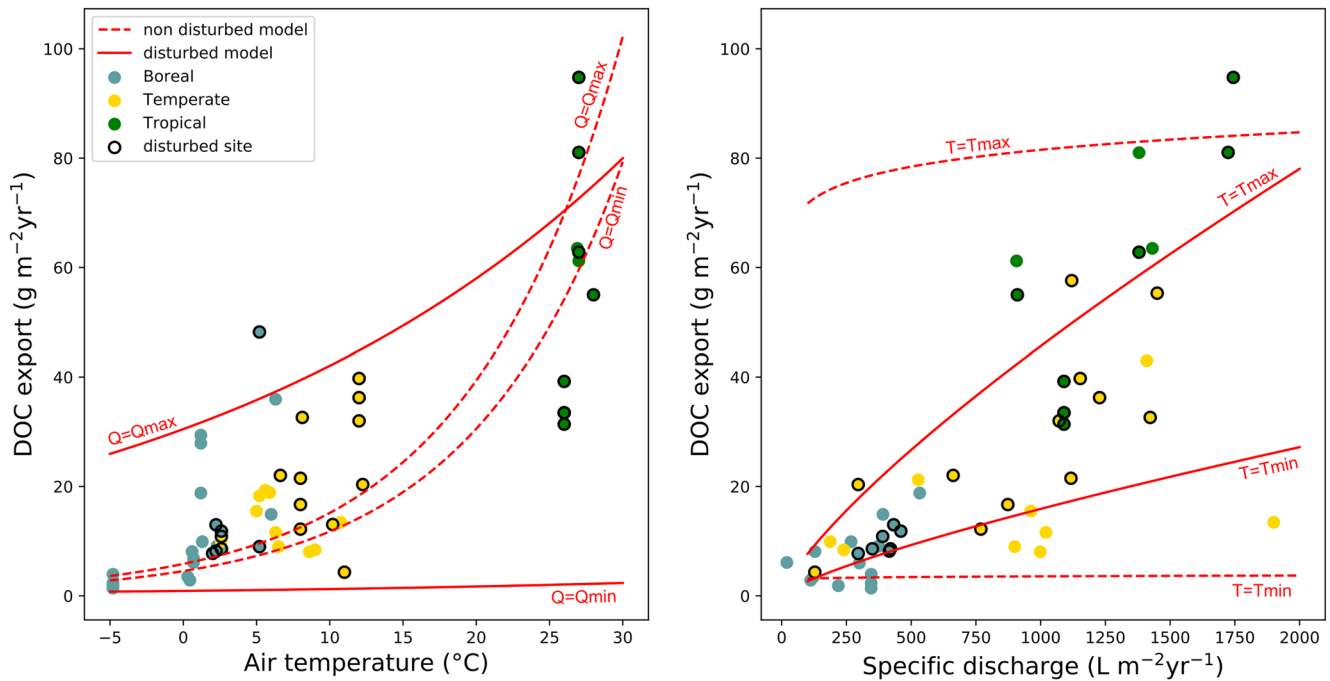


Figure 3. Prediction plots of the annual dissolved organic carbon (DOC) export from peatlands at the global scale depending on their degree of human disturbance. Predicted values of annual DOC export were back transformed into their original scale using exponential. In (a), models were defined by fixing mean annual specific discharge (Q) to the minimum (Q_{\min}) and the maximum (Q_{\max}) of the mean annual specific discharge observed in the 62 peatland sites reviewed. In (b), models were defined by fixing mean annual air temperature (T) to the minimum (T_{\min}) and the maximum (T_{\max}) of the mean annual air temperature observed in the 62 peatland sites reviewed.

Given that climate change will affect both precipitation and temperature (Almazroui et al., 2020; Scoccimarro et al., 2016), the future evolution of DOC exports is difficult to assess.

However, assumptions can be made on the expected responses by climate zones. Boreal and Arctic peatlands are severely threatened by intense climate change (Hugelius et al., 2020; Turetsky et al., 2020). At high latitude, permafrost peatland thaw might induce an increase in DOC fluvial exports (Frey & Smith, 2005; Olefeldt & Roulet, 2012). According to our study, air temperature increase will be the main driver of DOC export change for these ecosystems in the near future. We can expect that the combination with a longer vegetation period will increase fluvial organic carbon export from boreal peatlands. Tropical peatlands are widely disturbed by drainage, especially in Southeast Asia (Hoyt et al., 2020). In this area, a higher increase in DOC export is expected in relation to direct anthropogenic impact. The mobilization of old carbon from deep layers of peatlands has been evidenced in relation to drainage (Moore et al., 2013), whereas this phenomenon is expected to be lower at higher latitude (Evans et al., 2014).

Strong international commitment and policy efforts are needed to manage practices and restoration efforts at local and global scales to mitigate any positive hydrological offsets at peatland sites. Restoration practices based on water table rise have been shown to be effective in reducing fluvial carbon losses by disturbed peatlands (Kritzberg et al., 2020; Menberu et al., 2017).

3.3. Future Direction for Fluvial Organic Carbon Export by Peatland Studies

This fluvial carbon data set does not adequately represent the worldwide peatland distribution, as northern high latitudes and especially European peatlands largely dominate the 62 peatland sites reported in this study. For tropical peatlands, only Southeast Asia is represented. The inclusion of data from massive tropical peatland complex in the Congo Basin and Amazonia might modify the global estimate of DOC exports from tropical peatlands. Crucial data are missing not only from tropical peatlands, but also from the lowlands from central Siberia,

Patagonia or Mountain peatlands. The lack of field measurements in these regions has already been reported as an important issue in understanding environmental processes at a large geographical scale (Metcalf et al., 2018; Rocchini et al., 2011; Stropp et al., 2016). This study attempts to quantify DOC exports at the global scale despite these gaps in the data. It aims at raising awareness in the peatland scientific community on the need to report DOC exports from different regions across the globe. A first step would consist in initiating DOC export measurements at sites where GHG fluxes have already been assessed in order to complete peatland carbon balances at different latitudinal plots (Veber et al., 2018). Then, new projects should be conducted in montane (Hribljan et al., 2015) or tropical Amazonian and African peatlands (Dargie et al., 2017; Lähteenoja et al., 2009) to reduce the lack of knowledge about the carbon cycle in these regions where intense climate change and anthropogenic impacts are taking place (Beniston, 2006; Dargie et al., 2017).

The majority (54%) of DOC export estimates found in the literature were reported for entire watersheds and did not assess the specific contribution of peatland areas. This induces some uncertainty since non peatland areas of the watershed contribute to a different extent to DOC exports (Ågren et al., 2014; Laudon et al., 2011). Therefore, relevant DOC concentration and discharge monitoring has to be performed at locations closer to the outlet of peatlands. In the case of upstream hydrological connectivity (i.e., fen sites), at least the percentage of peatland cover and a second monitoring need to be performed at the main inlet of peatlands in order to disentangle the peatland DOC export contribution from the rest of the watershed (Olefeldt et al., 2013; Rosset et al., 2019; Urban et al., 1989).

In this study, peatlands were binary classified as disturbed or not disturbed following the information given in each publication. The listed human impacts referred to contemporary activities occurring during the last two decades before the DOC export estimations. However, as they are part of the environment, humans have always directly or indirectly impacted the natural functioning of ecological systems such as peatlands. Several paleo-ecological studies have reported grazing, logging or burning activities at peatland sites or the associated watershed for millennia (Rius et al., 2012; Sjögren et al., 2007). Hence, it is possible that peatlands considered here as nondisturbed may have been subject to unreferenced current or past human activities that still influence DOC exports nowadays. Further work should consist in ordering of classifying listed anthropogenic impacts by date and/or intensity to refine global trends. Currently, DOC export measurements for disturbed peatlands are too few and not similarly detailed from one site to another to establish a relevant statistical model about the impact of a specific human activity.

4. Conclusion

This study has confirmed that peatlands are key ecosystems regarding fluvial organic carbon transfer from terrestrial to aquatic ecosystems with a yearly global input estimated to be 91 ± 54 Tg C. Despite their small coverage of land surface, peatlands worldwide are a significant carbon source in rivers and this value will help to constrain the global estimate of the organic carbon transfers from terrestrial to aquatic ecosystems. Even with conservative hypotheses of carbon degradation in rivers, peatlands could contribute from 12% to 20% of global tDOC transfer to the ocean.

This contribution depends strongly on the biomes where the peatlands are located. Boreal peatlands dominate global export fluxes because of their extensive surfaces, whereas tropical peatlands play an important role with intense specific fluxes. The investigation of environmental drivers of fluvial organic carbon exports from peatlands revealed distinct models for disturbed and non-disturbed peatlands. This highlights that future trends for these fluxes under climate change will depend on the peatland status. Temperature and specific discharge are strong predictors of DOC export variability at the global scale, but the ranking between these two drivers shifts for disturbed sites.

In undisturbed peatlands, the link between DOC export and air temperature confirms that peatland will release more fluvial organic carbon with global warming. The establishment of a strong link between DOC export and outlet discharge for disturbed peatlands emphasizes the crucial role of restoration projects in reducing outlet discharge in order to increase the carbon sequestration capabilities of peatlands. This study highlights the knowledge gaps for fluvial export from peatlands, especially in terms of the spatial coverage of published studies and advocates an acceleration of research efforts in the coming years.

Data Availability Statement

The peatland map on Figure 1 was created using the PEATMAP data: <https://doi.org/10.5518/252>. The data used for this compilation are available online: <https://doi.org/10.1594/PANGAEA.936695> and <https://doi.org/10.1594/PANGAEA.936702>.

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