Earth's Future

RESEARCH ARTICLE

10.1029/2023EF004137

Key Points:

- We predict an increase of global soil dissolved organic carbon (DOC) leaching of up to 42% or 395 Tg C yr^{-1} by 2100
- The sub-tropical zone experienced the greatest relative DOC leaching growth, while the tropics had a notable absolute increase
- The primary driver for the future surge in DOC leaching is the rising atmospheric CO_2 and its fertilizing effect on terrestrial NPP

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

M. (A.) Nakhavali,
nakhavali@iiasa.ac.at

Citation:

Nakhavali, M. (A.), Lauerwald, R., Regnier, P., & Friedlingstein, P. (2024). Predicting future trends of terrestrial dissolved organic carbon transport to global river systems. *Earth's Future*, *12*, e2023EF004137. https://doi.org/10.1029/2023EF004137

Received 25 SEP 2023
Accepted 1 MAR 2024

Predicting Future Trends of Terrestrial Dissolved Organic Carbon Transport to Global River Systems

Mahdi (André) Nakhavali[1], Ronny Lauerwald[2], Pierre Regnier[3], and Pierre Friedlingstein[4,5]

[1]International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, [2]Université Paris-Saclay, INRAE, AgroParisTech, UMR ECOSYS, Palaiseau, France, [3]Biogeochemistry and Modelling of the Earth System, Department Geoscience, Environment and Society, Université Libre de Bruxelles, Bruxelles, Belgium, [4]LMD/IPSL, ENS, PSL Université, École Polytechnique, Institut Polytechnique de Paris, Sorbonne Université, CNRS, Paris, France, [5]University of Exeter, College of Engineering, Mathematics and Physical Sciences, Exeter, UK

Abstract A fraction of CO_2 uptake by terrestrial ecosystems is exported as organic carbon (C) through the terrestrial-aquatic continuum. This translocated C plays a significant role in the terrestrial C balance; however, obtaining global assessments remains challenging due to the predominant reliance on empirical approaches. Leaching of dissolved organic C (DOC) from soils to rivers represents an important fraction of this C export and is assumed to drive a large proportion of the net-heterotrophy of river systems and the related CO_2 emissions. Using the model JULES-DOCM, we projected DOC leaching trends over the 21st century based on three scenarios with high (RCP 2.6), intermediate (RCP 4.5), and low (RCP 8.5) climate mitigation efforts. The RCP 8.5 scenario led to the largest DOC leaching increase of +42% to 395 Tg C yr^{-1} by 2100. In comparison, RCP 2.6 and RCP 4.5 led to increases of 10% and 21%, respectively. Under RCP 8.5, the sub-tropical zone showed the highest relative increase of 50% above current levels. In the boreal and tropical zones, the simulations revealed similar increases of 48% and 41%, respectively. However, given the pre-eminence of the tropics in DOC leaching, the absolute increment is markedly substantial from this region (+59 Tg C yr^{-1}). The temperate zone displayed the lowest relative increase with 35%. Our analysis identified the rising atmospheric CO_2 concentration and its fertilizing effect on terrestrial NPP as the main reason for the future increase in DOC leaching.

Plain Language Summary Terrestrial ecosystems absorb CO_2 and some of this is transformed into dissolved organic carbon (DOC) that leaches from soils to inland waters, driving aquatic CO_2 emissions. Using the JULES-DOCM model, we analyzed future DOC leaching trends under different climate scenarios. The scenario of low climate change mitigation led to the most significant leaching increase by the end of the century. Among various regions, the sub-tropical areas showed the greatest relative growth in DOC leaching, with the tropics also seeing a substantial rise. This increase in DOC leaching is mainly driven by rising atmospheric CO_2 levels, which boosts plant growth and productivity on land.

1. Introduction

The process of carbon (C) transfer from terrestrial vegetation and soils to river systems is crucial for ecological dynamics in both terrestrial and aquatic ecosystems (Aitkenhead & Mcdowell, 2000; Kalbitz et al., 2000). However, quantification of the carbon transfer from soils to rivers is complex and challenging. Traditional approaches have provided approximate estimations, typically derived from budget calculations (Battin et al., 2023; Drake et al., 2018; Regnier et al., 2022). These calculations often combine data on riverine C exports to coastal areas with estimates of CO_2 emissions from inland waters and carbon burial in aquatic sediments. Such methods, while informative, may not fully capture the intricate nature of carbon translocation processes across different ecosystems, in particular when the temporal variability needs to be resolved (Regnier et al., 2022).

Global estimates range between 1.9 and 3.1 Pg C yr^{-1} (Battin et al., 2023; Cole et al., 2007; Regnier et al., 2013; Tranvik et al., 2009), which is about 2%–5% of terrestrial NPP (Regnier et al., 2013). Overlooking the flux of terrestrial carbon (C) to rivers could lead to inaccuracies in predicting terrestrial C budget responses to anthropogenic CO2 emissions. This might result in an inflated estimate of C accumulation in soils or in soil heterotrophic respiration (Ciais et al., 2021; Lauerwald et al., 2020). Incorporating this flux into Earth System Models (ESM) is vital for enhancing the accuracy of global C cycle projections and its climate interactions, particularly under different representative concentration pathways (RCP) scenarios (Ciais et al., 2013). At the same time, an accordingly upgraded ESM would be the ideal tool to project future changes in lateral C exports from soils in response to global change, and its effect on the terrestrial C budget.

Leaching of dissolved organic carbon (DOC) from soils to rivers represents an important fraction of this C export, and is assumed to drive a large proportion of the net-heterotrophy of river systems and the related CO_2 emissions (Battin et al., 2008). As the soil organic carbon (SOC) is the main source of DOC in the soil, drivers that affect SOC are potential controls of the long-term evolution of the DOC leaching flux. These drivers are climate related, such as temperature (Freeman et al., 2001; Rind et al., 1990) and precipitation (Hongve et al., 2004), atmospheric CO_2 (Clair et al., 1999) and land-use change (Brye et al., 2001). In addition, the DOC leaching flux is strongly controlled by hydrology, which determines which fraction of the DOC in the soil column is exported with runoff, and which fraction of the DOC is left to be decomposed within the soil column.

Recently, we developed a process-based model, JULES-DOCM (Nakhavali et al., 2018) which simulates C budgets of terrestrial vegetation and soils, explicitly representing the cycling of DOC within the soil column and the leaching of DOC from the soil into the river network. This model has been successfully applied to obtain an estimate of present-day soil DOC stocks and DOC leaching fluxes at the global scale (Nakhavali et al., 2021) and to reconstruct the spatio-temporal evolution of the DOC leaching flux over the historical period (Nakhavali et al., 2024).

In this study, we use the model to project the spatio-temporal evolution of DOC leaching fluxes over the 21st century following the three RCPs, RCP 2.6 (Van Vuuren et al., 2007), RCP 4.5 (Clarke et al., 2007) and RCP 8.5 (Riahi et al., 2007). We analyze how DOC leaching will respond to the different aspects of global change, that is, increasing atmospheric CO_2 levels, climate change and land use change, and we localize the expected hotspots of future change in DOC leaching.

2. Materials and Methods

In order to study the future evolution of DOC leaching from soils at the global scale we used the newly developed extension of Joint UK Land Environment Simulator (JULES) (D. B. Clark et al., 2011) version 4.4, JULES-DOCM (Nakhavali et al., 2018). In JULES-DOCM, vegetation is represented by the TRIFFID model in nine distinct plant functional types (Harper et al., 2016) and soil C processes are defined by the RothC model (Jenkinson et al., 1990) down to three m, and SOC stocks are distributed over four soil layers (0–10 cm, 10–35 cm, 35–100 cm and 100–300 cm) assuming an exponential decay in concentration with depth (Jobbágy & Jackson, 2000). Various processes of DOC cycling, including production, decomposition, and ad/desorption, as well as the diffusion across different soil layers and the leaching of DOC to the river network, control the dynamics of soil DOC concentrations. The leaching flux (DOC_L) scales linearly to the concentrations:

$$DOC_L = \frac{S_{DOC} \times Q_R}{T_m}$$

where DOC_L is the DOC leaching flux (kg C m^{-2} $days^{-1}$), S_{DOC} is the DOC concentration (kg m^{-2}), Q_R is the rate of either surface or subsurface runoff (m day^{-1}), and T_m denotes the thickness of the relevant soil layer (m).

The model delineates this export flux differently for distinct soil depths: for the topsoil layer (0–35 cm), leaching is calculated based on surface runoff, while for the deeper soil layer (35–300 cm), it is calculated using subsurface runoff (for more detail see Nakhavali et al., 2018).

The calibrated global version of JULES-DOCM was tested successfully (Nakhavali et al., 2021) and used for studying the historical trend of DOC leaching for the historical period (1860–2010) (Nakhavali et al., 2024). Here we study the response of DOC leaching to future environmental changes, following three RCP scenarios (2.6, 4.5 and 8.5). The number for each RCP represents the increase in radiative forcing level from 1750 to 2100, as 2.6 W m^{-2}, 4.5 W m^{-2}, and 8.5 W m^{-2}. Each of these scenarios were produced by different Integrated Assessment Models: RCP 2.6 by the Integrated Model to Assess the Global Environment (Van Vuuren et al., 2007), RCP 4.5 by the MiniClimate Assessment Model (Clarke et al., 2007) and RCP 8.5 by the Model for Energy Supply Alternative and their General Environmental Impact (MESSAGE) (Riahi et al., 2007).

The RCP 2.6 scenario includes the highest level of mitigation. This scenario considers the lowest energy use and dependency on fossil fuels, assumes the highest shift in energy supply to biofuels and high advances in

10.1029/2023EF004137

Table 1
Historical and Future C Fluxes and Stocks

	Average1860s	Average2000s	Average2090s		
	Historical		RCP 2.6	RCP 4.5	RCP 8.5
Avg. NPP (Pg C/yr)	69	83	89	104	138
Avg. RESP (Pg C/yr)	69	81	88	101	130
Avg.DOC LCH(Pg C/yr)	0.24	0.27	0.31	0.34	0.4
Avg. SOC (Pg C)	900	955	993	1,062	1,181
Avg. DOC (Pg C)	0.2	0.255	0.27	0.275	0.289

technologies regarding C capture and storage, which result in a CO_2 emission reduction. Hence the atmospheric CO_2 reaches 443 ppm in 2050 and decreases down to 421 ppm in 2100. The RCP 4.5 is the intermediate scenario which relies more on fossil fuels compared to RCP 2.6, but considers some sources of cleaner energy and possibility of C capture and storage. In this scenario, the atmospheric CO_2 is at 487 ppm in 2050 and will reach 538 ppm by 2100. The RCP 8.5 scenario represents a lack of mitigation before 2100 and the lowest advances in C capture and storage technologies. It includes the highest dependency on fossil fuels and highest level of CO_2 emission resulting in the accelerated increase in atmospheric CO_2 from 541 ppm in 2050 to 936 ppm in 2100 (Moss et al., 2010).

In terms of forcing for JULES-DOCM, we used the climate forcing for historical (1860–2005) and future (2006–2100) period following three RCP scenarios (2.6, 4.5, and 8.5) produced by the HadGEM2-ES model (Martin et al., 2011) at N96 resolution (1.875° longitude × 1.25° latitude). We prescribed the land use change using cropland and pasture cover data from HYDE version 3.1 (Klein Goldewijk et al., 2011) for the historical period, and according to each RCP scenario for the future. The JULES-DOCM model captures LUC impacts on terrestrial C cycling, tracing the influence from vegetation cover alterations on plant productivity to changes in Gross Primary Production (GPP) and NPP (Burton et al., 2019), subsequently affecting SOC and DOC production, decomposition, and leaching (Nakhavali et al., 2024) (see Figure S1 in Supporting Information S1). Atmospheric CO2 forcing was taken from historical observations (Dlugokencky & Tans, 2013) and directly from the RCPs for the future (Meinshausen et al., 2011).

In order to start transient simulations from pre-Industrial SOC and DOC pools in a steady state, we used the accelerated spin-up method in JULES (Harper et al., 2016), explained in our historical study (Nakhavali et al., 2024). The initial condition for the transient simulation over the historical period was defined by the final outputs of the spin-up. For each of the RCP scenarios, we ran the model over the whole simulation period from 1860 to 2100, collating historical and the respective future climate forcing data. All results were analyzed for temporal trends based on 10 years running means.

Finally, in order to study the atmospheric CO_2 influence and its fertilization effect on terrestrial NPP and DOC leaching flux, we ran the simulation with deactivated atmospheric CO_2 change for all three future scenarios, while the other changes were kept activated. Additionally, to study land use change impact on DOC leaching flux, we ran a simulation with deactivated land use change for all three scenarios. The impact of land use change was then calculated as the difference transient run (S_{ALL})- land use deactivated run (S_{LUC}), and atmospheric CO_2 increase as S_{ALL}-deactivated atmospheric CO_2 change run (S_{CO2}).

3. Results and Discussion

3.1. Current C Pools and Fluxes

Our present-day averaged global GPP was estimated at 122 Pg C yr^{-1}, which is marginally greater than the MTE's 118 ± 6 Pg C yr^{-1} benchmark (Jung et al., 2009) (Table 1) and estimated global NPP averaged at 83 Pg C yr^{-1}, significantly surpassing the MODIS-17's estimate of 54 ± 9 Pg C yr^{-1} (Zhao et al., 2005). However, our SOC stock estimation presented a deficit, coming in at 955 Pg C, about one fourth below HWSD's estimate of 1,263 Pg C (Nachtergaele et al., 2010). This shortfall can be attributed to the omission of peatlands and organic soils in current model version, which collectively account for approximately 20% of the SOC stocks found in the

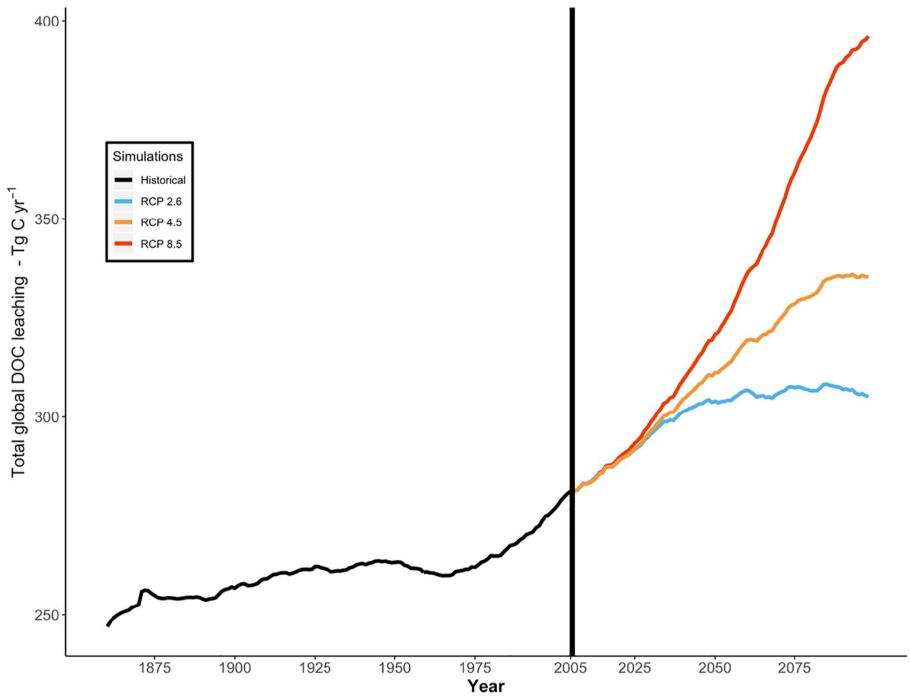

Figure 1. Historical and future dissolved organic carbon leaching.

HWSD and are significant sources of organic matter (Leifeld & Menichetti, 2018). This underscores the necessity of incorporating peatlands and organic soils to prevent underestimating SOC pools in subsequent studies.

The dynamics of present-day global DOC leaching flux have presented a flux rate of 277 Tg C yr^{-1} (Figure 1). This estimation delineates the major contributors by zones: the tropical zone imparting 142 Tg C yr^{-1}, followed by temperate at 56 Tg C yr^{-1}, the sub-tropical zones with 52 Tg C yr^{-1}, and the boreal zone's contribution was noted at 27 Tg C yr^{-1}. The specificity of these zones brings forth the differential carbon contributions and the potential impacts of varied regional ecosystems. In this study, utilizing HadGEM2-ES climate projections, the current flux deviates by less than 5% from our prior estimate grounded on CRU-NCEP climate forcing (Nakhavali et al., 2024). For clarity, a comparison between the Nakhavali et al. (2024) findings and the current ones is provided in Table 2. Notably, the present-day flux considerably exceeds the simulated flux for the pre-industrial period (1860s), at 243 Tg C yr^{-1}. Nevertheless, the influence and significance of each environmental factor (CO_2, climate, and land use change) on DOC leaching across different biomes has remained consistent in both historical and present-day conditions, as documented by Nakhavali et al. (2021, 2024).

Table 2
Dissolved Organic Carbon Leaching in Each Major Climate Zone

	Average 2000s		Average 2090s		
Averaged DOC leaching (Tg C yr^{-1})	Historical (HadGEM)	Historical (CRUNCEP)[a]	RCP 2.6	RCP 4.5	RCP 8.5
Global	277	292	306	335	395
Boreal zone	27	24	36	37	40
Temperate zone	56	49	63	67	76
Tropic zone	142	173	146	164	201
Sub-tropic zone	52	46	61	67	78

[a](Nakhavali et al., 2024).

3.2. Future Global Projections

The balance of terrestrial C is controlled by factors such NPP, heterotrophic respiration, and changes in land use (Chapin et al., 2006). To delve into the future patterns of soil DOC and its leaching to river systems, we first analyzed how NPP fluctuates under varying climate scenarios (Figure 2). Based on the RCP scenarios of 8.5, 4.5, and 2.6, we predicted NPP values of 138 Pg C yr^{-1}, 104 Pg C yr^{-1}, and 89 Pg C yr^{-1} respectively for the average period of the 2090s (Figure S2 in Supporting Information S1). There is a significant association between historical increases in DOC leaching and terrestrial NPP (Guo et al., 2020; Nakhavali et al., 2024). Consistent with this, future DOC leaching patterns correlate robustly with NPP across all scenarios (with an r^2 value of 0.8) (Figure S3 in Supporting Information S1). This is in line with previous empirical research which indicates a strong reliance of soil carbon levels on NPP (Todd-Brown et al., 2013). Our analysis suggests that the predominant driver for the global increased in NPP is the elevated atmospheric CO_2 and its associated fertilization. Consequently, simulations that isolate atmospheric CO_2 changes reveal a decline across all RCP scenarios leading up to 2100 (Figure S4 in Supporting Information S1). Crucially, while there was a decline in NPP, the forest biomass actually experienced an increase. This seemingly contradictory outcome can be better understood as a delayed effect of a prior increase in NPP and the lag in response which is attributed to the prolonged turnover time of tree biomass (Cao & Woodward, 1998).

Primary DOC is derived from incomplete decomposed SOC, indicating that parts of the original organic material remain in a state that can be solubilized and transported within and out of the soil matrix (Kalbitz et al., 2000). To gain a deeper understanding of this relationship, we delved into the variations in SOC as it responds to changes in NPP and examined these dynamics under various scenarios. The global SOC stock increased by 4%, 11% and 23% using RCP 2.6, 4.5, and 8.5, respectively which is driven by litterfall changes following the NPP changes.

The SOC shows a low relative increase when compared to NPP, which can be attributed to the enhanced decomposition of SOC under increased temperatures (Sitch et al., 2015). When we delve into the rates of soil respiration, they are conspicuously high (Table 1), and this trend persists across all scenarios (Figure S5 in Supporting Information S1). The decomposition rate of SOC is primarily influenced by two factors: temperature and moisture (Nakhavali et al., 2021). In future climatic conditions, as temperatures rise in future scenarios, rapid decomposition processes prevent the captured C from being accumulated in the soil for extended periods (Muñoz-Rojas et al., 2013). This increased decomposition rate subsequently leads to higher soil respiration, therefore even though there is an increase in NPP, the actual increase in SOC accumulation is less pronounced (Davidson et al., 2006).

In a parallel trend, DOC stocks have also seen a discernible increase (Table 2). Specifically, under the RCP 2.6, 4.5, and 8.5 scenarios, there was an increase in DOC stocks by 6%, 8%, and 13%, respectively. This rise in DOC stocks can be primarily attributed to the fluctuations in SOC stocks (Camino-Serrano et al., 2017). Therefore, the differing decomposition rates and soil respiration patterns inherently affect the DOC levels which results in comparable trends in DOC stock variations across the different RCP scenarios, mirroring those seen with SOC.

Our simulations project the most pronounced global increase in DOC leaching at 43% under the RCP 8.5 scenario, leading to an average flux of 395 Tg C yr^{-1} for the 2090s. Conversely, the RCP 4.5 and RCP 2.6 scenarios predict more moderate increases of 22% and 10%, with respective projected fluxes for the 2090s at 335 Tg C yr^{-1} and 306 Tg C yr^{-1}. While our analysis indicates a correlation between precipitation changes and DOC leaching across different scenarios, as suggested by a correlation coefficient (R^2 value: 0.8) shown in Figure S6 in Supporting Information S1, it is important to note that the linear model may not fully capture the complexity of the interaction between precipitation and DOC leaching. Particularly, it is observed that at very high precipitation rates, the relationship deviates from linearity, suggesting a limitation in DOC leaching under these conditions. This deviation highlights the non-linear dynamics of DOC leaching in response to extreme precipitation, which could be attributed to a substrate limitation that only becomes significant at very high runoff (Gommet et al., 2022; Nakhavali et al., 2021).

In our model, soil moisture emerges as a crucial factor influencing DOC production. Moreover the soil's water balance, determined by factors like precipitation and drainage, is pivotal in setting the soil DOC concentration (Lauerwald et al., 2017). It is important to recognize that the JULES DOCM employs the TOPMODEL hydrological framework, with a primary focus on the variability of soil moisture and the influence of topography on runoff (Clark & Gedney, 2008).

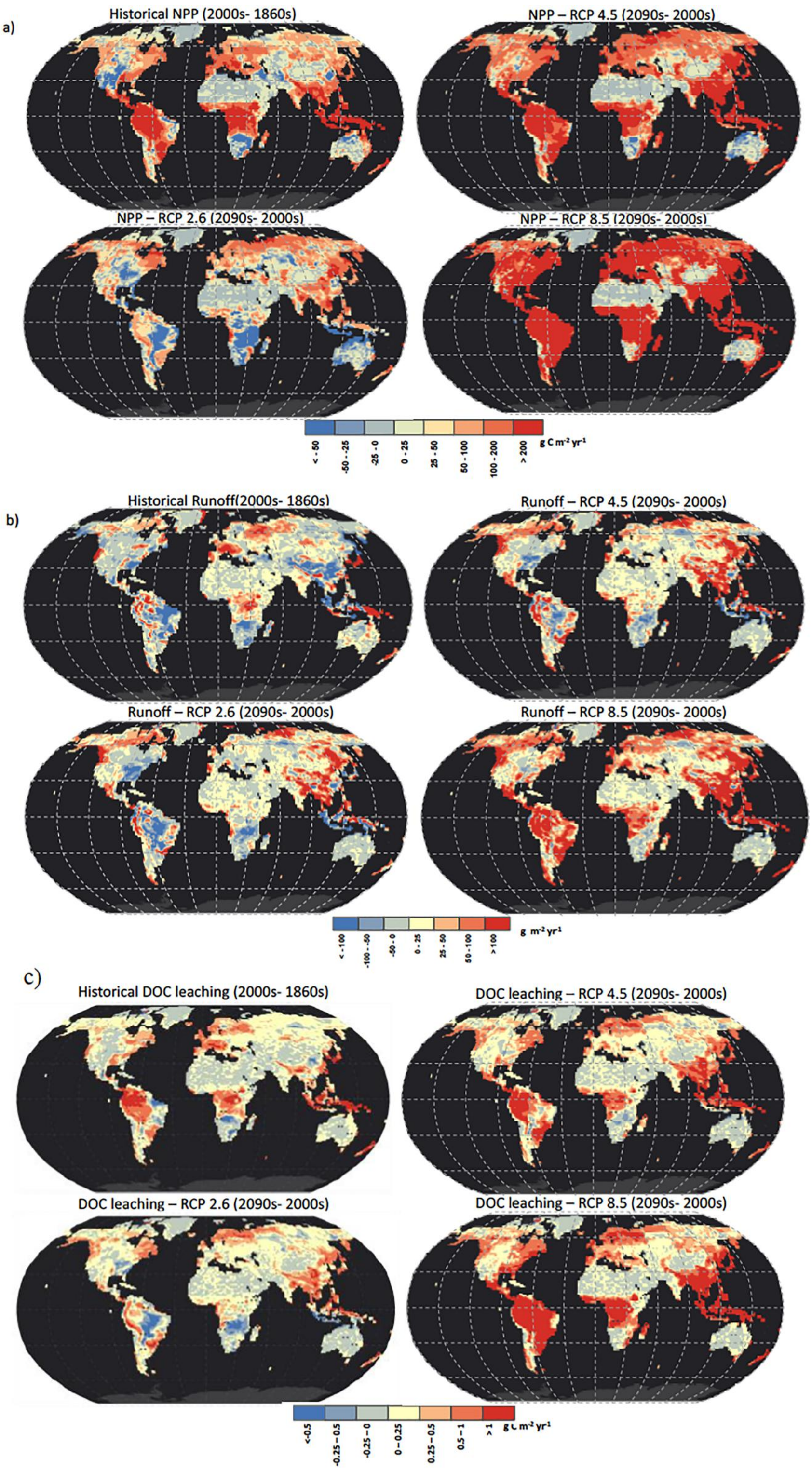

Figure 2. Historical and future prediction of changes in panels (a) NPP (g C m^{-2} yr^{-1}), (b) runoff (g m^{-2} yr^{-1}), and (c) dissolved organic carbon leaching (g C m^{-2} yr^{-1}).

However, this model does not adequately address critical geological factors, such as the hydrogeology and lithology of the catchment which can significantly impact the soil properties and hydrological processes (Covington et al., 2023; Virto et al., 2018). Most importantly, we do not account for effect of soil carbonates and pH of soil DOC cycling, although those have been found in empirical studies (see discussion in Rowley et al., 2018). Consequently, to enhance the model's precision in predicting DOC cycling, future enhancements should integrate more detailed information on soil chemistry and mineralogy. Furthermore, the precipitation is a crucial factor for runoff generation, which subsequently influences the transport of DOC from soil to river systems (Nakhavali et al., 2018).

Our analysis demonstrates that the relationship between precipitation and DOC leaching is more pronounced than the relationship between runoff and DOC leaching (Figure S7 in Supporting Information S1). This stronger correlation is largely due to the increase in soil DOC concentration, which is influenced by several factors, including soil moisture, directly affected by precipitation (Nakhavali et al., 2018). It's important to note that precipitation also influences evapotranspiration (ET), which in turn affects NPP and the availability of organic substrates for leaching (Li & Qin, 2019; Liu et al., 2021). Consequently, higher precipitation levels are more closely associated with increased DOC leaching, owing to the elevated availability of substrates, both from increased soil moisture and changes in NPP driven by ET.

On the other hand, the relationship with runoff illustrates a shift from being limited by transport to being limited by substrate availability (Nakhavali et al., 2021). Although there is an occurrence of higher runoff, this does not straightforwardly lead to a proportional increase in DOC leaching, as runoff is more or less equal to precipitation minus ET. This observation points to a threshold at which the availability of DOC becomes a more critical factor than its transport capacity in determining the extent of leaching processes.

However, it's worth noting that the correlation between runoff and DOC leaching remains stable across both historical data and future projections. Nevertheless, it is crucial to consider the substantial uncertainties in both the extent and global patterns of precipitation changes when interpreting these findings. Due to factors like model design and the unpredictability of natural phenomena, climate models inherently possess uncertainties (Wu et al., 2022). These models predict a rise in extreme precipitation events, predominantly in humid regions, yet this varies significantly based on local climatic conditions (Easterling et al., 2017; Tabari, 2020). Predictions are most reliable for higher latitudes and arid areas, whereas simulations for tropical areas tend to be less precise (Gründemann et al., 2022). While projections indicate that higher latitudes might experience increased precipitation and subtropical areas might become drier, the level of certainty in these predictions, especially for mid-latitude areas like the United States, remains notably high (Easterling et al., 2017).

At the global scale, the spatial pattern of changes in runoff (Figure 3b) coincides with those of changes in NPP (Figure 3a) which leads to strong hotspots of increase in DOC leaching (Figure 3c), which is consistent with the environmental factors controlling fluvial C exports to river systems (Lauerwald et al., 2020). As for the historical result, regions that are hotspots of DOC leaching include SE Asia, the Amazon basin, New-Zealand, Western Europe, and large portions of the Eastern part of North America. These patterns are similar between RCP 2.6 and historical with decrease in Africa and amazon basin and increase in China. Nevertheless, RCP 4.5 and 8.5 shows the similar patterns of increase, where the increase in West Russia, Amazon basin and East US is larger in RCP 8.5.

We calculated the ratio of DOC leaching flux to NPP. Comparing with studies conducted in Europe, where this ratio is observed to be around 1% (Gommet et al., 2022; H. Zhang, Lauerwald, Regnier, et al., 2022), our findings indicate a relatively stable trend, with ratios of 0.34%, 0.32%, and 0.28% for the RCP 2.6, 4.5, and 8.5, respectively, from the present day to the end of the 21st century. However, it is noteworthy that our calculated ratios are considerably lower than the 2% increase previously estimated for the tropical zone (Hastie et al., 2021). Nevertheless, the percentage of leached NPP for RCP 4.5 and 8.5 has decreased. This is due to the long residence times in biomass and SOC and later effect of decomposition and leaching (Hensgens et al., 2020).

Finally, we simulated the DOC leaching flux with deactivated land-use change for all three RCP (Figure 4). Additionally, we also run our model with deactivated atmospheric CO_2 change for all future scenarios (Figures S4–S8 in Supporting Information S1). Results from RCP 2.6 scenario runs using fixed land use change showed no major difference from runs with fixed land use setup for period 2090 to 2099. However, CO_2 fertilization has the largest impact on DOC leaching flux (70 Tg C yr^{-1}). Similar to RCP 2.6, results from RCP 4.5 showed no significant impact of land use change, but a main controlling impact CO_2 increase on DOC leaching (98 Tg C yr^{-1}). Results from RCP 8.5 for period 2090 to 2099 showed a positive impact of both CO_2 fertilization and land-use change, with a main controlling impact of CO_2 fertilization (171 Tg C yr^{-1}) and smaller impact of

10.1029/2023EF004137

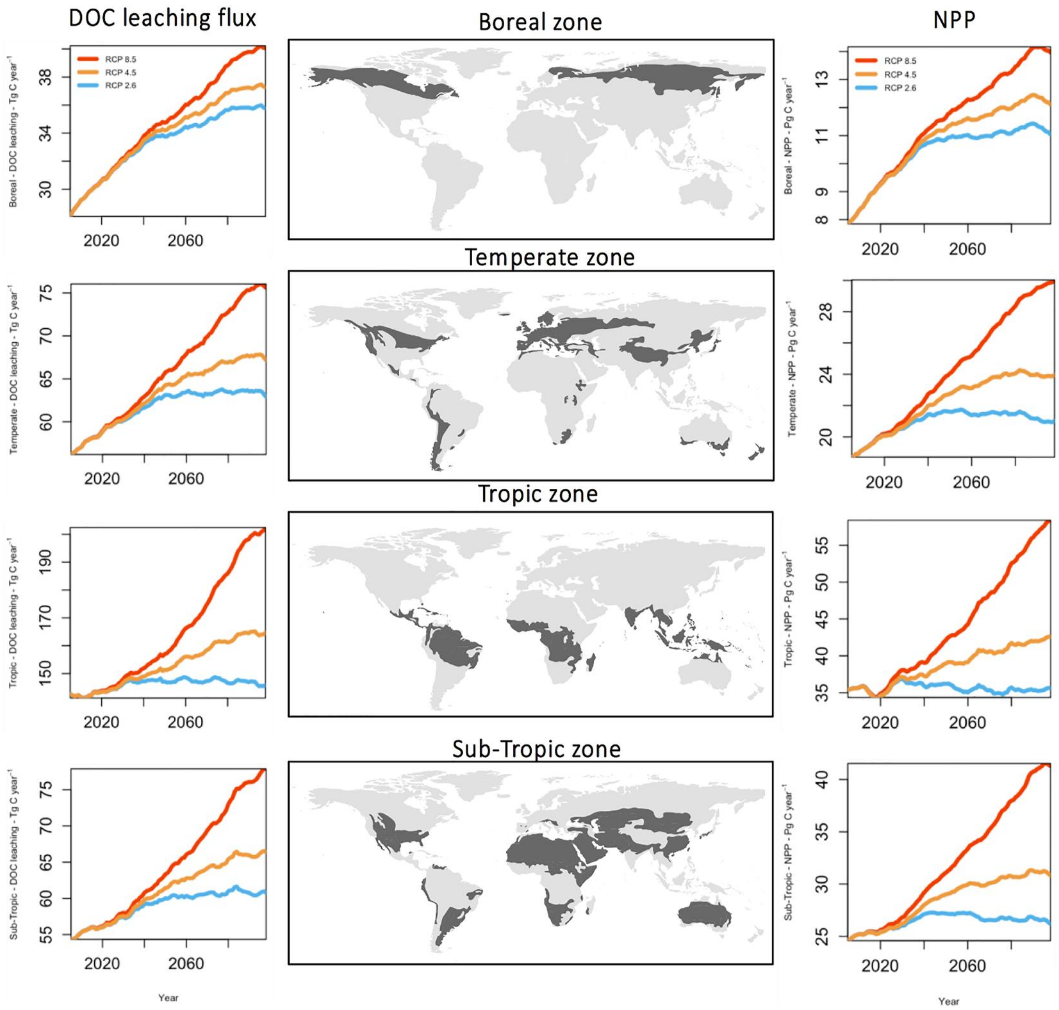

Figure 3. Future dissolved organic carbon leaching flux and NPP in each major climate zone.

land use change (4 Tg C yr^{-1}). However, the small increase in DOC from land use change is in line with our historical analysis (Nakhavali et al., 2024) and other empirical studies (Meybeck, 1993). Nevertheless, it is important to highlight that our current approach to land use change primarily focuses on updated vegetation cover driven by the competition among PFTs and does not encompass the soil biogeochemistry specific to wetlands. Wetlands are crucial, both as significant C stocks and in terms of their carbon accumulation rates (Botch et al., 1995). Additionally, land use impacts on these ecosystems have been shown to significantly contribute to their global decline (Dixon et al., 2016). Consequently, for a more accurate estimation of the effects of land use change on DOC leaching, future research should incorporate these ecosystems into the analysis.

Moreover, results indicate that atmospheric CO_2 change is the predominant factor influencing terrestrial NPP and DOC leaching flux across all three RCP scenarios for the period 2005–2100. Nevertheless, it is essential to recognize that factors such as land management and alteration in the terrestrial nitrogen cycle also play significant roles in modulating the CO_2 fertilization response of ecosystem C stocks (Fowler et al., 2013; Keenan & Williams, 2018; Pugh et al., 2019). However, the representation of these processes and their interactions with soil DOC cycling is yet to be developed in JULES-DOCM. The magnitude and persistence of CO_2-driven increases in terrestrial C storage remain a contentious topic, underscoring the prevalent uncertainties within process-based models which necessitate a thorough understanding of diverse processes and their interconnections at various scales, particularly in light of the global scope and long-term dynamics associated with increased atmospheric CO_2 and climate change (Walker et al., 2021). Historical analysis of environmental variables mirrors this trend,

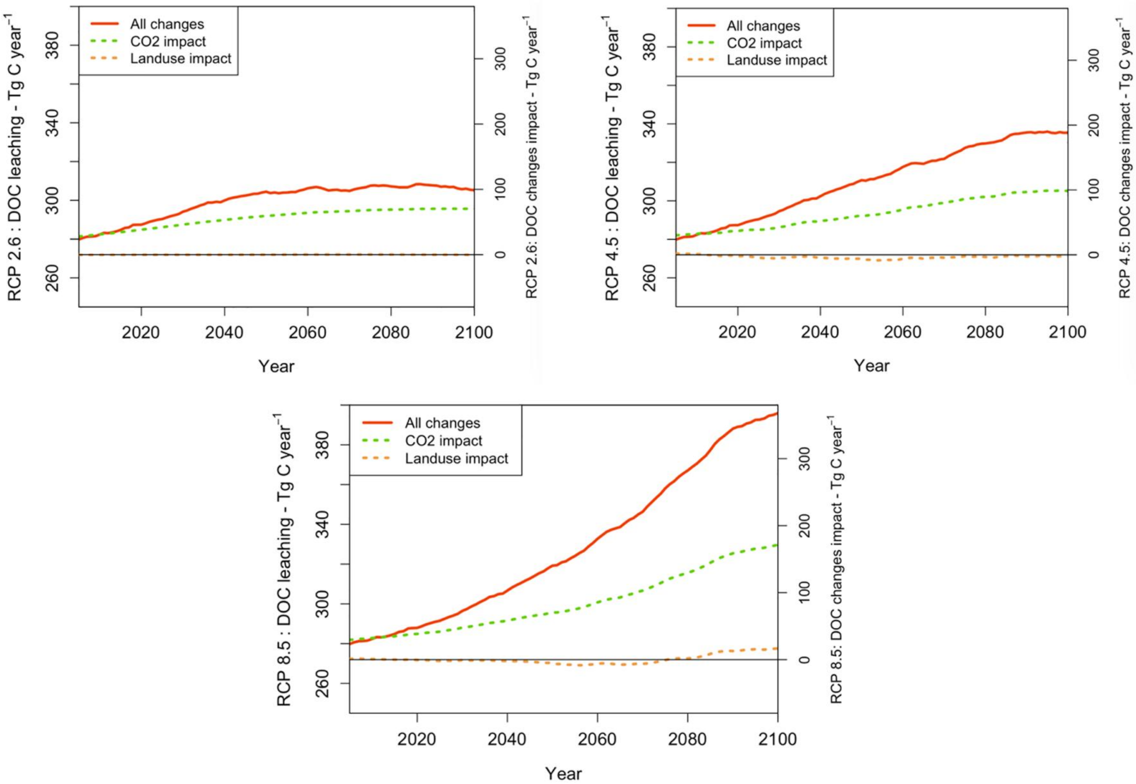

Figure 4. Dissolved organic carbon leaching controllers per three future scenarios.

with CO_2 fertilization effects predominantly impacting the rise in DOC leaching into European rivers (H. Zhang, Lauerwald, Ciais, et al., 2022).

However, when exploring the dynamics of SOC and DOC, it is crucial to differentiate between the unique behaviors in cropland-dominated and forested basins. Our model-based study only focusses on DOC leaching, while not representing SOC losses due to soil erosion. Soil erosion plays a more important role in removing C from cropland soils, where erosion is increased in particular during management-related periods of low vegetation cover and reduced soil infiltration capacity. Moreover, cropland soils often show decreased SOC stocks caused by reduced litter inputs through biomass outtake at harvest and increased SOC decomposition rates due to tillage (Oades et al., 1995; Weidhuner et al., 2021). Ultimately, the decreases in litter and SOC stocks may translate into decreases in production and leaching of DOC. In contrast, as shown by Wang et al. (2020), forested basins often show higher levels of riverine DOC, attributed to naturally higher SOC and DOC levels related to less perturbed litter and SOC stocks compared to agricultural areas. The representation of soil erosion and direct land management effects on soil C cycling in future versions of the JULES land surface model may thus allow for a more in-depth analyses of land use change effects on DOC leaching.

Nevertheless, it is essential to acknowledge that the JULES-DOCM model focuses solely on DOC, and thus does not encompass all pertinent processes of C transfers from soils to inland waters. This limitation is particularly evident in its exclusion of critical factors such as the erosional fluxes of soil and particulate organic carbon (POC), which are notably amplified when forested areas are transformed into agricultural land, thereby significantly affecting soil carbon budgets (Van Oost et al., 2012; Z. Wang et al., 2017). In this context, the recent studies by H. Zhang et al. (2020), H. Zhang, Lauerwald, Regnier, et al. (2022), and Lu et al. (2024), which integrates SOC erosion and deposition processes into their terrestrial C models, effectively capture the lateral movements of both DOC and POC. This enhancement not only improves the model's ability to account for the lateral transfer of carbon to river systems but also highlights an important gap in our current research. It underscores the need to incorporate these processes in future studies, thereby enabling a more comprehensive simulation and understanding of these lateral C losses from soils and their role in the terrestrial C budget.

Moreover, JULES-DOCM currently lacks representations of wetlands with organic soils and peatlands that are linked to the river network, which despite occupying a relatively small proportion of the Earth's total land area, play a crucial role as significant terrestrial C reservoirs (Blodau, 2002) and are an important source of DOC to inland waters (Billett et al., 2010). Globally, these wetlands may contribute ∼20% of riverine DOC loads (Nakhavali et al., 2021 based on Mayorga et al., 2010). Future trends in DOC leaching from organic soils may depend even more on changes in hydrology, as changes in soil carbon dynamics may be largely driven by changes in water table depth (Qiu et al., 2022). Moreover, soil C dynamics, including DOC leaching rates, of organic soils may more sensitive to land cover change (Qiu et al., 2021; Wit et al., 2015). Future work on the representation of organic wetland soils in JULES-DOCM will be necessary to assess the full impact of climate and land use change on DOC leaching to the river network.

3.3. Zonal Analysis

Our simulations revealed the highest relative increase in NPP within the boreal and sub-tropic zones, while the tropical zone showed the lowest increase (Figure 2). This pattern aligns with our findings for DOC leaching flux and reflects similar effect of the selected RCP across all four climate zones (Table 2).

In the boreal zone, estimates are 36 Tg C yr^{-1} (RCP 2.6), 37 Tg C yr^{-1} (RCP 4.5), and peak at 40 Tg C yr^{-1} (RCP 8.5). The temperate zone projections are 63, 67, and 76 Tg C yr^{-1} for RCPs 2.6, 4.5, and 8.5, respectively. In the tropical zone, the values escalate from 146 Tg C yr^{-1} (RCP 2.6) to 164 Tg C yr^{-1} (RCP 4.5) and reach 201 Tg C yr^{-1} under RCP 8.5. Finally, the sub-tropical zone sees a steady increase from 61 Tg C yr^{-1} (RCP 2.6) to 67 Tg C yr^{-1} (RCP 4.5), and up to 78 Tg C yr^{-1} for RCP 8.5.

When comparing the percentage increases across zones under RCP 8.5, the Sub-tropic zone experiences the highest increase in DOC leaching of 50%, followed by the Boreal zone with 48.2%, Tropics with 41.6%, and the Temperate zone with a 35.8% increase. Notably, the ranking of relative increase per climate zone remains consistent across all RCPs.

We delved deeper to identify the primary environmental drivers influencing DOC leaching flux variations across these distinct biomes and scenarios. For the boreal biome under RCP 8.5, a slight negative CO_2 effect suggests a limited role of CO_2 fertilization in enhancing NPP. However, a significant land-use change impact of −28% indicates a reduction in vegetation cover, subsequently leading to diminished productivity and more carbon available for leaching. This shift might further translate into a potential decrease in boreal forests, while in contrast, in sub-artic regions, a possible increase in tundra or even transitional forest zones (Xue et al., 2021). The dominant climate change impact of approximately 72% could be attributed to increased runoff events, boosting DOC leaching to rivers. RCP 4.5 shows a positive CO_2 effect of +8%, implying benefits from CO_2 fertilization on NPP. However, there's a minor negative impact of 6% from land-use change. Furthermore, land use change have altered both infiltration and ET rates, which subsequently influences runoff, a primary factor in CO_2 leaching (Piao et al., 2007). Significantly, the strong climate change effect of 98% to the total increase highlights the further emphasizes the crucial role of runoff. Finally, under RCP 2.6, a 9% positive CO_2 effect further accentuates the CO_2 fertilization's role. The climate change contribution remains substantial at 91%, reiterating the persistent influence of changing hydrology in this biome.

In the temperate zone RCP 8.5 exhibits a 26% positive CO_2 effect, pointing to the role of CO_2 fertilization in enhancing plant growth and NPP. A slight reduction due to land-use change implies minor forest cover reductions, slightly curbing productivity. The strong climate change effect of 78% indicates the prevailing influence of increased runoff. RCP 4.5 and RCP 2.6 both maintain the climate change impact around 86%, suggesting consistent runoff-driven dynamics irrespective of the atmospheric CO_2 concentrations and land-use changes. This is consistent with other modeling studies, such as the more detailed land-use incorporated DLEM model (Tian et al., 2015) and nitrogen (N) cycling representation (Yao et al., 2021), which emphasizes the dominant influence of climate variables followed by atmospheric CO_2 over historical periods, with a discernible negative impact from land use.

For the tropic zone RCP 8.5 forecasts a notable 58% CO_2 boost, highlighting the importance of CO_2 fertilization in augmenting NPP. The 14% positive land-use change indicates slight increased vegetation cover, further propelling productivity. Furthermore, our findings suggest that the CO_2 fertilization might play a role in the growth of the leaf area index and the acceleration of transpiration, leading to changes in runoff patterns (X. Zhang et al., 2022). Moving to RCP 4.5, the climate change effect jumps to 60%, emphasizing the increased significance of runoff dynamics, despite a decreased CO_2 benefit of 39%. Lastly, RCP 2.6 delineates a pattern where the climate's effect increases to 70%, indicating the rising influence of hydrological changes.

Lastly at the sub-tropic zone under RCP 8.5, the 40% positive CO_2 effect signals significant benefits from CO_2 fertilization. The slight uptick from land-use change suggests minor forest cover expansions, further fortifying productivity. However, the 59% climate change influence demonstrates the biome's pronounced vulnerability to changing precipitation and runoff patterns. Transitioning to RCP 4.5, the climate's impact rises to 69%, reinforcing the biome's sensitivity to climatic dynamics. RCP 2.6 further highlights this trend with a 77% climate change impact, illustrating the growing prominence of climate change effects over CO_2 and land-use dynamics. However, the pronounced sensitivity of the subtropic biome to climate change and the projected wetter climate aligns with the empirical findings of Yan et al. (2023).

4. Conclusion and Future Perspective

Our study offers a global assessment of future trends in DOC leaching into global river systems under various scenarios of future environmental change. Significant increases in DOC leaching have been projected across all examined scenarios, with the magnitude and regional distribution of these increases varying based on the specific pathway. Under the low mitigation scenario RCP 8.5, the simulated global increase in DOC leaching is highest, estimated at 43% from present-day, leading to an average flux of 395 Tg C yr^{-1} by the 2090s. Increases in DOC leaching are also projected under the RCP 4.5 and RCP 2.6 scenarios, though to a lesser extent compared to RCP 8.5. The subtropical zone is projected to experience the largest relative increase in DOC leaching compared to temperate zone, followed by the boreal and tropical zones. A significant absolute increase in the tropics has been highlighted, emphasizing the region's importance in the global carbon cycle.

The primary drivers of these changes have been identified as the rising atmospheric CO_2 concentration and its fertilization effect on terrestrial NPP, along with temperature-related increases in DOC production and decomposition rates, and alterations in runoff patterns. These factors are collectively contributing to the projected global increase in DOC leaching, highlighting the intricate interplay between climatic factors, the hydrological cycle and the carbon cycle.

The implications of these findings are significant for understanding the dynamics of the global C cycle, particularly in the context of ongoing climate change. Increased DOC leaching into river systems is expected to have profound effects on riverine ecosystems such as strengthening of net heterotrophy, browning of river waters (Battin et al., 2023) and the broader global C budget, including its anthropogenic perturbations. The need for incorporating lateral C exports in global C budget assessments has been underscored (e.g., Regnier et al., 2013, 2022). However, the exclusion of erosion-related losses of particulate C from soils and the lack of a comprehensive representation of organic soils and peatlands in the model remain areas for future development.

Data Availability Statement

Global calibrated version of JULES-DOCM and data which was modified for this paper can be found at: https://code.metoffice.gov.uk/svn/jules/main/branches/dev/mahdinakhavali/vn4.4_JULES_DOCM_GLOBAL_NAKHAVALI/ (registration is required).

Acknowledgments
The research leading to these results received funding from European Commission under the scope of the Forest Navigator project (grant agreement No: 101056875). P.F received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No: 821003 (4C project). RL received funding from the French state aid managed by the ANR under the "Investissements d'avenir" programme [ANR-16-CONV-0003].

References

Aitkenhead, J. A., & Mcdowell, W. H. (2000). Soil C:N ratio as a predictor of annual riverine DOC flux at local and global scales. *Global Biogeochemical Cycles*, *14*(1), 127–138. https://doi.org/10.1029/1999gb900083

Battin, T. J., Kaplan, L. A., Findlay, S., Hopkinson, C. S., Marti, E., Packman, A. I., et al. (2008). Biophysical controls on organic carbon fluxes in fluvial networks. *Nature Geoscience*, *1*(8), 95–100. https://doi.org/10.1038/ngeo602

Battin, T. J., Lauerwald, R., Bernhardt, E. S., Bertuzzo, E., Gener, L. G., Hall, R. O., et al. (2023). River ecosystem metabolism and carbon biogeochemistry in a changing world. *Nature*, *613*(7944), 449–459. https://doi.org/10.1038/s41586-022-05500-8

Billett, M. F., Charman, D. J., Clark, J. M., Evans, C. D., Evans, M. G., Ostle, N. J., et al. (2010). Carbon balance of UK peatlands: Current state of knowledge and future research challenges. *Climate Research*, *45*, 13–29. https://doi.org/10.3354/cr00903

Blodau, C. (2002). Carbon cycling in peatlands – A review of processes and controls. *Environmental Reviews*, *10*(2), 111–134. https://doi.org/10.1139/a02-004

Botch, M. S., Kobak, K. I., Vinson, T. S., & Kolchugina, T. P. (1995). Carbon pools and accumulation in peatlands of the former Soviet Union. *Global Biogeochemical Cycles*, *9*(1), 37–46. https://doi.org/10.1029/94gb03156

Brye, K. R., Norman, J. M., Bundy, L. G., & Gower, S. T. (2001). Nitrogen and carbon leaching in agroecosystems and their role in denitrification potential. *Journal of Environment Quality*, *30*(1), 58–70. https://doi.org/10.2134/jeq2001.30158x

Burton, C., Betts, R., Cardoso, M., Feldpausch, T. R., Harper, A., Jones, C. D., et al. (2019). Representation of fire, land-use change and vegetation dynamics in the Joint UK Land Environment Simulator vn4.9 (JULES). *Geoscientific Model Development*, *12*(1), 179–193. https://doi.org/10.5194/gmd-12-179-2019

Camino-Serrano, M., Guenet, B., Luyssaert, S., Ciais, P., Bastrikov, V., De Vos, B., et al. (2017). ORCHIDEE-SOM: Modeling soil organic carbon (SOC) and dissolved organic carbon (DOC) dynamics along vertical soil profiles in Europe. *Geoscientific Model Development Discussions*, 1–38. https://doi.org/10.5194/gmd-2017-255

Cao, M., & Woodward, F. I. (1998). Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change. *Global Change Biology*, *4*(2), 185–198. https://doi.org/10.1046/j.1365-2486.1998.00125.x

Chapin, F. S., Woodwell, G. M., Randerson, J. T., Rastetter, E. B., Lovett, G. M., Baldocchi, D. D., et al. (2006). Reconciling carbon-cycle concepts, terminology, and methods. *Ecosystems*, *9*(7), 1041–1050. https://doi.org/10.1007/s10021-005-0105-7

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., et al. (2013). Carbon and other biogeochemical cycles. In *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change* (pp. 465–570). Cambridge University Press.

Ciais, P., Yao, Y., Gasser, T., Baccini, A., Wang, Y., Lauerwald, R., et al. (2021). Empirical estimates of regional carbon budgets imply reduced global soil heterotrophic respiration. *National Science Review*, *8*(2). https://doi.org/10.1093/nsr/nwaa145

Clair, T. A., Ehrman, J. M., & Higuchi, K. (1999). Changes in freshwater carbon exports from Canadian terrestrial basins to lakes and estuaries under a 2xCO2 atmospheric scenario. *Global Biogeochemical Cycles*, *13*(4), 1091–1097. https://doi.org/10.1029/1999GB900055

Clark, D. B., & Gedney, N. (2008). Representing the effects of subgrid variability of soil moisture on runoff generation in a land surface model. *Journal of Geophysical Research*, *113*(D10). https://doi.org/10.1029/2007JD008940

Clark, D. B., Mercado, L. M., Sitch, S., Jones, C. D., Gedney, N., Best, M. J., et al. (2011). The Joint UK Land Environment Simulator (JULES), model description – Part 2: Carbon fluxes and vegetation dynamics. *Geoscientific Model Development*, *4*(3), 701–722. https://doi.org/10.5194/gmd-4-701-2011

Clarke, L. E., Edmonds, J. a., Jacoby, H. D., Pitcher, H. M., Reilly, J. M., & Richels, R. G. (2007). *Scenarios of greenhouse gas emissions and atmospheric concentrations* (Vol. 2011, p. 164). Program. https://doi.org/10.1002/yd.424

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., et al. (2007). Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems*, *10*(1), 172–185. https://doi.org/10.1007/s10021-006-9013-8

Covington, M. D., Martin, J. B., Toran, L. E., Macalady, J. L., Sekhon, N., Sullivan, P. L., et al. (2023). Carbonates in the critical zone. *Earth's Future*, *11*(1). https://doi.org/10.1029/2022EF002765

Davidson, E. A., Janssens, I. A., Marks, D., Murdock, M., Ahl, R. S., Woods, S. W., et al. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, *440*(7081), 165–173. https://doi.org/10.1038/nature04514

Dixon, M. J. R., Loh, J., Davidson, N. C., Beltrame, C., Freeman, R., & Walpole, M. (2016). Tracking global change in ecosystem area: The Wetland Extent Trends index. *Biological Conservation*, *193*, 27–35. https://doi.org/10.1016/j.biocon.2015.10.023

Dlugokencky, E., & Tans, P. (2013). Observed atmospheric CO2. http://www.esrl.noaa.gov/gmd/ccgg/trends

Drake, T. W., Raymond, P. A., & Spencer, R. G. M. (2018). Terrestrial carbon inputs to inland waters: A current synthesis of estimates and uncertainty. *Limnology and Oceanography Letters*, *3*(3), 132–142. https://doi.org/10.1002/lol2.10055

Easterling, D. R., Arnold, J. R., Knutson, T., Kunkel, K. E., LeGrande, A. N., Leung, L. R., et al. (2017). Ch. 7: Precipitation change in the United States. In *Climate science special report: Fourth national climate assessment* (Vol. I). https://doi.org/10.7930/J0H993CC

Fowler, D., Coyle, M., Skiba, U., Sutton, M. A., Cape, J. N., Reis, S., et al. (2013). The global nitrogen cycle in the twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *368*(1621), 20130164. https://doi.org/10.1098/rstb.2013.0164

Freeman, C., Evans, C. D., Monteith, D. T., Reynolds, B., & Fenner, N. (2001). Export of organic carbon from peat soils. *Nature*, *412*(6849), 785. https://doi.org/10.1038/35090628

Gommet, C., Lauerwald, R., Ciais, P., Guenet, B., Zhang, H., & Regnier, P. (2022). Spatiotemporal patterns and drivers of terrestrial dissolved organic carbon (DOC) leaching into the European river network. *Earth System Dynamics*, *13*(1), 393–418. https://doi.org/10.5194/esd-13-393-2022

Gründemann, G. J., van de Giesen, N., Brunner, L., & van der Ent, R. (2022). Rarest rainfall events will see the greatest relative increase in magnitude under future climate change. *Communications Earth & Environment*, *3*(1), 235. https://doi.org/10.1038/s43247-022-00558-8

Guo, Z., Wang, Y., Wan, Z., Zuo, Y., He, L., Li, D., et al. (2020). Soil dissolved organic carbon in terrestrial ecosystems: Global budget, spatial distribution and controls. *Global Ecology and Biogeography*, *29*(12), 2159–2175. https://doi.org/10.1111/geb.13186

Harper, A. B., Cox, P. M., Friedlingstein, P., Wiltshire, A. J., Jones, C. D., Sitch, S., et al. (2016). Improved representation of plant functional types and physiology in the Joint UK Land Environment Simulator (JULES v4.2) using plant trait information. *Geoscientific Model Development*, *9*(7), 2415–2440. https://doi.org/10.5194/gmd-9-2415-2016

Hastie, A., Lauerwald, R., Ciais, P., Papa, F., & Regnier, P. (2021). Historical and future contributions of inland waters to the Congo Basin carbon balance. *Earth System Dynamics*, *12*(1), 37–62. https://doi.org/10.5194/esd-12-37-2021

Hensgens, G., Laudon, H., Peichl, M., Gil, I. A., Zhou, Q., & Berggren, M. (2020). The role of the understory in litter DOC and nutrient leaching in boreal forests. *Biogeochemistry*, *149*(1), 87–103. https://doi.org/10.1007/s10533-020-00668-5

Hongve, D., Riise, G., & Kristiansen, J. F. (2004). Increased colour and organic acid concentrations in Norwegian forest lakes and drinking water – A result of increased precipitation? *Aquatic Sciences*, *66*(2), 231–238. https://doi.org/10.1007/s00027-004-0708-7

Jenkinson, D. S., Andrew, S. P. S., Lynch, J. M., Goss, M. J., & Tinker, P. B. (1990). The turnover of organic carbon and nitrogen in soil. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *329*(1255), 361–368. https://doi.org/10.1098/rstb.1990.0177

Jobbágy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, *10*(2), 423–436. https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2

Jung, M., Reichstein, M., & Bondeau, A. (2009). Towards global empirical upscaling of FLUXNET eddy covariance observations: Validation of a model tree ensemble approach using a biosphere model. *Biogeosciences Discussions*, *6*(3), 5271–5304. https://doi.org/10.5194/bgd-6-5271-2009

Kalbitz, K., Solinger, S., Park, J.-H., Michalzik, B., & Matzner, E. (2000). Controls on the dynamics of dissolved organic matter in soils: A review. *Soil Science*, *165*(4), 277–304. https://doi.org/10.1097/00010694-200004000-00001

Keenan, T. F., & Williams, C. A. (2018). The terrestrial carbon sink. *Annual Review of Environment and Resources*, *43*(1), 219–243. https://doi.org/10.1146/annurev-environ-102017-030204

Klein Goldewijk, K., Beusen, A., Van Drecht, G., & De Vos, M. (2011). The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecology and Biogeography*, *20*(1), 73–86. https://doi.org/10.1111/j.1466-8238.2010.00587.x

Lauerwald, R., Regnier, P., Camino-Serrano, M., Guenet, B., Guimberteau, M., Ducharne, A., et al. (2017). *ORCHILEAK: A new model branch to simulate carbon transfers along the terrestrial-aquatic continuum of the Amazon basin* (pp. 1–58). Geoscientific Model Development. https://doi.org/10.5194/gmd-2017-79

Lauerwald, R., Regnier, P., Guenet, B., Friedlingstein, P., & Ciais, P. (2020). How simulations of the land carbon sink are biased by ignoring fluvial carbon transfers: A case study for the Amazon Basin. *One Earth*, *3*(2), 226–236. https://doi.org/10.1016/j.oneear.2020.07.009

Leifeld, J., & Menichetti, L. (2018). The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature Communications*, *9*(1), 1071. https://doi.org/10.1038/s41467-018-03406-6

Li, Y., & Qin, Y. (2019). The response of net primary production to climate change: A case study in the 400 mm annual precipitation fluctuation zone in China. *International Journal of Environmental Research and Public Health*, *16*(9), 1497. https://doi.org/10.3390/ijerph16091497

Liu, Y., Zhou, R., Wen, Z., Khalifa, M., Zheng, C., Ren, H., et al. (2021). Assessing the impacts of drought on net primary productivity of global land biomes in different climate zones. *Ecological Indicators*, *130*, 108146. https://doi.org/10.1016/j.ecolind.2021.108146

Lu, H., Wang, X., Zhang, H., Xie, X., Nakhavali, M., Quine, T. A., et al. (2024). Soil organic carbon lateral movement processes integrated into a terrestrial ecosystem model. *Journal of Advances in Modeling Earth Systems*, *16*(1). https://doi.org/10.1029/2023MS003916

Martin, G. M., Bellouin, N., Collins, W. J., Culverwell, I. D., Halloran, P. R., Hinton, T. J., et al. (2011). Model development the HadGEM2 family of met office unified model climate configurations. *Geoscientific Model Development*, *4*(3), 723–757. https://doi.org/10.5194/gmd-4-723-2011

Mayorga, E., Seitzinger, S. P., Harrison, J. A., Dumont, E., Beusen, A. H. W., Bouwman, A. F., et al. (2010). Environmental modelling & software global nutrient export from WaterSheds 2 (NEWS 2): Model development and implementation. *Environmental Modelling & Software*, *25*(7), 837–853. https://doi.org/10.1016/j.envsoft.2010.01.007

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J. F., et al. (2011). The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climate Change*, *109*(1–2), 213–241. https://doi.org/10.1007/s10584-011-0156-z

Meybeck, M. (1993). Riverine transport of atmospheric carbon: Sources, global typology and budget. *Water, Air, & Soil Pollution*, *70*(1–4), 443–463. https://doi.org/10.1007/BF01105015

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*(7282), 747–756. https://doi.org/10.1038/nature08823

Muñoz-Rojas, M., Jordán, A., Zavala, L. M., González-Peñaloza, F. A., De La Rosa, D., Pino-Mejias, R., & Anaya-Romero, M. (2013). Modelling soil organic carbon stocks in global change scenarios: A CarboSOIL application. *Biogeosciences*, *10*(12), 8253–8268. https://doi.org/10.5194/bg-10-8253-2013

Nachtergaele, F., Velthuizen, H. van, Verelst, L., Batjes, N. H., Dijkshoorn, K., Engelen, V. W. P. van, et al. (2010). The harmonized world soil database. In *Proceedings of the 19th world congress of soil science* (pp. 34–37). Soil Solutions for a Changing World.

Nakhavali, M., Friedlingstein, P., Lauerwald, R., Tang, J., Chadburn, S., Camino-Serrano, M., et al. (2018). Representation of dissolved organic carbon in the JULES land surface model (vn4.4_JULES-DOCM). *Geoscientific Model Development*, *11*(2), 593–609. https://doi.org/10.5194/gmd-11-593-2018

Nakhavali, M., Lauerwald, R., Regnier, P., & Friedlingstein, P. (2024). Historical trends and drivers of the laterally transported terrestrial dissolved organic carbon to river systems. *Science of the Total Environment*, *917*, 170560. https://doi.org/10.1016/j.scitotenv.2024.170560

Nakhavali, M., Lauerwald, R., Regnier, P., Guenet, B., Chadburn, S., & Friedlingstein, P. (2021). Leaching of dissolved organic carbon from mineral soils plays a significant role in the terrestrial carbon balance. *Global Change Biology*, *27*(5), 1083–1096. https://doi.org/10.1111/gcb.15460

Oades, J. M., Lefroy, R. D. B., Blair, G. J., & Craswell, E. T. (1995). *Soil organic matter management for sustainable agriculture: A workshop held in Ubon, Thailand, 24–26 August 1994*. Australian Centre for International Agricultural Research.

Piao, S., Friedlingstein, P., Ciais, P., de Noblet-Ducoudré, N., Labat, D., & Zaehle, S. (2007). Changes in climate and land use have a larger direct impact than rising CO2 on global river runoff trends. *Proceedings of the National Academy of Sciences*, *104*(39), 15242–15247. https://doi.org/10.1073/pnas.0707213104

Pugh, T. A. M., Lindeskog, M., Smith, B., Poulter, B., Arneth, A., Haverd, V., & Calle, L. (2019). Role of forest regrowth in global carbon sink dynamics. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(10), 4382–4387. https://doi.org/10.1073/pnas.1810512116

Qiu, C., Ciais, P., Zhu, D., Guenet, B., Chang, J., Chaudhary, N., et al. (2022). A strong mitigation scenario maintains climate neutrality of northern peatlands. *One Earth*, *5*(1), 86–97. https://doi.org/10.1016/j.oneear.2021.12.008

Qiu, C., Ciais, P., Zhu, D., Guenet, B., Peng, S., Petrescu, A. M. R., et al. (2021). Large historical carbon emissions from cultivated northern peatlands. *Science Advances*, *7*(23). https://doi.org/10.1126/sciadv.abf1332

Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F. T., Gruber, N., Janssens, I. a., et al. (2013). Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nature Geoscience*, *6*(8), 597–607. https://doi.org/10.1038/ngeo1830

Regnier, P., Resplandy, L., Najjar, R. G., & Ciais, P. (2022). The land-to-ocean loops of the global carbon cycle. *Nature*, *603*(7901), 401–410. https://doi.org/10.1038/s41586-021-04339-9

Riahi, K., Grubler, A., & Nakicenovic, N. (2007). Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technological Forecasting and Social Change*, *74*(7), 887–935. https://doi.org/10.1016/j.techfore.2006.05.026

Rind, D., Goldberg, R., Hansen, J., Rosenzweig, C., & Ruedy, R. (1990). Potential evapotranspiration and the likelihood of future drought. *Journal of Geophysical Research*, *95*(D7), 9983–10004. https://doi.org/10.1029/JD095iD07p09983

Rowley, M. C., Grand, S., & Verrecchia, É. P. (2018). Calcium-mediated stabilisation of soil organic carbon. *Biogeochemistry*, *137*(1–2), 27–49. https://doi.org/10.1007/s10533-017-0410-1

Sitch, S., Friedlingstein, P., Gruber, N., Jones, S. D., Murray-Tortarolo, G., Ahlström, A., et al. (2015). Recent trends and drivers of regional sources and sinks of carbon dioxide. *Biogeosciences*, *12*(3), 653–679. https://doi.org/10.5194/bg-12-653-2015

Tabari, H. (2020). Climate change impact on flood and extreme precipitation increases with water availability. *Scientific Reports*, *10*(1), 13768. https://doi.org/10.1038/s41598-020-70816-2

Tian, H., Yang, Q., Najjar, R. G., Ren, W., Friedrichs, M. A. M., Hopkinson, C. S., & Pan, S. (2015). Anthropogenic and climatic influences on carbon fluxes from eastern North America to the Atlantic Ocean: A process-based modeling study. *Journal of Geophysical Research: Biogeosciences*, *120*(4), 752–772. https://doi.org/10.1002/2014JG002760

Todd-Brown, K. E. O., Randerson, J. T., Post, W. M., Hoffman, F. M., Tarnocai, C., Schuur, E. A. G., & Allison, S. D. (2013). Causes of variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations Earth System. *Biogeosciences*, *10*(3), 1717–1736. https://doi.org/10.5194/bg-10-1717-2013

Tranvik, L. J., Downing, J. A., Cotner, J. B., Loiselle, S. A., Striegl, R. G., Ballatore, T. J., et al. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology & Oceanography*, *54*(1), 2298–2314. https://doi.org/10.4319/lo.2009.54.6_part_2.2298

Van Oost, K., Verstraeten, G., Doetterl, S., Notebaert, B., Wiaux, F., Broothaerts, N., & Six, J. (2012). Legacy of human-induced C erosion and burial on soil–atmosphere C exchange. *Proceedings of the National Academy of Sciences*, *109*(47), 19492–19497. https://doi.org/10.1073/pnas.1211162109

Van Vuuren, D. P., Den Elzen, M. G. J., Lucas, P. L., Eickhout, B., Strengers, B. J., Van Ruijven, B., et al. (2007). Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. *Climatic Change*, *81*(2), 119–159. https://doi.org/10.1007/s10584-006-9172-9

Virto, I., Antón, R., Apesteguía, M., & Plante, A. (2018). Role of carbonates in the physical stabilization of soil organic matter in agricultural mediterranean soils. In *Soil management and climate change* (pp. 121–136). Elsevier. https://doi.org/10.1016/B978-0-12-812128-3.00009-4

Walker, A. P., De Kauwe, M. G., Bastos, A., Belmecheri, S., Georgiou, K., Keeling, R. F., et al. (2021). Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO_2. *New Phytologist*, *229*(5), 2413–2445. https://doi.org/10.1111/nph.16866

Wang, S., Wang, X., He, B., & Yuan, W. (2020). Relative influence of forest and cropland on fluvial transport of soil organic carbon and nitrogen in the Nen River basin, northeastern China. *Journal of Hydrology*, *582*, 124526. https://doi.org/10.1016/j.jhydrol.2019.124526

Wang, Z., Hoffmann, T., Six, J., Kaplan, J. O., Govers, G., Doetterl, S., & Van Oost, K. (2017). Human-induced erosion has offset one-third of carbon emissions from land cover change. *Nature Climate Change*, *7*(5), 345–349. https://doi.org/10.1038/nclimate3263

Weidhuner, A., Hanauer, A., Krausz, R., Crittenden, S. J., Gage, K., & Sadeghpour, A. (2021). Tillage impacts on soil aggregation and aggregate-associated carbon and nitrogen after 49 years. *Soil and Tillage Research*, *208*, 104878. https://doi.org/10.1016/j.still.2020.104878

Wit, F., Müller, D., Baum, A., Warneke, T., Pranowo, W. S., Müller, M., & Rixen, T. (2015). The impact of disturbed peatlands on river outgassing in Southeast Asia. *Nature Communications*, *6*(1), 10155. https://doi.org/10.1038/ncomms10155

Wu, Y., Miao, C., Fan, X., Gou, J., Zhang, Q., & Zheng, H. (2022). Quantifying the uncertainty sources of future climate projections and narrowing uncertainties with bias correction techniques. *Earth's Future*, *10*(11). https://doi.org/10.1029/2022EF002963

Xue, S. Y., Xu, H. Y., Mu, C. C., Wu, T. H., Li, W. P., Zhang, W. X., et al. (2021). Changes in different land cover areas and NDVI values in northern latitudes from 1982 to 2015. *Advances in Climate Change Research*, *12*(4), 456–465. https://doi.org/10.1016/j.accre.2021.04.003

Yan, Y., Lauerwald, R., Wang, X., Regnier, P., Ciais, P., Ran, L., et al. (2023). Increasing riverine export of dissolved organic carbon from China. *Global Change Biology*, *29*(17), 5014–5032. https://doi.org/10.1111/gcb.16819

Yao, Y., Tian, H., Pan, S., Najjar, R. G., Friedrichs, M. A. M., Bian, Z., et al. (2021). Riverine carbon cycling over the past century in the mid-Atlantic region of the United States. *Journal of Geophysical Research: Biogeosciences*, *126*(5). https://doi.org/10.1029/2020JG005968

Zhang, H., Lauerwald, R., Ciais, P., Van Oost, K., Guenet, B., & Regnier, P. (2022). Global changes alter the amount and composition of land carbon deliveries to European rivers and seas. *Communications Earth and Environment*, *3*(1), 245. https://doi.org/10.1038/s43247-022-00575-7

Zhang, H., Lauerwald, R., Regnier, P., Ciais, P., Van Oost, K., Naipal, V., et al. (2022). Estimating the lateral transfer of organic carbon through the European river network using a land surface model. *Earth System Dynamics*, *13*(3), 1119–1144. https://doi.org/10.5194/esd-13-1119-2022

Zhang, H., Lauerwald, R., Regnier, P., Ciais, P., Yuan, W., Naipal, V., et al. (2020). Simulating erosion-induced soil and carbon delivery from uplands to rivers in a global land surface model. *Journal of Advances in Modeling Earth Systems*, *12*(11). https://doi.org/10.1029/2020MS002121

Zhang, X., Jin, J., Zeng, X., Hawkins, C. P., Neto, A. A. M., & Niu, G. (2022). The compensatory CO_2 fertilization and stomatal closure effects on runoff projection from 2016–2099 in the western United States. *Water Resources Research*, *58*(1). https://doi.org/10.1029/2021WR030046

Zhao, M., Heinsch, F. A., Nemani, R. R., & Running, S. W. (2005). Improvements of the MODIS terrestrial gross and net primary production global data set. *Remote Sensing of Environment*, *95*(2), 164–176. https://doi.org/10.1016/j.rse.2004.12.011