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TOPICAL REVIEW

Modeling exports of dissolved organic carbon from landscapes: a review of challenges and opportunities

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Abstract

Inland waters receive large quantities of dissolved organic carbon (DOC) from soils and act as conduits for the lateral transport of this terrestrially derived carbon, ultimately storing, mineralizing, or delivering it to oceans. The lateral DOC flux plays a crucial role in the global carbon cycle, and numerous models have been developed to estimate the DOC export from different landscapes. We reviewed 34 published models and compared their characteristics to identify challenges in model applications and opportunities for future model development. We classified these models into three types: indicator-driven, hydrology-forced, and process-based DOC export simulation models. They differ mainly in their environmental inputs, simulation approaches for soil DOC production, leaching from soils to inland waters, and transit through inland waters. It is essential to consider landscape characteristics, climate conditions, available data, and research questions when selecting the most appropriate model. Given the substantial assumptions associated with these models, sufficient measurements are required to benchmark estimates. Accurate accounting of terrestrially derived DOC export to oceans requires incorporating the DOC produced in aquatic ecosystems and deposited with rainwater; otherwise, global export estimates may be overestimated by 40.7%. Additionally, improving the representation of mineralization and burial processes in inland waters allows for more accurate accounting of carbon sequestration through land ecosystems. When all the inland water processes are ignored or assuming DOC leaching is equivalent to DOC export, the loss of soil carbon through this lateral flux could be underestimated by 43.9%.

1. Introduction

The land-to-ocean carbon flux through inland waters connects the terrestrial and marine carbon reservoirs, and accounting for this land-to-ocean component of the carbon cycle is crucial in reconciling the discrepancy between top-down estimates of land-atmosphere carbon exchange and bottom-up estimates of land carbon stock changes [1–3]. Initially, dissolved organic carbon (DOC) is transported from soils to inland waters through runoff, representing a significant component of this lateral carbon flux [4, 5]. In aquatic ecosystems, a portion of the terrestrially derived DOC is either mineralized and released to the atmosphere or buried in sediments, with the remainder eventually delivered to coastal oceans [6, 7]. Previous studies estimated that the annual global flux of DOC ultimately delivered to coastal oceans ranges from 132 to 360 Tg C, with an average of 211 Tg C per year (table S1).

To account for the DOC export (E_{DOC}) from different landscapes, calculating the product of the average riverine DOC concentration (C_{DOC}) and total river discharge (Q) for a given period is a common approach ($E_{DOC} = C_{DOC} \times Q$) [8]. River discharge can be continuously monitored at the landscape outlet by measuring both the stream velocity and the cross-sectional area, or alternatively, it can be estimated using hydrological models [9, 10]. Numerous methods, including *in situ* measurements, remote sensing products, and estimation models, can be used to obtain the riverine DOC concentration [11, 12]. However, each approach has its advantages and disadvantages concerning methodological limitations and sources of error. *In situ* measurements of riverine DOC concentrations are generally low-frequency, short-term, and insufficient at representing the DOC concentration for the entire cross-section of the river [13]. Riverine DOC concentrations can be inferred by the riverine chromophoric dissolved organic matter (CDOM) concentrations [14]. However, the complex optical properties of inland waters, ice cover, and limited datasets combine to limit the applicability of remote sensing images in estimating riverine CDOM concentrations [15]. Another challenge is the atmospheric conditions, including haze, aerosols, and humidity, which can obscure the low water-leaving radiances and reduce reliabilities of remotely-sensed riverine CDOM concentrations [16]. Models can provide long-term estimates of riverine DOC concentrations, but they require reliable measurements to calibrate their parameters and validate their results [17]. In addition to using the product of DOC concentrations and river discharges, numerous simulation models can directly estimate the total DOC export from a landscape [18, 19].

Modeling the DOC export from a landscape involves three critical processes: production in soils, leaching from soils to inland waters, and transit through inland waters [20, 21]. Soil DOC originates from the degradation of soil organic matter, exudation from roots, rainwater deposition, and the movement of organic compounds via vegetation throughfall [22–24]. DOC production rate and content in the soil are influenced by various environmental factors such as temperature and available nitrogen [25–27]. The leaching of DOC from soils to inland waters is predominantly governed by the soil sorption/desorption capability and hydrological force [28, 29]. As DOC transits through inland waters, a fraction may be mineralized or buried, with rates being affected by water conditions such as water temperature, microbial abundance, and residence time [30, 31].

Numerous models have been developed to estimate the DOC export by incorporating different climate variables and key hydrological and biogeochemical processes. These models have been implemented to estimate long-term DOC exports from various landscapes and examine their spatio-temporal patterns. Therefore, a thorough comparison and evaluation of these models is essential for their application and for enhancing their simulation capabilities. In this study, we conducted a comprehensive review and comparison of published models designed for estimating DOC export, aiming to address these challenges and potential opportunities.

2. Materials and methods

For this study, we searched 34 models using Google Scholar, Web of Science, and ScienceDirect with keywords 'dissolved organic carbon', 'DOC', 'export', 'flux', 'model', and 'simulation'. These models, developed between 1994 and 2021, have been applied to estimate the DOC export across various scales, ranging from individual catchments to the global level (table S2). If a model was not given a specific name in the original paper, we defined a name using the initials of its critical input environmental factors or its significant DOC flux processes. For example, Clair *et al* [32] employed the basin area, slope index, and precipitation to predict the annual DOC export from a basin; we thus named this model 'ASP'. Birkel *et al* [33] developed a model intertwining hydrology and biogeochemistry, with a focus on hydrological connectivity and soil biogeochemistry, leading us to name it 'HB-DOC'.

Considering their core structure and estimation methodologies, we categorized the 34 models into three distinct types: indicator-driven, hydrology-forced, and process-based models. Indicator-driven models rely on either univariate (using a single environmental factor) or multivariate regression (using multiple environmental factors) to estimate the DOC export from a landscape. Unlike the other two types, hydrology-forced models do not directly estimate the DOC export from a landscape over a specified time frame. Instead, they determine the DOC export as the product of the river discharge and its average DOC concentration over a given period. These models consist of two modules: one estimates the river discharge from a landscape, and the other determines the corresponding average riverine DOC concentration. Process-based models offer an all-encompassing method by representing the complete terrestrial ecosystem. Apart from hydrological processes, they encompass biogeochemical functions like vegetation photosynthesis, biomass distribution, respiration, and the decomposition of soil organic carbon.

Moreover, we reviewed, summarized, and compared model characteristics including input drivers, the simulation time step, the definition of single simulation units, the environmental factors strongly related to the DOC flux, and the methods employed to simulate critical hydrological and biogeochemical processes. Given that environmental factors including temperature, precipitation, available nitrogen, and land cover type have strong relationships with the lateral DOC flux and are commonly integrated into

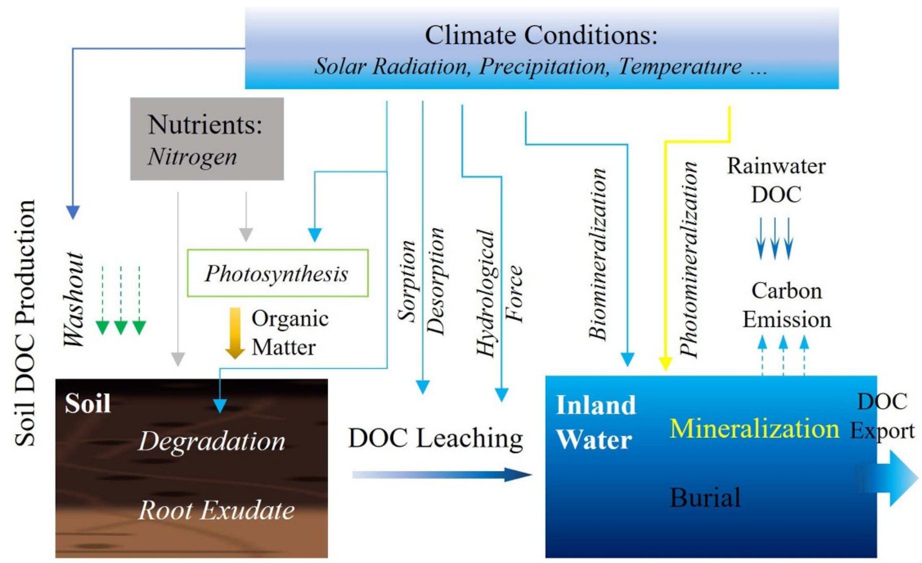

Figure 1. Key processes considered for estimating the DOC export from a landscape, as reviewed in this study.

these simulation models, we examined and summarized these factors for each model. Crucially, we delved into the key processes of DOC production in soils, its leaching from soils to inland waters, and its transit through inland waters, identifying challenges in model applications and opportunities in future model development (figure 1).

3. Model grouping, summary, and comparison

3.1. Model classification

Seven models were classified as indicator-driven models (table 1). They typically operate on an annual time step, except for the Soil C:N model, for which the simulation time step is not applicable. Fourteen models were categorized as hydrology-forced models. Most of these operate on a daily simulation time step, though DISC-CARBON and DCWBM-OLS operate monthly. It is important to note that the Generic Model and Landscape-Mixing lack a hydrology module for discharge simulations and instead rely on field measurements. Due to the similarity in their estimation method to other hydrological DOC models, we categorized them as hydrology-forced models. In addition, SWAT-DOC uses a simplified version of the environmental policy integrated climate (EPIC) model for simulating vegetation growth but does not encompass the entire terrestrial ecosystem [34]. Consequently, we have categorized it as a hydrology-forced model. Ten models fall under the process-based category. Specifically, they can capture the relationship between soil DOC production and net primary production. TEM 6.0 and TRIPLEX-HYDRA operate on a monthly time step, the rest run on a daily basis. To describe an individual simulated land unit, both indicator-driven and hydrology-forced models often use terms such as "catchment", "watershed", or "basin" (table 1). These terms refer to a drainage landscape that channels water from rain or snow melt into the inland water system. However, these terms do not have distinctions based on the size of the study area. In contrast, process-based models, often referred to as "column" models, simulate the DOC flux either for a singular site (one grid) or for a region comprising multiple grids of a consistent size.

3.2. Model input drivers

Temperature and precipitation have significant influences on the entire land-to-ocean terrestrially derived DOC flux process. Lower temperatures have the potential to reduce both DOC production in soils and its decomposition rate in waters [60, 61]. An increase in precipitation increases runoff, subsequently bolstering the hydrological force responsible for transporting more DOC from soils to inland waters [62]. Simultaneously, rapid river flows caused by heavy precipitation can decrease the water retention time, leading to a reduction in the mineralization and burial of DOC within inland water ecosystems [63]. These two factors are integrated into several indicator-driven models, but they are integral to the functionality of hydrology-forced and process-based models (figure 2). Notable exceptions include the landscape-mixing and the generic model, which lack a hydrology module and instead depend on observed river discharge. In hydrology-forced models, temperature and precipitation are crucial inputs, driving the simulation of river discharge [64]. For process-based

Table 1. The 34 dissolved organic carbon (DOC) export simulation models, classified into three categories: indicator-driven models ($n = 7$), hydrology-forced models ($n = 17$), and process-based models ($n = 10$).

Model name	Time step	Land unit	References
Indicator-driven models (7 models)			
ASP	Annual	Basin	Clair *et al* [32]
D-S-SO	Annual	Basin	Ludwig *et al* [35]
Soil C:N	NA	Biome	Aitkenhead and McDowell [19]
NEWS-DOC	Annual	Basin	Harrison *et al* [36]
Wetland-DOC	Annual	Catchment	Creed *et al* [37]
DOC-FE	Annual	Catchment	Lauerwald *et al* [38]
TAF-DOC	Annual	Watershed	Wei *et al* [20]
Hydrology-forced models (17 models)			
TOPMODEL-DOC	Daily	Catchment	Hornberger *et al* [39]
CLSM-LOADEST	Daily	Watershed	McClelland *et al* [40]
INCA-C	Daily	Catchment	Futter *et al* [41]
MMWH-CDE	Daily	Basin	Yurova *et al* [42]
GWLF-DOC	Daily	Catchment	Naden *et al* [43]
DOC-3-ForHyM	Daily	Catchment	Jutras *et al* [12]
RRM-DOM	Daily	Catchment	Xu *et al* [44]
HB-DOC	Daily	Catchment	Birkel *et al* [33]
Landscape-Mixing	Daily	Catchment	Tiwari *et al* [17]
HBV-ECOSSE	Daily	Catchment	Lessels *et al* [45]
WTD-DOC	Daily	Catchment	Bernard-Jannin *et al* [46]
SWAT-DOC	Daily	Watershed	Du *et al* [47]
Generic Model	Daily	Basin	Fabre *et al* [48]
BioRT-Flux-PIHM	Daily	Catchment	Wen *et al* [9]
DISC-CARBON	Monthly	Basin	van Hoek *et al* [49]
DCWBM-OLS	Monthly	Watershed	Edwards *et al* [50]
PWBM-DOC	Daily	Basin	Rawlins *et al* [51]
Process-based models (10 models)			
TEM 6.0	Monthly	$0.5^\circ \times 0.5^\circ$	Kicklighter *et al* [18]
TRIPLEX-DOC	Daily	Site[a]	Wu *et al* [52]
DLEM 2.0	Daily	9.2×9.2 km	Ren *et al* [21]
ORCHILEAK	Daily	$1^\circ \times 1^\circ$	Lauerwald *et al* [53]
JULES-DOCM	Daily	Site[a]	Nakhavali *et al* [54]
LPJ-GUESS	Daily	50×50 m	Tang *et al* [55]
ECO3D	Daily	500×500 m	Liao *et al* [56]
TRIPLEX-HYDRA	Monthly	$0.5^\circ \times 0.5^\circ$	Li *et al* [57]
ORCHIDEE MICT-LEAK	Daily	$0.5^\circ \times 0.5^\circ$	Bowring *et al* [58]
RHESSys	Daily	500×500 m	Tague and Band [59]

[a] A site or single grid simulation.

models, these variables not only shape runoff estimations but also play roles in various biogeochemical processes, from photosynthesis to soil organic carbon decomposition [52, 55].

Increased nitrogen supply boosts net primary production, thereby enriching the soil with organic carbon, a substrate essential for DOC production [27]. However, an increased nitrogen supply also elevates soil acidity, subsequently diminishing the activity of soil microbes that play an important role in DOC production [65]. In addition, nitrogen-abundant aquatic systems generally experience high rates of DOC decomposition [66]. Nitrogen is rarely incorporated into indicator-driven and hydrology-forced models (except for SWAT-DOC), but four process-based models incorporate the nitrogen cycle in their DOC export simulations (figure 2). The four models mainly emphasize the influence of nitrogen on terrestrial ecosystem processes, including the rate of photosynthesis, vegetation growth, biomass distribution, and decomposition of soil organic carbon [21]. However, they ignore the influence of nitrogen in inland water ecosystems regarding DOC mineralization.

Land cover is crucial for indicator-driven models and is a necessary input for all process-based models when estimating DOC export (figure 2). However, its function varies significantly between the two model types. Wetlands within a drainage region are significant contributors to the DOC in inland waters; thus, a decrease in wetland area can dramatically reduce DOC export from a landscape [67]. This significant relationship is incorporated into indicator-driven models. On the other hand,

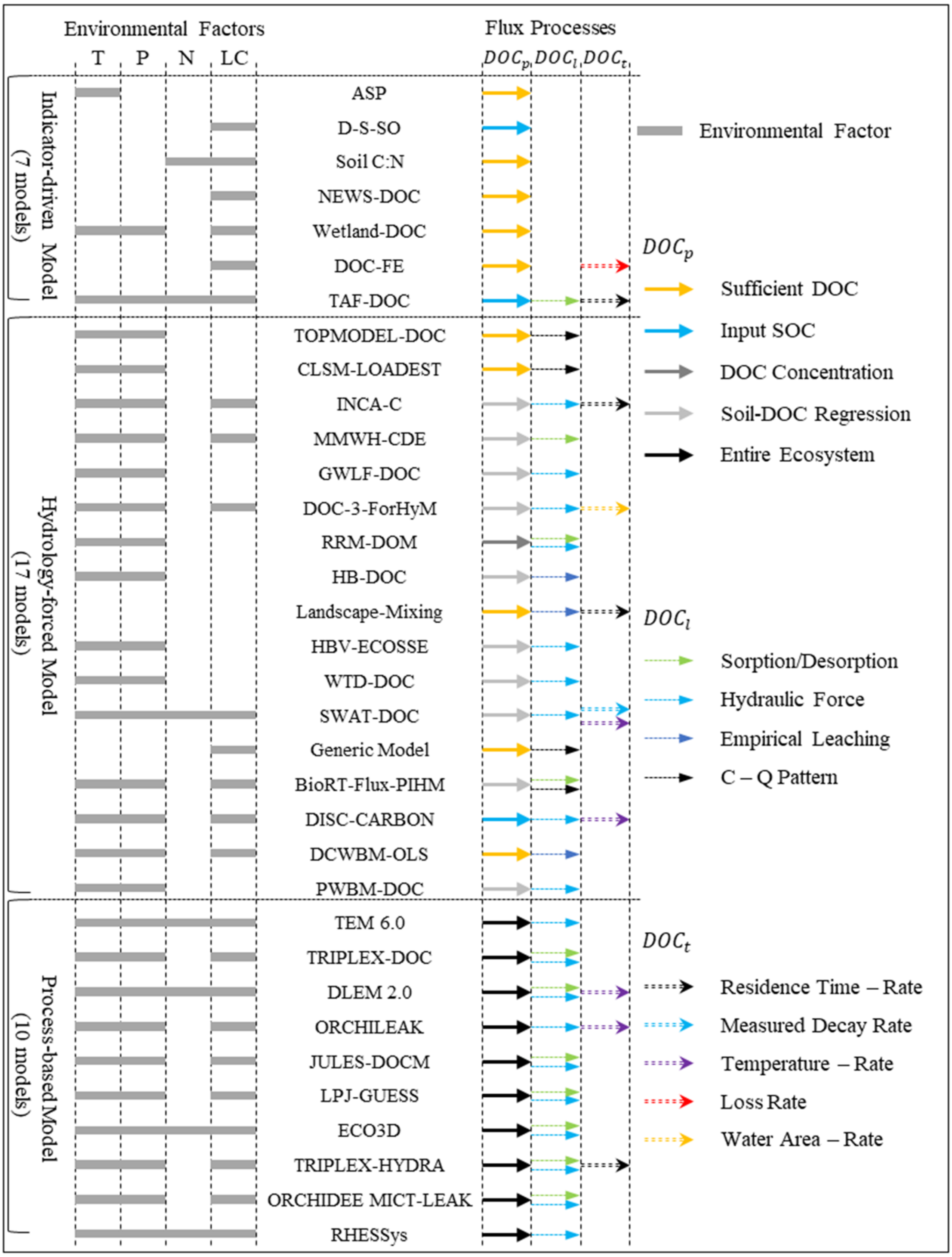

Figure 2. Reviewed environmental factors include temperature (T), precipitation (P), nitrogen input or available soil nitrogen (N), and land cover type (LC). Summarized approaches used to model the DOC production in the soil (DOC_p), leaching from soils to inland waters (DOC_l), and transit through inland waters (DOC_t).

process-based models require land cover information that specifies the proportion of different vegetation types, such as the fraction of coniferous forest. This information is vital in process-based models, as it determines the simulation approach for each vegetation type. Eight of these hydrology-forced models require land cover information as input data, which the hydrology module utilizes to estimate the discharge.

3.3. Soil DOC production

Across three types of models, the methods used for estimating soil DOC production and pool size are categorized into five distinct groups (figure 2, table S2). The first method (sufficient DOC) assumes that the amount of soil DOC is sufficient to be moved by runoff and has no influence on the DOC leaching from soils to inland waters ($n = 10$). The second method (input SOC) assumes that the soil organic carbon is static. It uses existing soil carbon data as an indicator in the empirical regression model to directly estimate the DOC export or as input data to further estimate the soil DOC pool (n = 3). The third method (DOC concentration) is based on the field-measured soil DOC density to roughly model the soil DOC pool size (n = 1). The fourth method (Soil-DOC regression) directly models the soil DOC density by using environmental factors in conjunction with an empirical regression model (n = 10). Using soil moisture and temperature as indicators is the most popular way to simulate the dynamics of the soil DOC pool (table S2). The fifth method (Entire ecosystem) estimates the soil organic matter content through simulating the entire terrestrial system including plant growth, litter fall, and soil organic carbon dynamics, which is used by all process-based models (n = 10).

3.4. Terrestrial-aquatic DOC leaching

Four distinct methods are employed in these models to simulate the DOC leaching from soils to inland waters or the riverine DOC concentration (figure 2, table S2). Since hydrology-forced models utilize riverine DOC concentration to estimate DOC export, and given that this concentration is influenced by the leaching process, we summarized the methods for estimating riverine DOC concentration in this section. The first method infers the DOC leaching from soils to inland waters by modeling the soil DOC sorption/desorption capacity, a critical determinant of the leaching process (n = 10). The second method postulates that the DOC flux is regulated by the soil hydraulic conductivity and the runoff rate (hydraulic force) (n = 19). Consequently, either the soil water content or runoff is employed to estimate the riverine DOC concentration or total DOC leaching. The third method adopts an empirical leaching model, integrating environmental variables such as glacier area and soil type (table S2), to predict the riverine DOC concentration (n = 3). The fourth method leverages the time-dependent or independent correlation between river discharges and riverine DOC concentrations, known as the C–Q pattern (n = 4). Each model applies one or a combination of these methods to simulate the DOC leaching from soils to inland waters.

3.5. Inland water DOC transit

Of the three types of models, ten account for the potential fates of terrestrially derived DOC in inland waters, including at least one of the major processes: DOC burial or DOC mineralization (table S2). However, only three (i.e. DOC-FE, TAF-DOC, and DOC-3-ForHyM) estimate the amount of DOC buried in the sediment. These ten models employ five distinct approaches to model the fates of terrestrially derived DOC in inland waters (figure 2, table S2). The first approach uses the water residence time or travel time in aquatic ecosystems coupled with the rate of microbial DOC mineralization (n = 4). The second approach uses either the measured decay rate or the fraction of mineralized DOC as input parameters to estimate the mineralized DOC during its transit (n = 1). The third strategy employs a temperature-dependent DOC mineralization rate function to estimate the amount of DOC decomposed during transit (n = 3). The fourth approach uses a loss rate to project the overall DOC reduction during transit, potentially accounting for both mineralized and buried DOC (n = 1). Finally, the fifth method leverages the open water area within a drained landscape and combines it with an empirical regression method to model the quantity of DOC that is either mineralized or buried (n = 1).

4. Challenges in model application

Indicator-driven models depend on one or multiple key environmental factors and can adequately represent the overall DOC export from a landscape [19]. Due to their dependence on given relatively static indicators, such as land cover information (figure 2), they may not fully capture climate influence, ecosystem dynamics, seasonal trends, and inter-annual dynamics (figure 3). Hydrology-forced models can reliably simulate the discharge from a landscape [47]. However, when modeling the riverine DOC concentration based on the estimated discharge, they could not incorporate the influence of ecosystem dynamics and climate change on soil DOC production. In contrast, process-based models simulate biogeochemical process dynamics for the entire terrestrial ecosystem and so can estimate soil DOC production and pool size according to the influence of climate variables (table S2). As one-dimensional 'column' models, they have a limited spatial representation of the interface between terrestrial and aquatic ecosystems.

The observed diluting response, where DOC concentration decreases during high flow events [68, 69], may be attributed to insufficient soil DOC or strong soil sorption capacity. In addition, Zarnetske *et al* [23] suggested that watersheds with less than 20% wetland coverage might be more source-limited. Consequently, excluding modeling soil DOC production and pool size could lead to an overestimation of DOC export during high flow events or in watersheds with limited wetland coverage (figure 3). While using soil organic carbon or DOC concentration as input data might mitigate the diluting response, characterizing the impact of climate on soil DOC dynamics remains challenging. Additionally, the need for intense location-specific measurements can increase the workload for model input data preparation. The soil-DOC regression approach can incorporate specific climate factors, but it necessitates substantial measurements for parameter calibration (figure 3). Process-based models, which simulate the entire terrestrial ecosystem, can holistically

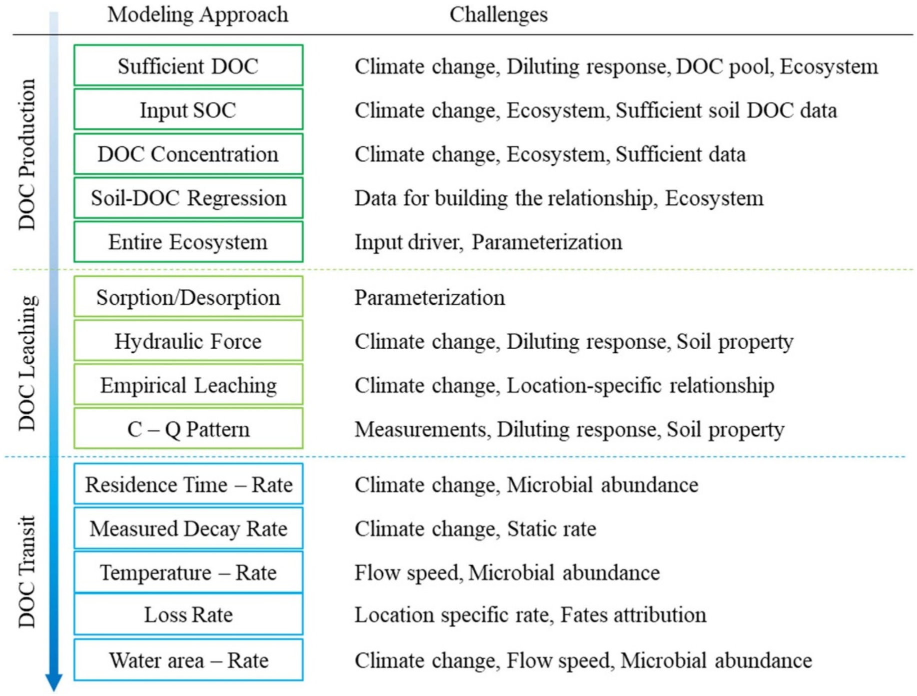

Figure 3. Overview of challenges faced by different modeling approaches. Modeling DOC production faces challenges like integrating climate change impacts, addressing dilution response, estimating the soil DOC pool, and representing the terrestrial ecosystem, alongside data requirements and parameterization. In modeling DOC leaching, challenges include the influence of climate change, dilution response, representing soil properties, and requirements for measurements and relationship analysis. For DOC transit modeling, the key challenges are the influence of climate change, the effect of microbial abundance, variation in decay rates, the impact of flow speed on retention time, and accurate attribution of fates.

represent soil DOC production and account for its climate-induced dynamics (figure 3). However, variations exist among these models in their estimations of soil DOC production and pool size. They may use the soil organic matter degradation approach, include carbon displaced by the washout of organic compounds during vegetation throughfall, assume a fraction of soil organic matter is DOC, or apply a temperature-dependent DOC production rate (table S2). Moreover, fully representing the entire terrestrial ecosystem requires numerous parameters and input data, which can significantly increase the model setup workload.

Incorporating soil sorption/desorption in estimating the DOC leaching is another useful way to eliminate the diluting response. Given that the rates of DOC sorption and desorption are influenced by factors such as temperature, moisture, pH, and the concentrations of cations and anions in the soil water [70], this approach offers a way to capture the effects of climate change on DOC leaching. However, the model parameters need calibration based on location-specific characteristics such as soil types (figure 3) [71]. While hydraulic force and C–Q pattern approaches prioritize runoff over soil properties, they fall short in eliminating the diluting response and depicting the impacts of climate change on DOC leaching [69]. Additionally, given that the DOC concentration is an instantaneous measurement, obtaining a reliable C–Q relationship demands extensive measurements of both the DOC concentration and the corresponding river discharge (figure 3) [13]. The empirical leaching method, which uses single or multiple indicators to model DOC leaching, is highly sensitive to landscape characteristics [33]. This sensitivity can limit its applicability to different regions.

Current models typically employ factor-dependent (e.g. residence time, temperature, water area) rates of mineralization and burial, measured mineralization rates, or a total loss rate to simulate DOC burial and mineralization, either through photolytic or microbial processes (figure 2). While factor-dependent approaches focus on a single key determinant, they often overlook the interplay among climate conditions, microbial abundance, flow velocity, and the air-water and water column interfaces (figure 3). Using a measured decay rate, which is a static parameter, may not adequately capture the fluctuations in climate and water conditions [47]. Though the loss rate can encompass both mineralization and burial, it does not distinctly partition these two potential fates [17]. Given that DOC sediment in inland waters can act as a long-term carbon sink, this approach might lead to an underestimation of the carbon sequestration through land ecosystems.

Due to these limitations, benchmarks are essential for validating the simulated DOC exports. The dominant approach is using measured DOC exports at the watershed outlet. This is calculated as the product of average DOC concentration and total discharge over a specified period. In addition, hydrology-forced models can assess their estimates by comparing both discharges and DOC concentrations. Process-based models might use measured carbon pool sizes, such as aboveground biomass and soil organic carbon, or carbon fluxes such as gross primary production and net ecosystem exchange, to validate their performance in simulating the entire terrestrial ecosystem [72]. However, DOC leaching, mineralization, and burial are rarely validated in existing simulations. While ignoring the validation of these processes and only validating the DOC export might obtain reliable estimated DOC exports from a landscape, it raises the concern that terrestrial-aquatic DOC leaching could be either overestimated or underestimated.

5. Opportunities in model development

Existing models primarily consider the degradation of soil organic matter as the primary source of soil DOC. However, DOC production, whether exuded by roots, transported with the washout of organic compounds in vegetation throughfall, or derived from rainwater, is rarely included (figure 1, table S2). Current research offers substantial data concerning soil DOC concentration [73–76], rainwater DOC deposition (table S3), root exudation [77, 78], and the washout of organic compounds in vegetation throughfall [79, 80], which can enhance and validate soil DOC estimates. By adopting a comprehensive approach to modeling and validating both soil DOC production and pool size, the performance of current models can be greatly enhanced. This is especially advantageous for regions with limited wetlands and for areas that frequently experience heavy precipitation.

Rather than quantifying the DOC leaching from each individual soil layer, current models commonly assume that all DOC entering inland waters originates from a singular soil layer (table S2). However, DOC leaching rates can vary significantly between different soil layers. Distributing the soil organic carbon across multiple soil layers and assuming an exponential DOC production rate with depth provides a useful method for differentiating DOC carbon pools in various soil layers [29, 81]. To obtain the rate of DOC leaching from each soil layer, the initial mass isotherm is an efficient approach. This method quantifies the fraction of DOC in each soil layer that moves from the soil to inland waters through plotting the amount of DOC retained or released per mass of soil against the initial amount of DOC added to the soils [82]. This approach presents opportunities to enhance modeling simulation, but it necessitates extensive experiments and measurements.

Most of these models assume streams and rivers as pipes and simply deliver the terrestrially derived DOC directly and unaltered via flow to the coastal ocean; however, field inventories reveal that the transportation process of DOC through aquatic ecosystems is more complex [83]. In inland waters, microbes biomineralize DOC to inorganic carbon and release it into the atmosphere [84]. Chromophoric DOC, the light-absorbing fraction of terrestrially derived DOC, can be mineralized by solar radiation [85]. Moreover, it is probable that DOC can reach the lake bottom and be buried in the sediment [86]. Additionally, the in-water production of DOC from aquatic plants and algae [87], as well as inputs from rainwater [88], is of higher importance than previously thought. Numerous studies have been undertaken to quantify DOC mineralization and burial [84, 89, 90]. Synthesizing these studies offers opportunities for developing state-of-the-art approaches to model the processes of DOC transit in inland waters.

To investigate the influence of these aquatic processes on the land-to-ocean terrestrially derived DOC flux, we synthesized existing studies and formulated a global terrestrially derived DOC flux budget (figure 4). Our findings indicate that global inland waters receive approximately 21 $\pm$ 7 TgC/year of DOC from rainwater, with around 8 $\pm$ 3 TgC/year eventually delivered to coastal oceans (tables S3 and S4). The DOC ultimately exported to coastal oceans includes 53 $\pm$ 25 TgC/year produced by aquatic ecosystems (table S5). Current research estimates the annual global DOC exported to coastal oceans to be 211 $\pm$ 65 TgC/year (table S1). Therefore, the contribution of terrestrially derived DOC to this export is estimated to be 150 $\pm$ 37 TgC/year (table S6). Our synthesis suggests that 40% of terrestrially derived DOC is exported to coastal oceans, while 25% gets buried in sediments and 30% is mineralized during its transit through inland waters (table S6). Therefore, we estimated that about 376 $\pm$ 92 TgC/year of DOC leaches from soils to inland waters (figure 4, table S6). Within the inland waters, approximately 132 $\pm$ 32 TgC/year of DOC is mineralized and released into the atmosphere, and about 94 $\pm$ 23 TgC/year is buried in sediments. Consequently, on a global scale, neglecting aquatic DOC production and DOC contributions from rainwater might lead to an overestimation of the exports of terrestrially derived DOC to coastal oceans by 40.7% (table S6). Additionally, when all the inland water processes including aquatic DOC production, contributions of DOC from rainwater, DOC mineralization, and DOC burial are overlooked (assuming DOC leaching is equivalent to DOC export), the loss of soil carbon through this lateral flux could be underestimated by 43.9% (table S6).

Disturbances such as fire, hurricanes, and forest harvesting substantially impact the DOC flux [91]. Through combusting a large quantity of soil organic carbon, which is the substrate of soil DOC production, fires significantly reduce the soil DOC production [92]. In addition, forest harvesting

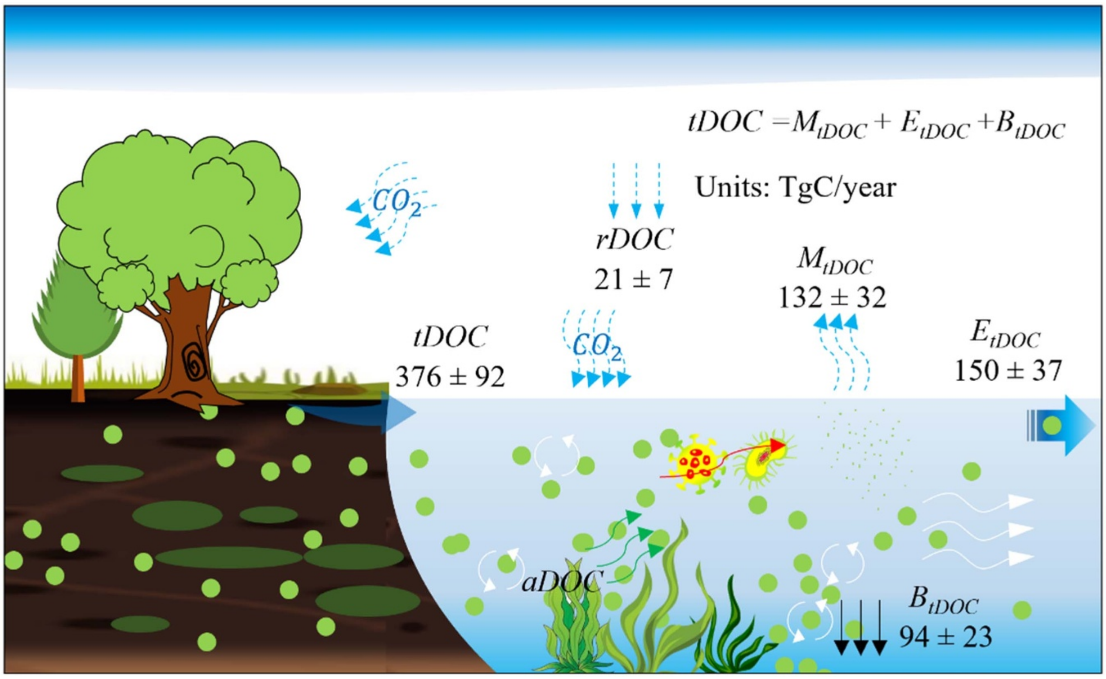

Figure 4. Budget for global land-to-ocean flux of the terrestrially derived DOC (See Tables S1 and S2–S6 for details on the estimations.). tDOC = terrestrially derived DOC, aDOC = DOC produced by aquatic plants and algae, rDOC = DOC deposition in rainwater, M_{tDOC} = mineralized terrestrially derived DOC in inland waters, B_{tDOC} = buried terrestrially derived DOC in inland waters, E_{tDOC} = exported terrestrially derived DOC to coastal oceans.

significantly diminishes the soil organic matter, which in turn leads to a decrease in soil DOC production, resulting in a reduced amount of terrestrially derived DOC [93]. Hurricanes produce heavy precipitation, which affects the performance of models based on the dilution C–Q pattern [9] and potentially brings substantial DOC with rainwater to the inland waters [94]. It is difficult to incorporate these disturbances in indicator-driven models and hydrology-forced models, whereas process-based models have the potential ability to include these disturbances. Currently, the effects of disturbances on DOC export are rarely comprehensively represented in modeling studies. The frequency of fires and hurricanes is projected to increase with global warming [95], and so it will be necessary to model these disturbances in future studies to better characterize the dynamics of DOC export.

6. Conclusions

By reviewing, analyzing, and comparing 34 published DOC export simulation models, we identified challenges for selecting the most appropriate model to estimate the DOC export from a landscape, such as the available environmental factors, target simulation time step, and landscape characteristics. Our findings indicate that assuming sufficient soil DOC while ignoring the production process can lead to an overestimation of DOC export in source-limited regions. Therefore, process-based models, which simulate the entire terrestrial ecosystem, are the optimal choice. Additionally, in regions subject to frequent heavy precipitation, models that can comprehensively simulate soil DOC production and desorption process are crucial. These models effectively eliminate the diluting effect, where DOC concentration decreases during high flow events, ensuring more reliable results. Moreover, current simulation models for estimating the DOC transit through inland waters rely heavily on numerous assumptions about unmeasured or unknown quantities, rates, and mechanisms. Although benchmarks collected at the river outlet are generally used to validate the results, overlooking processes of DOC in inland waters may not have a significant influence on the estimation of DOC eventually exported from a landscape. However, this neglect could lead to inaccurate estimates of both soil DOC loss and terrestrially derived DOC exported from the landscape. Therefore, our analysis of existing measurements and the development of a detailed budget for global land-to-ocean terrestrially derived DOC flux present opportunities for enhancing current models and validating estimates.

Author contributions

Xinyuan Wei and Daniel Hayes conceived the research idea. Xinyuan Wei collected the data, conducted the analysis, and wrote the original draft. All authors contributed to reviewing and editing the manuscript.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Regnier P, Resplandy L, Najjar R G and Ciais P 2022 The land-to-ocean loops of the global carbon cycle *Nature* **603** 1–10
[2] Battin T J, Luyssaert S, Kaplan L A, Aufdenkampe A K, Richter A and Tranvik L J 2009 The boundless carbon cycle *Nat. Geosci.* **2** 598–600
[3] Casas-Ruiz J P, Bodmer P, Bona K A, Butman D, Couturier M, Emilson E J, Finlay K, Genet H, Hayes D and Karlsson J 2023 Integrating terrestrial and aquatic ecosystems to constrain estimates of land-atmosphere carbon exchange *Nat. Commun.* **14** 1571
[4] Butman D, Stackpoole S, Stets E, McDonald C P, Clow D W and Striegl R G 2016 Aquatic carbon cycling in the conterminous United States and implications for terrestrial carbon accounting *Proc. Natl Acad. Sci.* **113** 58–63
[5] Laudon H, Berggren M, Ågren A, Buffam I, Bishop K, Grabs T, Jansson M and Köhler S 2011 Patterns and dynamics of dissolved organic carbon (DOC) in boreal streams: the role of processes, connectivity, and scaling *Ecosystems* **14** 880–93
[6] Drake T W, Raymond P A and Spencer R G 2018 Terrestrial carbon inputs to inland waters: a current synthesis of estimates and uncertainty *Limnol. Oceanogr. Lett.* **3** 132–42
[7] Wei X, Hayes D J, Li D, Butman D E and Brewin R J 2024 Fates of terrigenous dissolved organic carbon in the Gulf of Maine *Environ. Sci. Technol.* **58** 3258–66
[8] Stets E G and Striegl R G 2012 Carbon export by rivers draining the conterminous United States *Inland Waters* **2** 177–84
[9] Wen H, Perdrial J, Abbott B W, Bernal S, Dupas R, Godsey S E, Harpold A, Rizzo D, Underwood K and Adler T 2020 Temperature controls production but hydrology regulates export of dissolved organic carbon at the catchment scale *Hydrol. Earth Syst. Sci.* **24** 945–66
[10] Wickland K P, Waldrop M P, Aiken G R, Koch J C, Jorgenson M T and Striegl R G 2018 Dissolved organic carbon and nitrogen release from boreal Holocene permafrost and seasonally frozen soils of Alaska *Environ. Res. Lett.* **13** 065011
[11] Lee E-J, Yoo G-Y, Jeong Y, Kim K-U, Park J-H and Oh N-H 2015 Comparison of UV–VIS and FDOM sensors for *in situ* monitoring of stream DOC concentrations *Biogeosciences* **12** 3109–18
[12] Jutras M-F *et al* 2011 Dissolved organic carbon concentrations and fluxes in forest catchments and streams: DOC-3 model *Ecol. Modell.* **222** 2291–313
[13] Hirsch R M, Moyer D L and Archfield S A 2010 Weighted regressions on time, discharge, and season (WRTDS), with an application to Chesapeake Bay river inputs 1 *J. Am. Water Resour. Assoc.* **46** 857–80
[14] Vantrepotte V, Danhiez F-P, Loisel H, Ouillon S, Mériaux X, Cauvin A and Dessailly D 2015 CDOM-DOC relationship in contrasted coastal waters: implication for DOC retrieval from ocean color remote sensing observation *Opt. Express* **23** 33–54
[15] Griffin C, McClelland J, Frey K, Fiske G and Holmes R 2018 Quantifying CDOM and DOC in major Arctic rivers during ice-free conditions using Landsat TM and ETM+ data *Remote Sens. Environ.* **209** 395–409
[16] Kuhn C *et al* 2019 Performance of Landsat-8 and Sentinel-2 surface reflectance products for river remote sensing retrievals of chlorophyll-a and turbidity *Remote Sens. Environ.* **224** 104–18
[17] Tiwari T, Laudon H, Beven K and Ågren A M 2014 Downstream changes in DOC: inferring contributions in the face of model uncertainties *Water Resour. Res.* **50** 514–25
[18] Kicklighter D W, Hayes D J, McClelland J W, Peterson B J, McGuire A D and Melillo J M 2013 Insights and issues with simulating terrestrial DOC loading of Arctic river networks *Ecol. Appl.* **23** 1817–36
[19] Aitkenhead J and McDowell W H 2000 Soil C: n ratio as a predictor of annual riverine DOC flux at local and global scales *Glob. Biogeochem. Cycles* **14** 127–38
[20] Wei X, Hayes D J, Fernandez I, Fraver S, Zhao J and Weiskittel A 2021 Climate and atmospheric deposition drive the inter-annual variability and long-term trend of dissolved organic carbon flux in the conterminous United States *Sci. Total Environ.* **771** 145448
[21] Ren W, Tian H, Cai W J, Lohrenz S E, Hopkinson C S, Huang W J, Yang J, Tao B, Pan S and He R 2016 Century-long increasing trend and variability of dissolved organic carbon export from the Mississippi River basin driven by natural and anthropogenic forcing *Glob. Biogeochem. Cycles* **30** 1288–99
[22] Neff J C and Asner G P 2001 Dissolved organic carbon in terrestrial ecosystems: synthesis and a model *Ecosystems* **4** 29–48
[23] Zarnetske J P, Bouda M, Abbott B W, Saiers J and Raymond P A 2018 Generality of hydrologic transport limitation of watershed organic carbon flux across ecoregions of the United States *Geophys. Res. Lett.* **45** 11,702–11
[24] Willey J D, Kieber R J, Eyman M S and Avery G B Jr 2000 Rainwater dissolved organic carbon: concentrations and global flux *Glob. Biogeochem. Cycles* **14** 139–48
[25] Moore T R, Paré D and Boutin R 2008 Production of dissolved organic carbon in Canadian forest soils *Ecosystems* **11** 740–51
[26] Walker T W, Kaiser C, Strasser F, Herbold C W, Leblans N I, Woebken D, Janssens I A, Sigurdsson B D and Richter A 2018 Microbial temperature sensitivity and biomass change explain soil carbon loss with warming *Nat. Clim. Change* **8** 885–9
[27] Sawicka K, Monteith D, Vanguelova E, Wade A J and Clark J M 2016 Fine-scale temporal characterization of trends in soil water dissolved organic carbon and potential drivers *Ecol. Indic.* **68** 36–51
[28] Leinemann T, Preusser S, Mikutta R, Kalbitz K, Cerli C, Höschen C, Mueller C, Kandeler E and Guggenberger G 2018 Multiple exchange processes on mineral surfaces control the transport of dissolved organic matter through soil profiles *Soil Biol. Biochem.* **118** 79–90
[29] Nakhavali M, Lauerwald R, Regnier P, Guenet B, Chadburn S and Friedlingstein P 2021 Leaching of dissolved organic carbon from mineral soils plays a significant role in the terrestrial carbon balance *Glob. Change Biol.* **27** 1083–96
[30] Vachon D, Prairie Y T, Guillemette F and Del Giorgio P A 2017 Modeling allochthonous dissolved organic carbon mineralization under variable hydrologic regimes in boreal lakes *Ecosystems* **20** 781–95

[31] Mendonça R, Müller R A, Clow D, Verpoorter C, Raymond P, Tranvik L J and Sobek S 2017 Organic carbon burial in global lakes and reservoirs *Nat. Commun.* **8** 1694
[32] Clair T, Pollock T and Ehrman J 1994 Exports of carbon and nitrogen from river basins in Canada's Atlantic Provinces *Glob. Biogeochem. Cycles* **8** 441–50
[33] Birkel C, Soulsby C and Tetzlaff D 2014 Integrating parsimonious models of hydrological connectivity and soil biogeochemistry to simulate stream DOC dynamics *J. Geophys. Res.* **119** 1030–47
[34] Neitsch S L, Arnold J G, Kiniry J R and Williams J R 2011 *Soil and Water Assessment Tool Theoretical Documentation Version 2009* (Texas Water Resources Institute)
[35] Ludwig W, Probst J L and Kempe S 1996 Predicting the oceanic input of organic carbon by continental erosion *Glob. Biogeochem. Cycles* **10** 23–41
[36] Harrison J A, Caraco N and Seitzinger S P 2005 Global patterns and sources of dissolved organic matter export to the coastal zone: results from a spatially explicit, global model *Glob. Biogeochem. Cycles* **19** GB4S04
[37] Creed I, Beall F, Clair T, Dillon P and Hesslein R 2008 Predicting export of dissolved organic carbon from forested catchments in glaciated landscapes with shallow soils *Glob. Biogeochem. Cycles* **22** GB4024
[38] Lauerwald R, Hartmann J, Ludwig W and Moosdorf N 2012 Assessing the nonconservative fluvial fluxes of dissolved organic carbon in North America *J. Geophys. Res.* **117** G01027
[39] Hornberger G, Bencala K and McKnight D 1994 Hydrological controls on dissolved organic carbon during snowmelt in the Snake River near Montezuma, Colorado *Biogeochemistry* **25** 147–65
[40] McClelland J, Stieglitz M, Pan F, Holmes R and Peterson B 2007 Recent changes in nitrate and dissolved organic carbon export from the upper Kuparuk River, North Slope, Alaska *J. Geophys. Res.* **112** G04S60
[41] Futter M, Butterfield D, Cosby B, Dillon P, Wade A and Whitehead P 2007 Modeling the mechanisms that control in-stream dissolved organic carbon dynamics in upland and forested catchments *Water Resour. Res.* **43** W02424
[42] Yurova A, Sirin A, Buffam I, Bishop K and Laudon H 2008 Modeling the dissolved organic carbon output from a boreal mire using the convection-dispersion equation: importance of representing sorption *Water Resour. Res.* **44** W07411
[43] Naden P S, Allott N, Arvola L, Järvinen M, Jennings E, Moore K, Aonghusa C N, Pierson D and Schneiderman E 2010 *The Impact of Climate Change on European Lakes* (Springer) pp 221–52
[44] Xu N, Saiers J E, Wilson H F and Raymond P A 2012 Simulating streamflow and dissolved organic matter export from a forested watershed *Water Resour. Res.* **48** W05519
[45] Lessels J S, Tetzlaff D, Carey S K, Smith P and Soulsby C 2015 A coupled hydrology–biogeochemistry model to simulate dissolved organic carbon exports from a permafrost-influenced catchment *Hydrol. Process.* **29** 5383–96
[46] Bernard-Jannin L, Binet S, Gogo S, Leroy F, Défarge C, Jozja N, Zocatelli R, Perdereau L and Laggoun-Défarge F 2018 Hydrological control of dissolved organic carbon dynamics in a rehabilitated Sphagnum-dominated peatland: a water-table based modelling approach *Hydrol. Earth Syst. Sci.* **22** 4907–20
[47] Du X, Zhang X, Mukundan R, Hoang L and Owens E M 2019 Integrating terrestrial and aquatic processes toward watershed scale modeling of dissolved organic carbon fluxes *Environ. Pollut.* **249** 125–35
[48] Fabre C, Sauvage S, Probst J-L and Sanchez-Pérez J M 2020 Global-scale daily riverine DOC fluxes from lands to the oceans with a generic model *Glob. Planet. Change* **194** 103294
[49] van Hoek W J, Wang J, Vilmin L, Beusen A H, Mogollón J M, Müller G, Pika P A, Liu X, Langeveld J J and Bouwman A F 2021 Exploring spatially explicit changes in carbon budgets of global river Basins during the 20th century *Environ. Sci. Technol.* **55** 16757–69
[50] Edwards R T, D'Amore D V, Biles F E, Fellman J B, Hood E W, Trubilowicz J W and Floyd W C 2021 Riverine dissolved organic carbon and freshwater export in the eastern Gulf of Alaska *J. Geophys. Res.* **126** e2020JG005725
[51] Rawlins M A, Connolly C T and McClelland J W 2021 Modeling terrestrial dissolved organic carbon loading to western Arctic rivers *J. Geophys. Res.* **126** e2021JG006420
[52] Wu H, Peng C, Moore T, Hua D, Li C, Zhu Q, Peichl M, Arain M and Guo Z 2014 Modeling dissolved organic carbon in temperate forest soils: TRIPLEX-DOC model development and validation *Geosci. Model Dev.* **7** 867–81
[53] Lauerwald R, Regnier P, Camino-Serrano M, Guenet B, Guimberteau M, Ducharne A, Polcher J and Ciais P 2017 ORCHILEAK (revision 3875): a new model branch to simulate carbon transfers along the terrestrial–aquatic continuum of the Amazon basin *Geosci. Model Dev.* **10** 3821–59
[54] Nakhavali M, Friedlingstein P, Lauerwald R, Tang J, Chadburn S, Camino-Serrano M, Guenet B, Harper A, Walmsley D and Peichl M 2018 Representation of dissolved organic carbon in the JULES land surface model (vn4. 4-JULES-DOCM) *Geosci. Model Dev.* **11** 593–609
[55] Tang J, Yurova A Y, Schurgers G, Miller P A, Olin S, Smith B, Siewert M B, Olefeldt D, Pilesjö P and Poska A 2018 Drivers of dissolved organic carbon export in a subarctic catchment: importance of microbial decomposition, sorption-desorption, peatland and lateral flow *Sci. Total Environ.* **622** 260–74
[56] Liao C, Zhuang Q, Leung L R and Guo L 2019 Quantifying dissolved organic carbon dynamics using a three-dimensional terrestrial ecosystem model at high spatial-temporal resolutions *J. Adv. Model. Earth Syst.* **11** 4489–512
[57] Li M, Peng C, Zhou X, Yang Y, Guo Y, Shi G and Zhu Q 2019 Modeling global riverine DOC flux dynamics from 1951 to 2015 *J. Adv. Model. Earth Syst.* **11** 514–30
[58] Bowring S P, Lauerwald R, Guenet B, Zhu D, Guimberteau M, Regnier P, Tootchi A, Ducharne A and Ciais P 2020 ORCHIDEE MICT-LEAK (r5459), a global model for the production, transport, and transformation of dissolved organic carbon from Arctic permafrost regions–part 2: model evaluation over the Lena River basin *Geosci. Model Dev.* **13** 507–20
[59] Tague C L and Band L E 2004 RHESSys: regional hydro-ecologic simulation system—an object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling *Earth Interact.* **8** 1–42
[60] Huntington T G, Balch W M, Aiken G R, Sheffield J, Luo L, Roesler C S and Camill P 2016 Climate change and dissolved organic carbon export to the Gulf of Maine *J. Geophys. Res.* **121** 2700–16
[61] Bowering K L, Edwards K A, Prestegaard K, Zhu X and Ziegler S E 2020 Dissolved organic carbon mobilized from organic horizons of mature and harvested black spruce plots in a mesic boreal region *Biogeosciences* **17** 581–95
[62] Raymond P A, Saiers J E and Sobczak W V 2016 Hydrological and biogeochemical controls on watershed dissolved organic matter transport: pulse-shunt concept *Ecology* **97** 5–16
[63] Maavara T, Lauerwald R, Regnier P and Van Cappellen P 2017 Global perturbation of organic carbon cycling by river damming *Nat. Commun.* **8** 15347
[64] Lauri H, Räsänen T A and Kummu M 2014 Using reanalysis and remotely sensed temperature and precipitation data for hydrological modeling in monsoon climate: Mekong River case study *J. Hydrometeorol.* **15** 1532–45
[65] Findlay S E 2005 Increased carbon transport in the Hudson River: unexpected consequence of nitrogen deposition? *Front. Ecol. Environ.* **3** 133–7
[66] Attermeyer K, Hornick T, Kayler Z, Bahr A, Zwirnmann E, Grossart H-P and Premke K 2014 Enhanced bacterial decomposition with increasing addition of autochthonous to

allochthonous carbon without any effect on bacterial community composition *Biogeosciences* **11** 1479–89

[67] Wei X, Hayes D J, Fernandez I, Zhao J, Fraver S, Chan C and Diao J 2021 Identifying key environmental factors explaining temporal patterns of DOC export from watersheds in the conterminous United States *J. Geophys. Res.* **126** e2020JG005813

[68] Wymore A S, Fazekas H M and McDowell W H 2021 Quantifying the frequency of synchronous carbon and nitrogen export to the river network *Biogeochemistry* **152** 1–12

[69] Wei X, Hayes D J, Ku P, Yang X and Ricciuto D M 2023 Diminishing marginal effect in estimating the dissolved organic carbon export from a watershed *Environ. Res. Commun.* **5** 031003

[70] Kalbitz K, Solinger S, Park J-H, Michalzik B and Matzner E 2000 Controls on the dynamics of dissolved organic matter in soils: a review *Soil Sci.* **165** 277–304

[71] Futter M N and de Wit H A 2008 Testing seasonal and long-term controls of streamwater DOC using empirical and process-based models *Sci. Total Environ.* **407** 698–707

[72] Huntzinger D, Schwalm C, Michalak A, Schaefer K, Wei Y, Cook R and Jacobson A 2014 NACP MsTMIP summary of model structure and characteristics *ORNL DAAC*

[73] van den Berg L J, Shotbolt L and Ashmore M R 2012 Dissolved organic carbon (DOC) concentrations in UK soils and the influence of soil, vegetation type and seasonality *Sci. Total Environ.* **427** 269–76

[74] Wang D, Yi W, Zhou Y, He S, Tang L, Yin X, Zhao P and Long G 2021 Intercropping and N application enhance soil dissolved organic carbon concentration with complicated chemical composition *Soil Tillage Res.* **210** 104979

[75] Camino-Serrano M *et al* 2014 Linking variability in soil solution dissolved organic carbon to climate, soil type, and vegetation type *Glob. Biogeochem. Cycles* **28** 497–509

[76] Li M, Wang J, Guo D, Yang R and Fu H 2019 Effect of land management practices on the concentration of dissolved organic matter in soil: a meta-analysis *Geoderma* **344** 74–81

[77] Liu Y, Evans S E, Friesen M L and Tiemann L K 2022 Root exudates shift how N mineralization and N fixation contribute to the plant-available N supply in low fertility soils *Soil Biol. Biochem.* **165** 108541

[78] Calvo O C, Franzaring J, Schmid I and Fangmeier A 2019 Root exudation of carbohydrates and cations from barley in response to drought and elevated CO 2 *Plant Soil* **438** 127–42

[79] Chen H, Tsai K-P, Su Q, Chow A T and Wang J-J 2019 Throughfall dissolved organic matter as a terrestrial disinfection byproduct precursor *ACS Earth Space Chem.* **3** 1603–13

[80] Ryan K A, Adler T, Chalmers A, Perdrial J, Shanley J B and Stubbins A 2021 Event scale relationships of DOC and TDN fluxes in throughfall and stemflow diverge from stream exports in a forested catchment *J. Geophys. Res.* **126** e2021JG006281

[81] Koven C, Riley W, Subin Z, Tang J, Torn M, Collins W, Bonan G, Lawrence D and Swenson S 2013 The effect of vertically resolved soil biogeochemistry and alternate soil C and N models on C dynamics of CLM4 *Biogeosciences* **10** 7109–31

[82] Vandenbruwane J, De Neve S, Qualls R G, Sleutel S and Hofman G 2007 Comparison of different isotherm models for dissolved organic carbon (DOC) and nitrogen (DON) sorption to mineral soil *Geoderma* **139** 144–53

[83] Cole J J *et al* 2007 Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget *Ecosystems* **10** 172–85

[84] Maavara T, Brinkerhoff C, Hosen J, Aho K, Logozzo L, Saiers J, Stubbins A and Raymond P 2023 Watershed DOC uptake occurs mostly in lakes in the summer and in rivers in the winter *Limnol. Oceanogr.* **68** 735–51

[85] Allesson L, Koehler B, Thrane J E, Andersen T and Hessen D O 2021 The role of photomineralization for CO_2 emissions in boreal lakes along a gradient of dissolved organic matter *Limnol. Oceanogr.* **66** 158–70

[86] Donohue I and Garcia Molinos J 2009 Impacts of increased sediment loads on the ecology of lakes *Biol. Rev.* **84** 517–31

[87] McCallister S, Ishikawa N and Kothawala D 2018 Biogeochemical tools for characterizing organic carbon in inland aquatic ecosystems *Limnol. Oceanogr. Lett.* **3** 444–57

[88] Delpla I, Baurès E, Jung A-V and Thomas O 2011 Impacts of rainfall events on runoff water quality in an agricultural environment in temperate areas *Sci. Total Environ.* **409** 1683–8

[89] Krickov I V, Lim A G, Shirokova L S, Korets M A, Karlsson J and Pokrovsky O S 2023 Environmental controllers for carbon emission and concentration patterns in Siberian rivers during different seasons *Sci. Total Environ.* **859** 160202

[90] Hall B D, Hesslein R H, Emmerton C A, Higgins S N, Ramlal P and Paterson M J 2019 Multidecadal carbon sequestration in a headwater boreal lake *Limnol. Oceanogr.* **64** S150–S65

[91] Carignan R, D'Arcy P and Lamontagne S 2000 Comparative impacts of fire and forest harvesting on water quality in Boreal Shield lakes *Can. J. Fish. Aquat. Sci.* **57** 105–17

[92] Wei X, Hayes D J and Fernandez I 2021 Fire reduces riverine DOC concentration draining a watershed and alters post-fire DOC recovery patterns *Environ. Res. Lett.* **16** 024022

[93] Lajtha K and Jones J 2018 Forest harvest legacies control dissolved organic carbon export in small watersheds, western Oregon *Biogeochemistry* **140** 299–315

[94] Avery G B Jr, Kieber R J, Willey J D, Shank G C and Whitehead R F 2004 Impact of hurricanes on the flux of rainwater and Cape Fear River water dissolved organic carbon to Long Bay, southeastern United States *Glob. Biogeochem. Cycles* **18** GB3015

[95] Moritz M A, Parisien M-A, Batllori E, Krawchuk M A, Van Dorn J, Ganz D J and Hayhoe K 2012 Climate change and disruptions to global fire activity *Ecosphere* **3** 1–22