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SYNTHESIS

Forecasting climate and human alterations to coastal and estuarine dissolved organic matter

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Scientific Significance Statement

Human activities alter landscapes, impacting dissolved organic matter (DOM) sources and transformations from inland to coastal areas. Hydrological alterations and climate change further affect carbon and nutrient concentrations, as well as the transport and transformation of DOM and dissolved organic carbon (DOC). Along river networks, DOM and DOC are transported downstream to coastal regions, where human populations are expanding and the effects of sea levels are rapidly rising. Understanding the dynamics of DOM and DOC in anthropogenically affected regions is critical because both directly influence carbon cycling and coastal and estuarine water quality. Our synthesis examines how land use and hydrological changes affect DOC quantity and DOM quality along inland-to-coastal gradients. We predict DOC concentrations and microbial and algal sources of DOM will increase. We anticipate DOC concentrations and DOM sources will continue to change with climate change and human activities along inland-to-coastal gradients.

Abstract

River networks serve as conduits for dissolved organic matter (DOM) and carbon (DOC) from inland to coastal waters. Human activities and climate change are altering DOM sources, causing hydrological and biogeochemical shifts that impact DOC concentrations and changing the transport and transformation of DOM and DOC. Here, we synthesize current knowledge of changing DOM sources, DOC concentrations, and the associated hydrological and biogeochemical changes during transport along inland-to-coastal gradients, focusing on impacts to coastal and estuarine DOM and DOC. We project that continued land-use changes, hydrological management, and sea-level rise will result in more microbial and labile DOM, higher DOC concentrations, and an overall decoupling of DOC quantity and DOM quality. Understanding how these changes vary among river networks is essential to forecast coastal and estuarine water quality, ecosystem health, and global carbon cycling.

Climate- and human-driven hydrological alterations to watersheds affect dissolved organic matter (DOM) composition and dissolved organic carbon (DOC) concentrations. In this synthesis, we refer to DOM as the diverse mixture of organic compounds that constitute dissolved organic matter, highlighting its chemical characteristics and composition, and

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to DOC concentration as the amount of dissolved organic carbon present in a specific volume of water (Fig. 1, component 1 and 2). The composition of DOM along inland-to-coastal gradients is shaped by vegetation communities, soil composition and permeability, human land uses, and hydrological alterations of fresh and saltwater that impact DOM and DOC transformation and transport (Osburn et al. 2016; Bhattacharya and Osburn 2020; Leyva et al. 2022). Droughts and floods alter the inputs of terrestrial-derived DOM, influencing carbon cycling along inland-to-coastal gradients (Epstein et al. 2016). Further, hydrological management, such as dams, canals, and floodgates, alters the upstream–downstream transport of DOM and DOC throughout river networks (Xenopoulos et al. 2021). Hydrological and land-use alterations inland and coastal saltwater intrusion from sea-level rise can modify the quantity of DOC and quality of DOM in coastal and estuarine waters (Tully et al. 2019), potentially decoupling carbon sources and concentrations. There is a critical need to better synthesize the characteristics of DOM and concentrations of DOC in human-modified landscapes with altered hydrology to understand evolving dynamics of DOM sources, transport, and fates on coastal and estuarine water quality and the global carbon cycle (Drake et al. 2018).

The composition of DOM during transport through river networks has primarily been studied by established conceptual models. The River Continuum Concept (RCC) is a theoretical framework forecasting the longitudinal transformations of organic matter in river systems (Vannote et al. 1980). Although the RCC does not make specific predictions about DOM dynamics, it predicts higher concentrations and higher diversity of organic matter sources in headwaters (i.e., upland regions of watersheds containing lower-order streams and rivers) that will decrease toward the coast. The Pulse-Shunt Concept (PSC) expands on the RCC by introducing a temporal dimension to DOM dynamics, predicting that during episodes of extreme discharge, high quantities of DOM are transported from soils to streams (pulse) and subsequently exported conservatively to coastal systems due to elevated velocity and reduced residence time (shunt) (Raymond et al. 2016). Further research expands on the knowledge of DOM by explaining that riverine DOC follows a chemostatic pattern due to downstream homogenization of DOC concentration and a decrease in DOM aromaticity with increased stream order (Creed et al. 2015). For urban streams, the urban watershed continuum expands on the RCC by analyzing longitudinal, lateral, vertical, and temporal variables and their impact on DOM transport, transformation, and destiny (Kaushal and Belt 2012). Although these models are useful for understanding DOM dynamics across different scales and environments, they lack explicit consideration of DOM dynamics at the inland-coastal interface, where the transport and transformation of DOM and DOC are unique, complex, and rapidly changing (Anderson et al. 2024).

Coastal and estuarine ecosystems occupy regions of dynamic freshwater and marine influences. Saltwater intrusion, aggravated by sea-level rise due to increased global temperatures, poses an accelerating risk to fresh waters (Tully et al. 2019; Parkinson and Wdowinski 2022). Shallow coastal environments with karstic geology are especially vulnerable, as the porous limestone substrate facilitates the rapid movement of salt water into groundwater. This increased risk of saltwater intrusion, particularly in low-lying areas where underground aquifers are closely connected to coastal waters, is accelerating (Befus et al. 2020). While previous studies have explored the connection between sea-level rise and DOM (Ardón et al. 2016; Kominoski et al. 2020; Anderson et al. 2024), a synthesis of the cumulative impacts of anthropogenic hydrological modifications and saltwater intrusion on DOM sources and DOC concentrations in coastal and estuarine waters is needed (e.g., Smith et al. 2021).

Given expected increases in rates of sea-level rise, hydrological alterations, and human land-use change and activities,

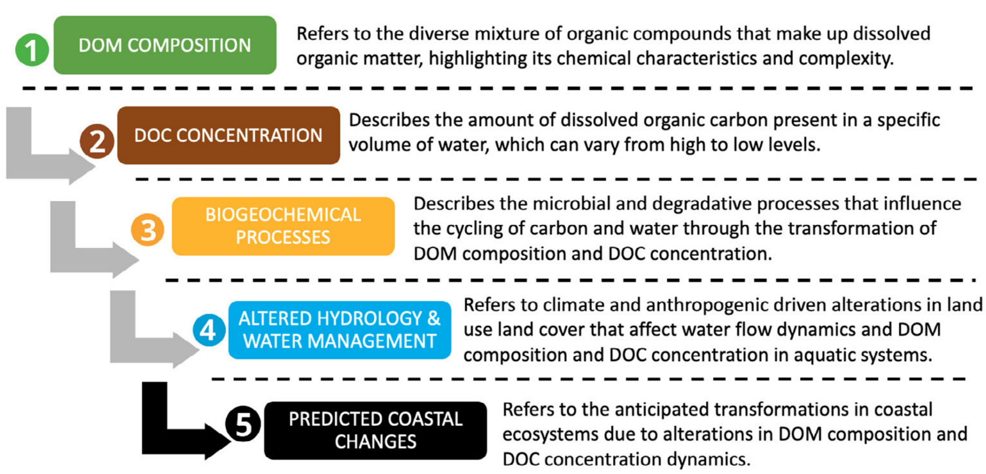

Fig. 1. Contextual flow chart explaining key terms and their meanings within this synthesis.

coastal and estuarine waters will likely experience an increasing disconnect between DOM sources and DOC concentrations. In this synthesis, we address the following: (1) Describe how diverse and dynamic sources of DOM and DOC vary along inland-to-coastal gradients (Fig. 2); (2) Characterize how biogeochemical transformations of DOM and DOC are changing with land-use change and hydrological alterations (Fig. 2); and (3) Forecast changes in spatial and temporal patterns of DOM composition and DOC concentrations throughout river networks that collectively impact downstream coastal and estuarine waters (Fig. 3).

Sources and alterations of dissolved organic matter composition and dissolved organic carbon concentrations

Stream and river networks are vital conduits for moving large quantities of carbon from land to sea, and recent estimates show an increase in terrestrial carbon export to oceans due to increased human activity (Drake et al. 2018). Dissolved organic carbon, the most abundant form of carbon in aquatic systems (Wetzel 1995), plays a vital role in the connectivity between terrestrial, aquatic, atmospheric, and oceanic carbon pools. The export of carbon from inland waters to the coast varies in its chemical structure from labile to recalcitrant, and this variability is highly dependent on different DOM sources that change along inland-to-coastal gradients (Lloret et al. 2016). The main points of this paper are synthesized in Table 1.

Autochthonous and allochthonous dissolved organic matter sources

In inland aquatic systems, DOM originates from a variety of allochthonous and autochthonous sources. Allochthonous DOM can be derived from soil, vegetation, and roots outside the stream, and its delivery is influenced by hydrologic pathways, conductivity, precipitation, wetlands, and land cover (Willey et al. 2000; Tank et al. 2010; Raymond and Spencer 2015). In forested watersheds, riparian leaf litter is a key source of allochthonous DOM, contributing up to 30% of DOM in small streams (Meyer et al. 1998). Watersheds with forested headwater, extensive floodplains, bottomland forests with organic-rich soils, inland and coastal peatlands and marshlands, and coastal forests typically export humic DOM with high DOC concentrations (Chen et al. 2013; Regnier et al. 2022). In grassland and non-forested watersheds, belowground allochthonous sources play a significant role in DOM flux to aquatic ecosystems, particularly in areas undergoing permafrost thaw, which release previously sequestered organic material. In these regions, surface water photochemical oxidation accounts for 70–95% of the total DOM processed in the water column (Cory et al. 2014). Additionally, tidal riverine and groundwater sources are important pathways for DOM exchange in coastal and estuarine environments (Xenopoulos et al. 2017; Smith et al. 2021).

Autochthonous DOM sources in aquatic ecosystems include macrophytes, algae, and biofilms, as well as decomposed organic matter produced by phytoplankton, zooplankton, bacteria, and viruses (Maie et al. 2006; Chen et al. 2010). Autochthonous production and sources of DOM are highly controlled by light and nutrient availability. Phytoplankton can produce DOM by autolysis during physiological stress conditions (Boekell et al. 1992). Dissolved organic matter can also be produced by zooplankton through the consumption of phytoplankton (Hygum et al. 1997). In addition, bacteria can produce DOM through cell division and viral lysis (Kawasaki and Benner 2006). Moreover, predominant viruses at the coast contribute to the release of DOM through the lytic cycle, where viral infection of microbial hosts results in cell lysis and the subsequent release of DOM into the surrounding waters (Lønborg et al. 2013).

Terrestrial dissolved organic matter sources

Terrestrial DOM originates from allochthonous sources, with the proportion and type of organic matter delivered and processed depending largely on land cover and the characteristics of the surrounding ecosystems. Although terrestrial ecosystems are major contributors of organic matter, the composition of DOM is chemically complex, comprising a wide range of organic compounds. For example, leaching of organic matter from soils and vegetation contributes DOM to aquatic systems (Meyer et al. 1998; Nakhavali et al. 2021). As acidic rainwater and surface runoff infiltrate the soil, organic humic materials, such as humic and fulvic acids, dissolve. Dissolved organic compounds, resulting from the degradation of plant and animal material, can contribute nearly half of the global DOM exported to coastal regions (Meybeck 1993). Additionally, lignin, a complex polymer found in plant cell walls, breaks down into aromatic compounds like phenolic acids and vanillin, contributing to the inland DOM pool. Carbohydrates, including simple sugars and polysaccharides like cellulose and hemicellulose, are also part of DOM. Proteins, amino acids, and organic acids derived from the breakdown of plant and animal tissues further enhance DOC concentration (Adeleke et al. 2017; Kroeger et al. 2021). Dissolved organic matter also includes a diverse array of compounds such as lipids, tannins, and alkaloids, which originate from the degradation of plant and animal materials. Proteins, amino acids, and various organic acids (including fatty acids, nucleic acids, and other small organic molecules) further enrich the DOC concentration, showcasing the intricate and multifaceted nature of DOM.

Peatlands and other organic-rich wetlands are primary sources of DOM in inland waters and play a crucial role in accumulating large amounts of partially decomposed plant material. Wetlands contribute substantial amounts of carbon to inland waters (e.g., up to 91 ± 54 Tg) increasing inland DOC concentrations and subsidizing carbon that is eventually

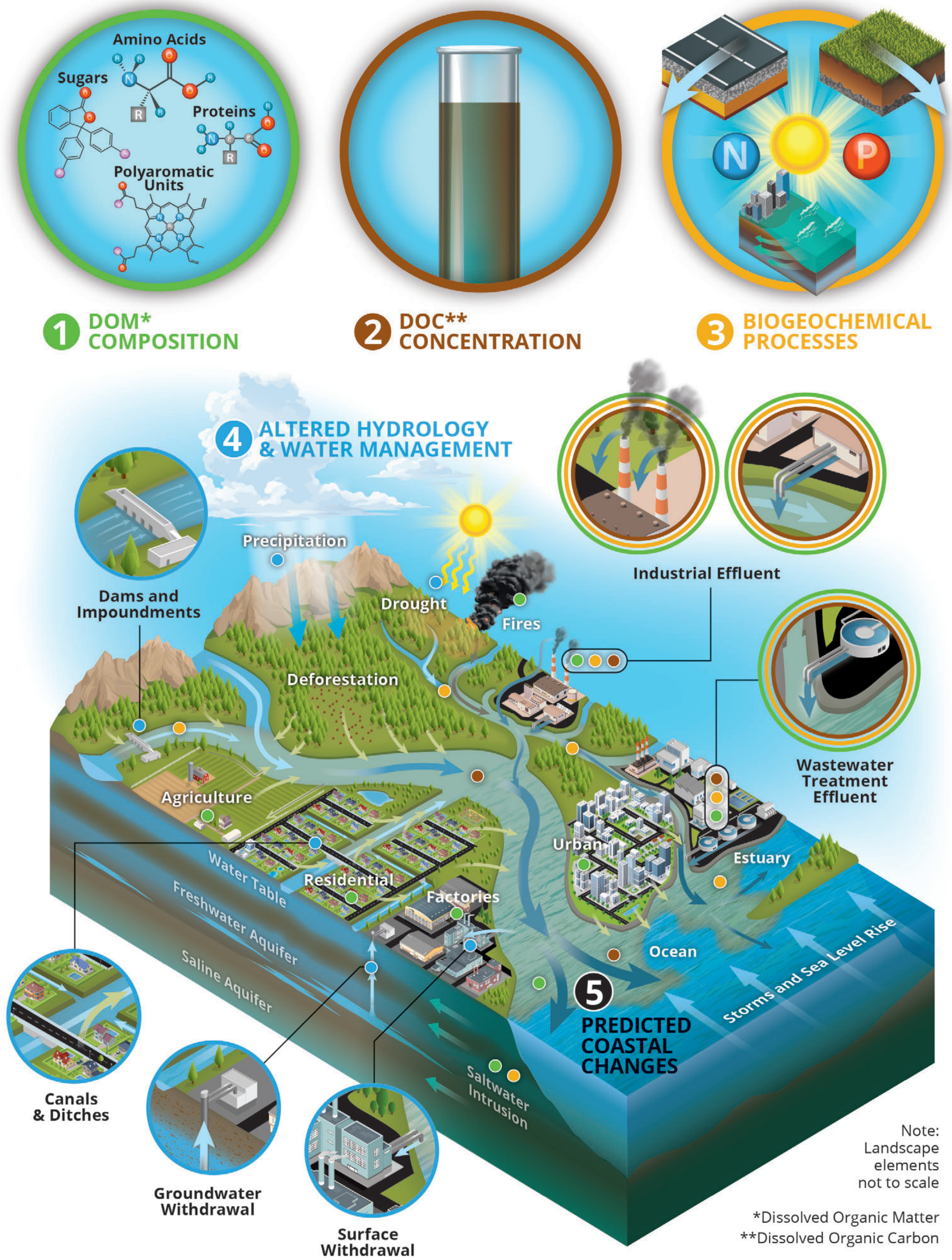

Fig. 2. Representation of locations and drivers of changes in dissolved organic matter (DOM) and dissolved organic carbon (DOC). The arrows illustrate the movement of water from inland areas to the coast. Colored dots indicate the drivers and locations where alterations in DOM composition and DOC concentration occur. (1) DOM Compositions: Changes in DOM composition occur in various settings, including agricultural and residential areas, factories, industrial effluents, and wastewater treatment plant effluents. Fires, saltwater intrusion, and mixing freshwater and saltwater also drive these changes. (2) DOC Concentration: Variations in DOC concentration are influenced by anthropogenic effluents, deforestation, reduced connectivity of organic matter, and natural organic matter changes in DOM sources along the inland-to-coastal gradient. (3) Biogeochemical Processes: These processes occur throughout the landscape and are driven by anthropogenic effluents, and the interaction between freshwater and saltwater is also driven by eutrophication, pH changes caused by saltwater intrusion, and photodegradation. (4) Altered Hydrology and Water Management: This section highlights the locations and types of water management practices that impact DOC and DOM. (5) Predicted Coastal Changes: Locations where changes in DOC concentration and DOM composition are expected to occur in coastal and estuarine waters. Figure designed by Hiram Henriquez.

transported downstream to coastal and estuarine waters (Rosset et al. 2022). Seasonal ecological variations, such as soil freeze/thaw cycles and deciduous leaf fall, influence DOC concentrations by flushing allochthonous dissolved and particulate organic matter into water bodies, introducing pulses of organic matter (Fork et al. 2018).

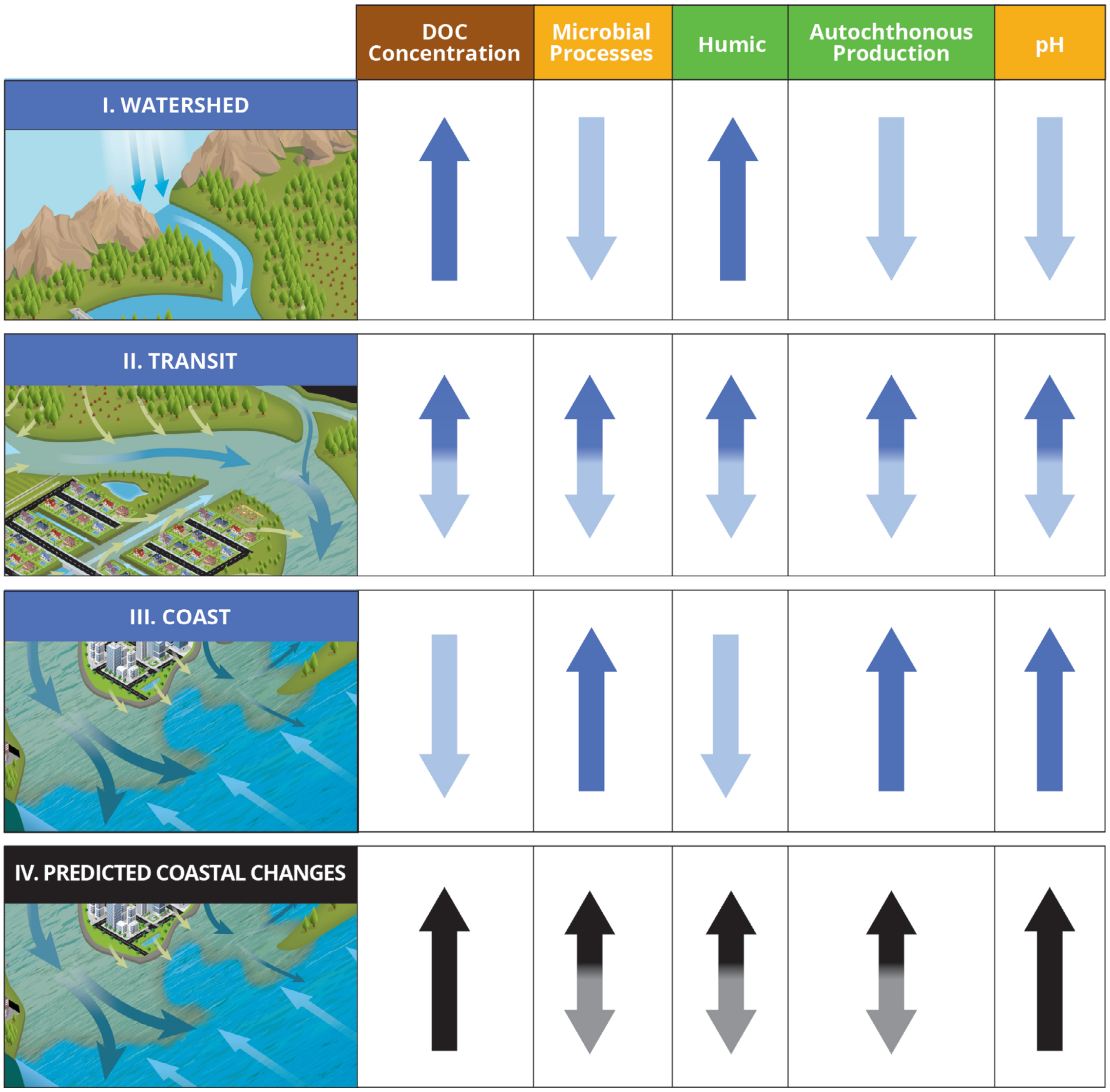

Fig. 3. Key drivers of changes in dissolved organic matter (DOM) compositions and dissolved organic carbon (DOC) concentrations along inland-to-coastal gradients. The left-side figures illustrate hydrological differences along this gradient. The header columns are color-coded as follows: brown for DOC concentration, yellow for biogeochemical processes, and green for DOM composition, as shown in Fig. 2. The blue arrows indicate general trends (increasing, decreasing, and both) of DOM based on current literature. The black arrows represent predicted coastal changes in DOM. (I) Inland Watershed Scale: DOC concentrations are typically high with pronounced humic characteristics due to greater connectivity with organic matter. (II) Transitional Zone: As water transits from inland areas to the coast, DOM and DOC characteristics change. These changes are influenced by anthropogenic activities, discharge levels, and varying organic matter sources, making the trends dependent on location and time. (III) Coastal Zone: Indicates that coastal waters generally have lower DOC concentrations and humic DOM than inland watershed areas. However, coastal and estuarine waters have high autochthonous production and microbially driven DOM. (IV) Predicted Coastal Changes: Increased water management, higher discharge toward the coast, and reduced residence time are expected to result in elevated DOC concentrations at the coast. The quality of DOM will vary depending on source interactions, but overall, we anticipate high autochthonous production with increased DOC concentrations in coastal areas due to increased water management export to the coast. Figure designed by Hiram Henriquez.

Agricultural and urban alterations and dissolved organic matter sources

Agricultural land use and urbanization have profound implications for the dynamics of organic carbon sources in aquatic ecosystems. Urban land use can alter the inputs of natural organic carbon, such as instream primary production, vegetation litter, and soils while introducing novel sources of organic matter (Fig. 2, component 1). Urbanization reduces the production and export of terrigenous organic matter into drainage networks due to deforestation and wetland losses (Hosen et al. 2014; Parr et al. 2015; Van Stan and Stubbins 2018; Bhattacharya and Osburn 2020; Gold

Table 1. Structured synthesis of the main sections of the paper. The "Section" column highlights the three primary sections, each bolded for clarity, while subsections within each section are italicized.

Section	Synthesis	Key references
Introduction	• Describe how diverse and dynamic sources of DOM and DOC vary along inland-to-coastal gradients. • Characterize how biogeochemical transformations of DOM and DOC are changing with land-use change and hydrological alterations. • Forecast changes in spatial and temporal patterns of DOM composition and DOC concentrations throughout river networks that collectively impact downstream coastal and estuarine waters.	
Sources and alterations of dissolved organic matter composition and dissolved organic carbon concentrations		
Autochthonous and allochthonous dissolved organic matter sources	• DOM comes from external (allochthonous) sources like soil, vegetation, and wetlands, and internal (autochthonous) sources like phytoplankton, bacteria, and viruses. • Allochthonous DOM is influenced by hydrological processes. • Autochthonous DOM production is driven by light, nutrients, and biological processes.	Maie et al. 2006; Chen et al. 2010; Tank et al. 2010; Lønborg et al. 2013; Cory et al. 2014; Raymond and Spencer 2015
Terrestrial dissolved organic matter sources	• Terrestrial DOM is leached from organic material (soils and vegetation), with high humic substances and DOC concentrations. • Microbial degradation of detritus affects DOM. Inland waters contribute significantly to global carbon export through DOM transport.	Drake et al. 2018; Rosset et al. 2022
Agricultural and urban alterations and dissolved organic matter sources	• Urbanization and agriculture alter DOM sources, introducing new forms like plastic-derived DOM, stormwater, and wastewater. • Urbanization and water management disrupt soil-stream connectivity and influence DOM export.	Griffith et al. 2009; Kaushal and Belt 2012; Hosen et al. 2014; Raymond et al. 2016; Xenopoulos et al. 2021; Kaushal et al. 2023
Coastal dissolved organic matter sources and emerging alterations	• Coastal DOM is transformed by microbial processes, which are increasing with climate change. • Increases in tides and temperatures accelerate microbial degradation, decreasing recalcitrant DOM. • Tidal rates and microbial activities alter DOM distribution and export to the ocean.	Jiao et al. 2010; Lønborg et al. 2020

(Continues)

Table 1. Continued

Section	Synthesis	Key references
Biogeochemical processes and alterations in dissolved organic matter quality and dissolved organic carbon quantity		
Types of dissolved organic matter and dissolved organic carbon transformations	• Microorganisms break down organic compounds. • Photodegradation reduces the structural complexity of DOM and decreases DOC concentrations. • Chemical transformations, like oxidation and hydrolysis, simplify complex organic matter. • Physical processes such as adsorption, sedimentation, and mixing also influence organic matter quality and its fate in aquatic ecosystems.	Wetzel et al. 1995; Horwath 2007; Cory et al. 2010, 2014; Groeneveld et al. 2020; Bercovici et al. 2023
Environmental-driven dissolved organic matter transport and transformation	• Environmental factors such as hydrology, water residence time, and water chemistry drive DOM transport and transformation. • Stream hydrology, especially during high discharge events, promotes rapid DOM transport and high allochthonous DOM input. • Temperature and hydrology influence DOM concentrations and composition, with low flow and high temperatures favoring algal production and photodegradation.	Vannote et al. 1980; Moran et al. 2000; Esteves et al. 2009; Bambakidis et al. 2024
Anthropogenic-driven dissolved organic matter transport and transformation	• Anthropogenic activities, such as eutrophication, salinization, and hydrological alterations, drive changes in DOM composition and affect biogeochemical cycles. ◦ Eutrophication promotes microbial metabolism and alters DOM composition, leading to algal blooms, hypoxia, and ecosystem changes. Agricultural and urban activities contribute to nutrient loading and enhance microbial processes. ◦ Salinization, caused by sea-level rise and human activities, reduces DOC concentrations through flocculation and degradation. ◦ Managed hydrology affects DOM and DOC transport and transformation, altering bioavailability and microbial processing.	Chislock et al. 2013; Bhattacharya et al. 2016; Bhattacharya and Osburn 2020; Xenopoulos et al. 2021; Kinsman-Costello et al. 2023

(Continues)

Table 1. Continued

Section	Synthesis	Key references
Forecasted changes and trends in coastal and estuarine dissolved organic matter and dissolved organic carbon		
Decoupling of dissolved organic carbon quantity and dissolved organic matter quality	• Water management, eutrophication, and saltwater intrusion drive shifts in DOM quality and quantity. • Higher DOC concentrations are expected at the coast due to reduced dilution and microbial degradation under pulsed stormwater flow. Saltwater intrusion will increase DOM lability. • Relative changes will be system and driver dependent. ◦ Human-induced nutrient enrichment accelerates microbial activity and DOM degradation, shifting to more labile DOM, while maintaining high DOC concentrations. ◦ Saltwater intrusion alters DOM composition by shifting inland water toward humic, high-molecular-weight DOM, influencing coastal trophic dynamics.	Chislock et al. 2013; Duan et al. 2015; Kominoski et al. 2015; Raymond et al. 2016; Tully et al. 2019; Gold et al. 2020; Anderson et al. 2024
Closing remarks	• Anthropogenic and natural factors will significantly impact DOM quality and quantity in urban coastal environments. • Climate change and hydrological modifications, such as continuous water management discharges downstream (constant shunt), are likely to increase DOC concentrations at the coast. • Due to sea level rise, DOM quality is expected to shift toward more labile forms, although system-specific factors may also contribute to the persistence of recalcitrant DOM.	

Abbreviation: DOC, dissolved organic carbon; DOM, dissolved organic matter

et al. 2020). Changes in forest community composition and the removal of riparian forests further contribute to shifts in the quantity and quality of fluvial DOM, increasing nutrient runoff (Webster et al. 2016) and stimulating autochthonous DOM production in streams (Pisani et al. 2020). Simultaneously, impervious surfaces disrupt the connection between soils and streams, decreasing a significant source of organic matter (Hosen et al. 2014). However, urbanization can also enhance organic matter loading by increasing stormwater runoff and the transport of diverse organic matter sources, including natural and anthropogenic inputs. Consequently, the urban DOM pool can become chemically complex, incorporating a wider range of organic compounds that influence microbial activity, nutrient cycling, and overall ecosystem function (Kaushal and Belt 2012; Smith et al. 2021; Kaushal et al. 2023) (Fig. 1, component 4; Fig. 2, component 4).

Anthropogenic sources alter the composition of DOM, introducing inputs ranging from wastewater to novel sources such as plastic-derived DOM (Fig. 2, component 3). Aging water infrastructure and leaking sewer and septic systems introduce labile organic matter into urban streams by releasing dissolved and particulate organic compounds from decaying infrastructure, wastewater, and sewage effluent. These compounds can contribute to increased microbial activity and alter the composition of DOM in urban watersheds (Capps et al. 2016; Smith et al. 2021). Additionally, microbial degradation and transformation of commercial plastics release humic-like and protein-like DOM, especially when exposed to UV light, posing challenges in differentiating plastic-derived organic matter from natural sources (Griffith et al. 2009; Galgani et al. 2019). Surface and stormwater runoff can directly introduce animal wastes and oils from vehicles and roads, and leachates from unlined landfills can enter groundwater. Furthermore, the emission of fossil fuels amplifies the influx of dissolved black carbon into the system, consequently elevating the presence of recalcitrant organic matter (Trilla-Prieto et al. 2021).

Previous studies have shown that DOC concentrations can increase (Kaushal and Belt 2012) or decrease (Kominoski and Rosemond 2012) with human activities, but DOC concentrations are balanced by losses of allochthonous inputs and increases in autochthonous microbial production (Parr et al. 2015). Overall, the rate of terrestrial organic carbon delivered to coastal ecosystems from inland waters is currently estimated to be 5.1 Pg C annually, increasing the inland carbon budget by $\sim$ 0.3 Pg C/y compared to previous estimates (Cole et al. 2007), due to anthropogenic activities and water management alterations (Drake et al. 2018). This increase in the carbon budget is driven by human activities such as land-use change, agriculture, and water management, which have amplified carbon fluxes to inland waters (Regnier et al. 2013). These activities enhance the lateral transport of organic matter, contributing to coastal browning and producing uncertainty in effects on coastal ecosystem dynamics (Drake et al. 2018).

Coastal dissolved organic matter sources and emerging alterations

Coastal sources of DOM include primary production by coastal wetlands and forests, biofilms, phytoplankton, marine detritus, macrophytes, benthic algae, sediments, and terrestrial inputs carried by rivers and coastal erosion (Lønborg et al. 2020). Phytoplankton blooms, often driven by anthropogenic nutrient inputs, produce significant amounts of DOC concentration through exudation and cell lysis (Boekell et al. 1992). Climate change alters these dynamics by intensifying phytoplankton blooms due to warmer waters (Dai et al. 2023), increased nutrient runoff from extreme rainfall events, and changes in upwelling driven by ocean circulation patterns (Lao et al. 2023). Studies have shown a > 10% increase in the spatial extent and a > 50% rise in the frequency of blooms across 126 countries from 2002 to 2020, primarily due to rising temperatures and shifting ocean circulation (Dai et al. 2023). Additionally, warmer temperatures and changes in light availability enhance coastal primary production, leading to greater DOC concentration release, with $\sim$ 50% of this release occurring in surface waters when nutrients are high (Rao et al. 2021). However, these effects on primary production are more evident in regions with traditionally cooler temperatures than in tropical regions, which already have temperature-based regulatory mechanisms (Dai et al. 2023). The degradation of marine organisms, such as dead phytoplankton and zooplankton, also contributes to the DOM pool (Lønborg et al. 2020), where the rates and concentrations are highly dependent on how each microbial community responds to warming water temperatures (Lønborg et al. 2019).

Terrestrial and marine processes influence DOM sources at the coast, resulting in a complex mix of organic carbon inputs. Rivers and streams transport DOM from inland areas to estuaries and coastal waters, contributing up to 10% of the total DOC concentration in the ocean pool (Benner 2004). However, climate change can affect these contributions. For instance, increased precipitation and stronger storms can drive higher terrestrial DOM inputs via rivers and coastal erosion, while sea-level rise may inundate coastal wetlands, altering their ability to sequester and export carbon (Alongi 2020). Coastal wetlands, such as salt marshes and mangroves, already export > 15% of their DOC concentration to the ocean, with mangroves releasing more than twice the amount of DOC concentration compared to salt marshes, driven by factors such as salinity, geomorphology, and tidal circulation (Alongi 2020). Thus, changes in hydrology and tidal regimes could further amplify DOM export to the coast. Additionally, incubation experiments suggest that sea-level rise could increase the remineralization of previously buried carbon, leading to a greater release of DOC concentration (Ward et al. 2019). Permafrost thawing is also expected to release large amounts of sequestered carbon into river systems, contributing to coastal DOM pools (Cory et al. 2014). The warming climate poses a particular concern in Arctic regions, where the release of labile terrigenous DOM from thawing permafrost and mobilized soils contributes to increased carbon inputs (Benner 2004). At the coast, terrestrial and marine sources combine to create heterogeneous DOC concentrations, often lower than those in inland waters (Wagner et al. 2020). However, climate-driven changes to ocean temperature and primary production could alter DOM sources at the coastal interface. For instance, photochemical processes in Arctic regions rapidly degrade terrigenous DOM, creating unique chemical properties in these high-latitude waters compared to those at lower latitudes (Benner 2004).

Biogeochemical processes and alterations of dissolved organic matter quality and dissolved organic carbon quantity

Along inland-to-coastal gradients, DOM undergoes biogeochemical processes involving various mechanisms of transformation and transport. Since DOM transport and transformation are inevitably intertwined, this section will cover the different transports and transformations driven by environmental and anthropogenic factors that influence DOM biogeochemical changes and DOC concentrations.

Types of dissolved organic matter and dissolved organic carbon transformations

Organic matter in aquatic environments undergoes various transformation processes that significantly influence DOM composition and bioavailability, and DOC concentrations. The primary types of organic matter transformation include biological degradation, photodegradation, and chemical transformation (Bercovici et al. 2023). Biological degradation is driven by microorganisms such as bacteria, fungi, and protozoa, which utilize extracellular enzymes to break down complex organic molecules into simpler compounds. Photodegradation, conversely, involves the breakdown of organic matter through exposure to sunlight, particularly ultraviolet (UV) radiation. This process can occur via direct photolysis, where UV light breaks chemical bonds, or indirect photolysis, where UV light generates reactive oxygen species that degrade organic matter, reducing the structural complexity of DOM and decreasing DOC concentrations (Wetzel et al. 1995). Photodegradation alters the chemical structure of DOM through photomineralization, photooxidation, and other photochemical reactions (Cory et al. 2018). This process reduces chromophoric dissolved organic matter (CDOM), aromatic carbon, high molecular weight DOM, and carboxyl carbon (Hernes and Benner 2003; Spencer et al. 2009). Aromatic or high molecular weight DOM can also undergo partial photodegradation, producing aliphatic or lower molecular weight compounds with relatively low CO_2 release compared to other degradation pathways, such as microbial decomposition (Cory et al. 2010; Ward et al. 2014). Additionally, photochemical O_2 consumption contributes to CO_2 production, generating new O-containing functional groups and oxidizing nitrogen-rich DOM components (Cory et al. 2010, 2014; Ward and Cory 2016). Photolabile components are consumed during these reactions, producing less labile matter with lower reactivity (Reader and Miller 2014). The impact of sunlight on DOM bioavailability varies depending on its source and composition (Wetzel et al. 1995). Photo-alteration of terrestrial DOM tends to produce low molecular weight acids and release nutrients (nitrogen and phosphorus), increasing bioavailability (Cotner and Heath 1990; Wetzel et al. 1995; Amado et al. 2007). In contrast, photo-alteration of algal-derived DOM reduces microbial bioavailability (Tranvik and Bertilsson 2001).

Organic matter can undergo chemical transformations through abiotic mechanisms, such as oxidation and hydrolysis (Fulton et al. 2004). Oxidation breaks down organic molecules through reactions with oxygen, where bonds may be broken, and new bonds can be formed (Horwath 2007). Hydrolysis cleaves bonds via water, converting complex organic matter into simpler, more bioavailable forms that affect nutrient cycling and microbial activity (Horwath 2007). Physical processes, including adsorption, sedimentation, and mixing, also transform organic matter (Groeneveld et al. 2020). Adsorption involves the binding of organic matter to mineral surfaces or particulate matter (Kaiser and Guggenberger 2000). Sedimentation leads to organic matter accumulation in sediments where it can either contribute to long-term carbon storage or undergo remineralization or resuspension (Hedges and Keil 1995). While organic matter in sediments may become chemically more complex over time through microbial transformation and increased bonding with minerals, high microbial activity accelerates degradation processes (Hedges and Keil 1995). The stability of organic matter in sediments is further influenced by varying oxygen levels, which create environments that either promote or decrease its preservation. Mixing disperses organic matter throughout the water column, influencing its spatial distribution and availability. Together, these transformation processes determine the fate of DOM and DOC in aquatic ecosystems, affecting biogeochemical cycles and ecosystem health.

Environmental-driven dissolved organic matter transport and transformation

Environmental factors, including hydrology, water residence time, and water chemistry characteristics, drive the transport and transformation processes of DOM (Figs. 1, 2). Established conceptual models, such as the RCC (Vannote et al. 1980), show that the diversity of DOM compounds decreases with increasing stream order due to DOM uptake in low-order streams. The concept also suggests that DOM is removed through the network via sediment biofilms (Newbold et al. 1982). Throughout the stream network, microbial activity also helps transform DOM. Microorganisms like bacteria and fungi transform organic molecules into simpler, more bioavailable compounds. Phytoplankton and cyanobacteria contribute to DOM production by fixing atmospheric carbon and altering DOM composition (Battin et al. 2008).

Stream hydrological dynamics drive the patterns and trends of DOM transport. During high-discharge events (pulse events), DOM is rapidly transported at high velocities (shunt events), which can lead to large inputs of terrestrial organic matter from upstream lakes and rivers into downstream reaches (Raymond et al. 2016). Further research shows that shorter water residence times increase the allochthonous to autochthonous DOM ratio, demonstrating rapid landscape-derived DOM movement during high-stream discharge (Bambakidis et al. 2024). Conversely, longer travel times enhance autochthonous production due to extended periods for in-stream primary production, heterotrophy, and photooxidation when river discharge is slow. In addition, various environmental variables in observed and experimental streams indicate that DOM concentrations and characteristics are influenced by hydrology parameters and temperature (Bambakidis et al. 2024). Low hydrology and high temperatures promote algal production and increase residence time due to reduced water flow, enhancing UV breakdown and photodegradation (Moran et al. 2000; Helms et al. 2008).

Along inland-to-coastal gradients, DOM transport and transformations can also change due to source variability and landscape interactions. Aromatic and polyaromatic molecules of high molecular weight dominate the inland DOM pool, characterized by fulvic compounds and lignin from leaf litter and soil (Fig. 3, component I) (Osburn and Stedmon 2011). As humic and terrigenous DOM sources approach the coast, the typically alkaline conditions (common in coastal waters due to mixing with marine salts) promote the degradation and conversion of aromatic structures into aliphatic units (Fig. 3, component III) (Esteves et al. 2009; Krachler et al. 2009). This pH-driven process is not restricted to specific locations but is generally applicable across many inland-to-coastal gradients, where an increase in pH facilitates the breakdown of complex high-molecular-weight aromatic compounds, such as lignin-derived molecules, into simpler, more labile aliphatic forms. These simpler compounds are more biodegradable and thus more readily utilized by microbial communities. Additionally, DOM near the coast is primarily benzoic acid-like or monolignol-like, originating from fresh plant materials with low humic content but high bioavailability (Zhuang et al. 2021; Romero et al. 2019).

Anthropogenic-driven dissolved organic matter transport and transformation

In combination with environmental-driven transformations that influence DOM characteristics along inland-to-coastal gradients, DOM composition also undergoes biogeochemical changes initiated by anthropogenic activities, mainly including eutrophication, salinization, and hydrological alterations (Fig. 1, component 3; Fig. 2, component 3). To better describe how anthropogenic-driven changes in combination with biogeochemical alterations change the quality of DOM in human-modified landscapes, we explain the causes of independent but co-occurring changes in quality: eutrophication, salinization, and saltwater intrusion, and managed hydrology.

Eutrophication impacts on dissolved organic matter transport and transformation

Eutrophication occurs due to increased nutrient levels in a system, typically involving nitrogen (N) and phosphorus (P). This phenomenon triggers the growth and natural consumption rate of microorganisms, potentially reducing the dissolved oxygen levels within the system (Chislock et al. 2013). Eutrophication can occur naturally, but human activities, such as nutrient runoff from urban and agricultural lands (e.g., fertilizer use and stormwater runoff), wastewater effluent (e.g., untreated or partially treated sewage), and industrial processes (e.g., discharge from factories and chemical plants), significantly contribute to this process (Bhattacharya et al. 2016). Agricultural practices constitute a persistent source of reactive N and P to terrestrial ecosystems, capable of altering terrestrial productivity and soil organic matter pools (Bhattacharya et al. 2016). Increased N deposition can impact organic matter exports by either changing the composition and stability of soil DOM through humification processes (Whittinghill et al. 2012) or by modifying the production and consumption of soil organic matter.

Agriculture and urban activities increase microbial metabolism in anthropogenic-driven streams due to increased light availability and nutrient inputs (Fuß et al. 2017). Anthropogenic runoff (e.g., agricultural, sewage, and wastewater) increases protein-like organic matter in streams, increasing the oxygen demand and bioavailability (Baker and Inverarity 2004; Smith et al. 2021). The impact of human activities on biogeochemical cycling is noticeable in coastal areas, characterized by dense populations and the resultant carbon and nutrient influx, which contribute to the eutrophication of coastal ecosystems (Petrone et al. 2011). Moreover, increased biological activity due to nutrient inputs in coastal areas can lead to algal blooms and hypoxia, resulting in changes to the composition of DOM (Peter et al. 2016). Finally, urban wetlands are likely to have reduced nutrient removal capacity through salinization due to changes in ionic strength and ion exchanges that occur at elevated salinities (Kinsman-Costello et al. 2023).

Salinization impacts on dissolved organic matter transport and transformation

Salinization of inland waters occurs through salts added to roads and sidewalks, other urban runoff, agricultural fertilizers, and through sea-level rise in coastal regions (Entrekin et al. 2018; Tully et al. 2019). Salinity has been known to lower DOC concentrations by decreasing the terrestrial-derived organic matter production (e.g., aquatic and stream-adjacent terrestrial vegetation) and annual gross ecosystem production by up to $\sim 25\%$ (Krauss et al. 2009; Neubauer 2013) (Fig. 3). In coastal systems, DOC concentration can decrease through a process known as flocculation, which involves removing humic compounds and reducing the molecular size by transforming DOM into particulate organic flocs. Flocculation can reduce the DOM pool from less than 10% to nearly a third (Sholkovitz 1976; Powell et al. 1996; Mulholland 1981). In coastal forested wetlands, drought-induced salinity pulses can decrease estuarine DOC concentrations by more than half (Ardón et al. 2016). Moreover, increased salinity could also promote photodegradation and degrade DOC concentration due to the combined photochemical and microbial degradation processes of terrestrial DOM (Minor et al. 2006). The resulting increase in ionic strength within the increasing salinization of DOM can enhance the bioavailability of coastal and estuarine DOM, accelerating the degradation process (Minor et al. 2006; Ardón et al. 2016).

Saltwater intrusion can also affect the quantity and quality of DOM through alterations of biological activities (Chen et al. 2013; Regier et al. 2020; Kaushal et al. 2021). Microbial activity in coastal streams is known to accelerate the degradation of organic matter, leading to faster decomposition of recalcitrant compounds in coastal waters (Lønborg et al. 2020). In addition, at higher salinities, pH and ionic strength increase, producing biogeochemical processes that alter organic matter mobilization, particularly by dissolving humic substances and promoting the release of labile, low molecular weight compounds (Ardón et al. 2016). As the concentration of saltwater rises within a freshwater environment, the pH tends to shift toward a more alkaline state (Tully et al. 2019; Kaushal et al. 2021). This alteration in pH promotes the dissolution of recalcitrant substances, leading to a transition toward labile, low molecular weight DOM (Ardón et al. 2016).

Coastal streams that experience the interaction of surface water, groundwater, and saltwater intrusion can change the biogeochemical characteristics of DOM by promoting autochthonous production as well as increasing or decreasing DOC concentrations (Weston et al. 2011; Minor et al. 2006; Smith et al. 2023). With the increase in tides and salinity, higher nutrient concentrations and horizontal groundwater flow are expected (McKenzie et al. 2021), which could potentially decrease DOC concentrations at coastal freshwater wetlands due to the increase in flocculation and decrease of primary production (Ardón et al. 2016; Kaushal et al. 2021). Gardner et al. (2005) found that CDOM in the Neponset River Estuary decreases with higher salinity, a relationship attributed to interactions between river flow, tidal forcing, and meteorological fluctuations. In addition, CDOM is higher and extends throughout the estuary more at low tide when saltwater intrusion is minimal. Besides CDOM concentrations, DOC concentrations are 30–50% lower in marine sites than in river endmember sites (Asmala et al. 2013). Overall, salinity has the potential to stimulate autochthonous production of DOM and dissolve humic DOM at a faster rate (Roebuck et al. 2020). Saltwater intrusion also decreases the production of terrestrial organic matter (Chen et al. 2013; Regier et al. 2020). Finally, mixing groundwater and surface water with saltwater intrusion further changes DOM sources and DOC concentrations while increasing the presence of human signatures in urban coastal waters (Smith et al. 2021).

Impacts of managed hydrology on dissolved organic matter transport and transformation

In the 21st Century, nearly 50% of the world's human population lives in coastal regions and relies on managed water to meet their daily needs (Martínez et al. 2007). Streams, rivers, and urban canals play a crucial societal role by contributing to domestic and recreational water supplies (Nilsson et al. 2003). Due to their societal importance, numerous streams have been redirected and engineered within human-modified landscapes, influencing carbon dynamics in aquatic systems, often transporting DOM sources from different environments to coastal systems (Meyer et al. 2005) (Fig. 1, component 4; Fig. 2, component 4). Alterations to stream morphology affect DOM's storage, transformation, and export from inland waters (Wohl 2017). Anthropogenic managed water flow, such as the introduction of dams, canals, and floodgates, alters residence times, which in turn impact DOM sources and their export to the coastline (Xenopoulos et al. 2021). Longer residence times can enhance photodegradation and increase the concentration of labile DOM, while peak discharges may export more humic or allochthonous DOM. Although some studies suggest that dams do not influence DOM quality (Nadon et al. 2015), variations in water residence times often increase DOC concentrations and the export of both humic and autochthonous sources (Ulseth and Hall 2015).

Human-dominated landscapes often include structures that regulate water flow to combat floods and droughts. During droughts or base flow, organic matter inputs originate primarily from groundwater, contributing protein-like sources and high primary production (Hosen et al. 2018). During floods, dams and gates are often opened to minimize human risks, facilitating the export of high quantities of DOM, characterized by high molecular weight organic matter, thus increasing DOC concentration export to the coastline (Xenopoulos et al. 2021). Flood- or drought-induced changes in water residence times have a notable impact on DOM (Cory et al. 2018). Even with a brief exposure to solar radiation, DOC concentrations can drop by > 10% (Jones et al. 2016). As water residence time increases, photodegradation triggers a higher rate of microbial activity by up to 90% (Moran et al. 2000; Cory et al. 2014), leading to a more pronounced degradation of humic DOM.

Landscape hydrology is one of the most important factors explaining DOM export (Regier et al. 2016; Bambakidis et al. 2024). For instance, modeling rainfall and water management flow in South Florida explains almost 90% of DOM fluxes to the coast (Regier et al. 2016). Hydrological modifications, such as drainage and navigation projects, create interbasin mixing of water that alters the quantity and quality of DOM in coastal landscapes (Siddik et al. 2023; Anderson et al. 2024). In the Everglades, for example, canal systems transport DOM from upstream marshes to coastal mangroves, where humic-rich organic matter shapes the unique DOM composition in subtropical coastal environments (Duan et al. 2015; Regier et al. 2016).

Overall, changes in DOM transport caused by hydrological alterations are driven by three main factors: frequency and magnitude of storms, droughts, and tides (Wu et al. 2023; Haq et al. 2018); water use (e.g., surface and groundwater withdrawals for drinking water and irrigation) (Xenopoulos et al. 2021); and hydrological connectivity (e.g., agricultural, canals, impervious grounds, and re-channelization) (Petrone et al. 2011; Hosen et al. 2018). The variation in these factors over space, time, and duration affects the transport and transformation of DOM from inland to the coast (Fig. 1, component 4; Fig. 2, component 4).

Forecasted changes and trends in coastal and estuarine dissolved organic matter and dissolved organic carbon

An understanding of how climate change and anthropogenic activities are changing the sources of DOM and concentrations of DOC is needed to forecast characteristics, transformations, and transport in inland waters and downstream impacts to coastal and estuarine ecosystems. Freshwater basin morphology and flow pattern changes, such as alterations in river meandering, dam construction, and canal dredging, would significantly influence the delivery of DOM to coastal regions, with potentially far-reaching ecological implications that demand better understanding (Fig. 3) (Xenopoulos et al. 2017). Despite some evidence that coastal DOM is more labile and DOC concentrations are lower than in inland waters (Fig. 3) (Jaffé et al. 2001, 2004; Chen et al. 2013), landscape modifications can alter both (Fig. 1, component 5; Fig. 2, component 5). Here, we examine anticipated outcomes resulting from freshwater and anthropogenic modifications and discuss expected DOM characteristics and DOC concentrations in coastal and estuarine waters (Fig. 3).

Decoupling of dissolved organic carbon quantity and dissolved organic matter quality

Our conceptual model (Fig. 3) outlines anticipated shifts in the quantity of DOC and quality of DOM as water management efforts intensify and saltwater intrusion progresses across a landscape. We forecast transformations in DOM quality within human- and climate-altered river networks. Managed water flows are expected to maintain flood pulse shunts (Raymond et al. 2016), decreasing the dilution and exporting high DOC concentrations to downstream coastal regions. Eutrophication is expected to continue to stimulate microbial and autochthonous productivity (Chislock et al. 2013), elevating DOC concentration and decreasing the humic quality of DOM. Similarly, saltwater intrusion from sea-level rise will produce more labile DOM further inland (Anderson et al. 2024), and freshwater alterations will continue to disconnect natural transport of upstream DOM sources and DOC concentrations to downstream waters. Overall, river networks subject to constant water management and climate-driven flood pulses will likely transport elevated concentrations of DOC to the coast due to a reduction in water residence times (Raymond et al. 2016). However, climate change can also cause drought conditions and shifts in precipitation patterns. Those alterations can prolong water residence times and alter the timing and magnitude of DOM export (Ardón et al. 2016), creating a more complex suite of scenarios that could explain DOM delivery to the coast based on shifting climate and hydrological patterns. Eutrophication and saltwater intrusion will increase the lability of DOM (Chislock et al. 2013; Liu et al. 2022). Consequently, the combination of water management, climate-driven flood pulses, saltwater intrusion, and eutrophication will give rise to higher DOC concentrations and DOM from more labile (microbial and algal) origins in coastal and estuarine waters (Fig. 3).

Increased dissolved organic matter lability and dissolved organic carbon concentrations

The expected increases in human alterations to watersheds driven by population growth include elevated nutrients, land-use changes, and water management that are anticipated to reshape DOM. Nutrient enrichment will initially enhance microbial activity and expedite breakdown rates (Kominoski et al. 2015), leading to faster degradation and a shift toward more labile DOM (Kominoski and Rosemond 2012; Anderson et al. 2023). It is important to note that we anticipate that the eutrophication-induced breakdown rates remain unaffected by DOC concentration, resulting in significant DOM breakdown even in high DOC concentrations (Liu et al. 2022). In other words, we predict that DOM breakdown will likely increase with elevated nutrients as the quality of DOM becomes increasingly more labile (Gold et al. 2020). However, DOC concentrations will broadly remain elevated due to increased human hydrological alterations, shunting water to the sea, and increasing water residence times at the coast due to sea-level rise (Raymond et al. 2016; Anderson et al. 2024; Bambakidis et al. 2024). Concurrently, human-driven land-use change will decrease the supply of terrestrial organic matter (Liu et al. 2018), increasing light availability and promoting DOM photodegradation (Cory et al. 2018), subsequently boosting microbial activity and respiration, as well as photomineralization of DOM to CO_2 flux in inland waters (Wetzel et al. 1995; Cory et al. 2015; Jones et al. 2016). The combined impact of human alterations will likely elevate microbial and labile DOM, as well as photodegradation of DOM, and the effects on DOC concentrations will depend on the relative inputs vs. transformations of DOM.

Increased salinization of dissolved organic matter and pulses of riverine dissolved organic carbon in coastal and estuarine water

Human land-use changes and hydrologic modifications in coastal regions are interacting with climate-driven increases in sea levels. As coastal populations and water management continue to increase, water transfers from one basin to another are expected to rise (de Lucena Barbosa et al. 2021), but rapid increases in sea-level rise from climate change are also accelerating saltwater intrusion landward (Tully et al. 2019). The requirement for increased water supply to coastal regions will likely necessitate interbasin transfers from inland waters. Inland water typically contains high-molecular-weight DOM (Yamashita et al. 2010), and water movement from inland to coastal regions will likely increase inland DOM characteristics in coastal and estuarine waters (Baum et al. 2007; Duan et al. 2015). This phenomenon is anticipated to initially boost the presence of high-molecular-weight and humic DOM at the coast and decrease labile DOM within the system.

Consequently, trophic interactions are expected to shift due to reduced light availability (Bengtsson et al. 2018). However, saltwater intrusion from sea-level rise will likely decrease DOC concentrations and shift DOM composition (Ardón et al. 2016; Anderson et al. 2024).

Saltwater intrusion in surface waters is accelerating with the expansion of tidal flooding with sea-level rise and during high tide and storm events (Ensign and Noe 2018). Floodwater infiltrates the unsaturated zone and reaches the water table, salinizing shallow groundwater. Salinization can also occur from subsurface and groundwaters in karstic coastal regions (Saha et al. 2012; Dessu et al. 2018). Saltwater intrusion can cause stress and mortality of terrestrial vegetation (McDowell et al. 2022) and soil elevation loss (Charles et al. 2019), shifting coastal wetlands inland (Fagherazzi et al. 2020; Kirwan and Gedan 2019), except where human-engineered infrastructure restricts this migration. Large-scale declines in coastal forests with saltwater intrusion (White et al. 2022) will likely shift sources of terrestrial allochthonous carbon from more recalcitrant (forest) to more labile (wetland) carbon and further increase microbial mineralization of estuarine DOM (Weston et al. 2011; Fig. 3). In the absence of feedbacks that alter hydrological connectivity, the rate of the inland movement of saltwater will occur with relative sea-level rise along the coast. The complex interactions among extensive human modifications of coastal infrastructure and water management along inland-to-coastal gradients will influence how saltwater intrusion and sea-level rise alter estuarine DOM. As coastal populations continue to grow, it is crucial to consider the combined impacts of saltwater intrusion and human alterations on DOM in coastal regions. The increase in saltwater intrusion will shift inland waters toward a more basic, alkaline pH (Tully et al. 2019). This increase in alkaline conditions in freshwater environments will trigger the breakdown of humic-like DOM without necessarily reducing DOC concentrations (Haq et al. 2018). Further, salinization of coastal wetlands, the dominant source of DOM in coastal regions, is enhancing carbon mineralization (Weston et al. 2011; Neubauer et al. 2013; Lee et al. 2022), reducing the flux of DOC concentration from the coast to estuaries (Ardón et al. 2016) and varying the composition of DOM from riverine to coastal wetland sources (Medeiros et al. 2015; Anderson et al. 2024). Human water management, water consumption rates, and climate-driven droughts will further increase saltwater intrusion into inland waters (O'Donnell et al. 2024). We anticipate that regular and consistent water management practices will shift the dynamics of DOM changes from seasonally driven to storm-driven. This occurs because consistent water management establishes a steady pulse, minimizing the effects of seasonal precipitation and droughts. Additionally, we expect that the steady pulse would reduce residence time and transport higher DOC concentrations to the coast. In urbanized coastal systems, alterations in DOM quality will be predominantly influenced by storms, with tidal flooding exerting a noticeable impact on groundwater and surface water DOM (Smith et al. 2021). The release of humic DOM through water management will lead to an increase in humic DOM sources and higher DOC concentrations, but human-derived sources of DOM associated with urban runoff and wastewater are often labile (Fork et al. 2020; Smith et al. 2021). In addition, urban streams can export novel chemical compositions of human pharmaceuticals that are untreated by wastewater infrastructure (Fork et al. 2021). Saltwater intrusion will interact with changes in human-derived, labile, and humic-like DOM in complex ways that will change with freshwater and marine exchange, transformation, and export of DOM (Fig. 3).

Closing remarks

Understanding the impact of anthropogenic and natural factors on the quality and quantity of DOM in urban coastal environments is crucial for predicting ecosystem processes and trophic interactions. Due to current and anticipated climate and anthropogenic changes, coastal streams will inevitably undergo hydrological modifications that will alter DOM at the coast. Our synthesis predicts that DOC concentrations in coastal and estuarine waters will increase due to an expected increase in managed hydrological export, although the extent of this increase will depend on the balance among climate, water management practices, eutrophication, and relative sea-level rise. While DOM quality is anticipated to shift toward more labile, the specific characteristics of DOM will vary depending on the system and dominant drivers, which could also contribute to recalcitrant DOM. Moreover, the influence of seasonality on DOM delivery is expected to reduce as consistent water management establishes a steady pulse, reducing variability driven by seasonal precipitation and droughts. These anticipated changes at the coast may influence trophic levels, driven by variations in light availability, ecosystem metabolism, and microbial activity. Greater emphasis on long-term, continuous in situ data collection in coastal aquatic systems experiencing anthropogenic changes is crucial for better understanding landscape modifications, sea-level rise, and the relationship between increased human activities and DOM properties.

Author Contributions

Liz D. Ortiz Muñoz compiled and edited the initial draft of the text and figures. Liz D. Ortiz Muñoz and John S. Kominoski participated in conceptualizing and editing the manuscript. Both authors reviewed and approved the final manuscript.

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Conflicts of Interest

None declared.

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