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REVIEW

Urban heterogeneity drives dissolved organic matter sources, transport, and transformation from local to macro scales

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Abstract

Urbanization reshapes dissolved organic matter (DOM) sources, transport, and transformations through changes in vegetation, hydrology, and management of waste and water. Yet the impacts of urbanization on DOM are variable within and among cities. Predicting heterogeneous responses to urbanization is challenged by diverse human activities and underlying biophysical variation along stream networks. Using data from the 486 largest urban areas in the continental United States and seven focal cities, we identified macro and local scale urban gradients in social, built, and biophysical factors that are expected to shape DOM. We used these gradients and the literature to develop hypotheses about heterogeneity in DOM quantity and quality within and among cities. Interactions among landscape and infrastructure attributes across spatial and temporal scales result in heterogeneous responses in DOM. Characterizing and quantifying these inconsistent responses to urbanization in contrasting settings may help to better understand heterogeneity and identify generalities among urban watersheds.

Despite the relatively small land footprint of cities (only 5.8% of the conterminous United States was classified as "developed" in 2021; Dewitz 2023), urbanization impacts a large proportion of waterways in the United States (Hill et al. 2016). Even small proportions of urban land cover (< 10% impervious cover) can significantly impact stream ecosystems (Booth and Jackson 1997; King et al. 2011). Early syntheses of urban impacts on streams initially focused on the role of impervious surfaces and the dramatic hydrological impacts of land cover changes on stream ecosystems (Walsh et al. 2005; Schueler et al. 2009). However, urban watersheds are diverse and complex (Hopkins et al. 2025), and relationships between land cover and outcomes such as water quality, hydrology, and biotic communities can vary depending on climate, geomorphic template, and development patterns (Cuffney et al. 2011; Hopkins et al. 2015; Blaszczak et al. 2019b; Delesantro et al. 2021). Therefore, generalizable and synthetic predictions are needed to assess when, where, and how various aspects of urbanization are likely to matter.

Macrosystems ecology refers to the study of multiscale ecosystems, including regional to continental macroscales and how broad-scale patterns interact with finer-scale patterns (Heffernan et al. 2014). Within these systems, cross-scale interactions occur

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when processes at one scale interact with or affect processes at another scale, which can cause nonlinear dynamics (Heffernan et al. 2014; Soranno et al. 2014). Cross-scale interactions can be used to understand variable ecosystem behavior across regional to continental scales. For example, the region-specific relationship between wetland cover and lake phosphorus concentrations across the United States is strongly predicted by the region's agricultural landcover, where wetlands are positively associated with lake phosphorus in regions with low agricultural land use, but negatively associated with phosphorus in regions with high agricultural land use (Soranno et al. 2014). In urban streams, cross-scale interactions also explain variable relationships between stream biotic communities and urbanization gradients among cities (Cuffney et al. 2011). Climate and antecedent agricultural land use set the background conditions with which urbanization interacts, such that urbanization in areas with forested land cover, cooler temperatures, and higher precipitation had stronger declines in biotic communities with urbanization compared to cities with already reduced biotic assemblages due to agricultural land cover, warmer temperatures, and lower precipitation (Cuffney et al. 2011). The promise of macrosystems ecological approaches is therefore to enable translation of finer-scale processes to broader scales that enable ecological predictions across scales (Dodds et al. 2021).

Watershed- and river network-scale approaches have expanded understanding of processes across spatial scales in flowing waters. Continental gradients of precipitation and temperature set a template of water availability and watershed vegetation that can drive streamflow regimes and light availability (Dodds et al. 2019), but stream ecosystems are influenced by their position in river networks as much as they are shaped by continental gradients (Vannote et al. 1980; Raymond et al. 2016; Dodds et al. 2019). Streams are also influenced by both local instream and watershed-scale processes, and by connectivity between upstream and lateral systems that can vary with hydrology and physiography (Kaushal and Belt 2012; Raymond et al. 2016; Ledford et al. 2020; Thorp et al. 2023). Understanding the proximate drivers of ecosystem function, such as light, temperature, and streamflow regimes, which vary from local to macroscales, can inform predictions about ecosystems functions over space (Bernhardt et al. 2022), within watersheds, river networks, and through time (Raymond et al. 2016).

While human management of rivers, such as dam construction and management, shapes all river ecosystems (McCluney et al. 2014; Wohl 2019), urban watersheds represent an extreme of human modification because of the comprehensive changes to soils, vegetation, land surfaces, and flow routing. Urban ecosystems are spatial mosaics of land uses, land covers, supporting surface and subsurface infrastructure networks, and dynamic human communities (Cadenasso et al. 2007; Steele and Wolz 2019). Spatial heterogeneity results from complex histories of interactions between social, biophysical, and technological processes and systems operating at scales from years to centuries (Capps et al. 2016; Parr et al. 2016; Grove et al. 2018). Biophysical patterns and processes such as underlying geomorphic (Steele and Wolz 2019), topographic, and climate heterogeneity (Hale et al. 2016) can place physical limits on urban development patterns, vegetation, and infrastructure (Burchfield et al. 2006). Shifting paradigms (Parr et al. 2016) and legacies of past water management, such as river corridor alterations (Wohl 2019), agricultural irrigation canals (Armstrong and Jackson-Smith 2017), and wastewater infrastructure (Brown et al. 2009), continue to shape present-day urban watersheds. Water management is closely linked to social, political, and economic legacies and their continued impacts on urban systems today (Grove et al. 2018). Processes such as displacement, migration, and segregation have shaped sociodemographic patterns at neighborhood to macroscales, which continue to influence patterns of infrastructure and service investment and thus ecosystem structure and function (Grove et al. 2018; Heck 2021; Hendricks and Van Zandt 2021). A macrosystems approach to urban watershed ecology can collectively consider biophysical and social gradients, watershed structure, and interactions to better understand biogeochemical patterns in cities.

Here, we synthesized existing spatial datasets to identify local to macroscale gradients along which we expected urban watershed function and urban dissolved organic matter (DOM) to vary. We included sociodemographic variables (e.g., income, race/ethnicity), biophysical variables (e.g., precipitation, temperature, elevation, canopy cover), and features of the built environment (e.g., housing density, housing age, canal infrastructure, wastewater infrastructure). To identify these gradients, we compiled data from the 486 urban areas in the conterminous United States with greater than 50,000 residents (defined as 2010 U.S. Census Bureau urban areas; U.S. Census Bureau 2022), along with seven focal cities distributed across the United States (Hopkins et al. 2024). We used these macroscale (continental) and local (census tracts within urban areas) gradients to develop hypotheses about how urban DOM might vary within and among cities. Finally, we hypothesized how cross-scale interactions might shape DOM responses to urbanization, specifically how within-city predictors of urban DOM might vary along continental gradients of climate and development. While our examples are US-centric and focused on relatively large urban areas, the gradients and principles of this approach may apply more broadly even as development patterns and climate gradients vary globally. Ultimately, we hope this framework provides a helpful construct for placing local studies within a broader geographic context, enhances understanding of mechanisms of urban impacts, and identifies approaches and opportunities for urban planning, management, and restoration.

Dissolved organic matter sources, transport, and transformations are shaped by urbanization

Rivers and streams are major contributors to continental and global carbon cycling. Inland streams function as major sources and sinks of carbon dioxide and deliver 900 Tg/yr of organic carbon to coastal ecosystems globally (Butman et al. 2016). Streams receive allochthonous organic matter (OM) from adjacent terrestrial systems in dissolved and particulate forms and produce autochthonous OM through primary production. The balance of these sources determines the quality and processing rates of DOM, which can vary depending on watershed and stream characteristics (Vannote et al. 1980; Bernhardt et al. 2022). Furthermore, the quality (e.g., source, composition, and lability) and quantity of DOM regulate many ecosystem functions in streams (Vannote et al. 1980; Duan et al. 2014; Ortiz Muñoz and Kominoski 2025). For example, DOM influences the cycling of other elements and is a primary energy source for microorganisms (Bernhardt and Likens 2002). Through modifications to watershed land cover, hydrology, vegetation structure, soils, nutrient loads, and direct changes to streams and riparian zones, urbanization can shape the quality, quantity, transport, and fate of DOM through river networks (Duan et al. 2014; Hosen et al. 2014). Here, we review variation in the sources, transport, and processing of DOM in urban watersheds (Figs. 1, 2), highlighting interactions between biophysical, social, and built features of cities that could generate heterogeneity in these patterns within and among cities. Importantly, this depiction of urbanization was derived from data from the conterminous United States and may be most relevant for temperate regions in higher-income economies.

Urbanization can shift the inputs of "natural" DOM sources, such as instream primary production, vegetation, and soils, as well as introduce novel sources of DOM (Figs. 1, 2). For example, in some cities, urbanization can decrease the production and export of terrigenous DOM into river drainage networks (Hosen et al. 2014) due to deforestation (Pisani et al. 2020), wetland losses (Bhattacharya and Osburn 2020), and stream burial (Beaulieu et al. 2014). Where cities retain (or plant) substantial tree canopy, how the fluxes of leaf fall are managed (i.e., by street sweeping) has important implications for water quality (Bratt et al. 2017; Hobbie et al. 2023). Loss of riparian forests can also increase light availability in urban streams, increasing instream primary production as an autochthonous source of DOM (Alberts et al. 2017), while stream burial can decrease light and instream production (Beaulieu et al. 2014). Wastewater can represent a major input of highly labile DOM to urban streams from leaking septic systems and sewage pipes, treatment plant discharges, and combined sewer overflow (Capps 2019; Smith et al. 2021), contributing most or even all of stream discharge, and therefore OM loads, in low-flow systems (Griffith et al. 2009). Urbanization is also associated with additional novel or anthropogenic sources of aquatic OM from household products and plastics (Griffith et al. 2009).

Urban stream DOM is also influenced by altered flow paths, which strongly influence the quality, quantity, and timing of the DOM entering surface water (Khamis et al. 2017; Chen et al. 2019). Water infrastructure can make novel connections in watersheds and provide new opportunities for DOM processing, affecting the quality and quantity of DOM transported to streams (Fork et al. 2018). Impervious surfaces disconnect soils from streams, cutting off a major source of OM to streams (Hosen et al. 2014), and curbed roads especially shunt storm flow to streams (Blaszczak et al. 2019b). The design of stormwater systems directly influences the transport of terrestrial DOM to streams, through impacts on urban hydrology (Eger et al. 2017), as well as potential opportunities for DOM processing and retention along those flow paths (Hobbie et al. 2014; Fork et al. 2018). For example, urbanization can increase the relative importance of stormflows (compared to baseflow) for DOM export, which could decrease the capacity of streams to process these fluxes (Delesantro et al. 2024). Canals in urban areas can transport water and OM long distances across drainage divides and create new opportunities for OM processing (Kelso and Baker 2020; Smith et al. 2021).

In streams, DOM is transformed by a variety of physical and biological processes and can be taken up by heterotrophic organisms (Tank et al. 2010) (Fig. 2). The processing and fate of DOM in streams are affected by the quality of DOM, microbial and other biological communities, and physical stream characteristics such as light, temperature, streamflow, and surface water–groundwater interactions (Duan et al. 2014; Cory and Kling 2018). Instream DOM primary production, measured as gross primary production, depends on local stream conditions, especially light availability, stream substrate, and flow regimes. Gross primary production may be elevated in urban compared to nonurban streams due to increased light availability (i.e., the loss of riparian canopy) and elevated nutrient concentrations (Ledford et al. 2021) or decreased by scouring of biofilms at high flows and elevated turbidity (Blaszczak et al. 2019a). Ecosystem respiration, which encapsulates the biological breakdown of particulate and DOM at the ecosystem scale, is driven by DOM availability and lability. Ecosystem respiration is often correlated with allochthonous inputs of DOM and nutrients, such as from wastewater treatment plants (WWTPs) (Ledford et al. 2021). In contrast, in systems where allochthonous inputs are decreased or scoured, ecosystem respiration is closely tied to gross primary production because autotrophs respire and produce DOM for heterotrophs (Beaulieu et al. 2014). Lining or channelizing streams can affect connectivity to DOM sources, disconnecting riparian and groundwater sources of DOM and changing instream and hyporheic zone DOM processing (Duan et al. 2014). Some fractions of the DOM pool are particularly photosensitive (e.g., chromophoric, aromatic, and high molecular weight DOM), such that photodegradation can be a major loss pathway in some aquatic systems (Cory and Kling 2018). The loss of more terrigenous, photosensitive DOM with urbanization may decrease the importance of DOM photodegradation

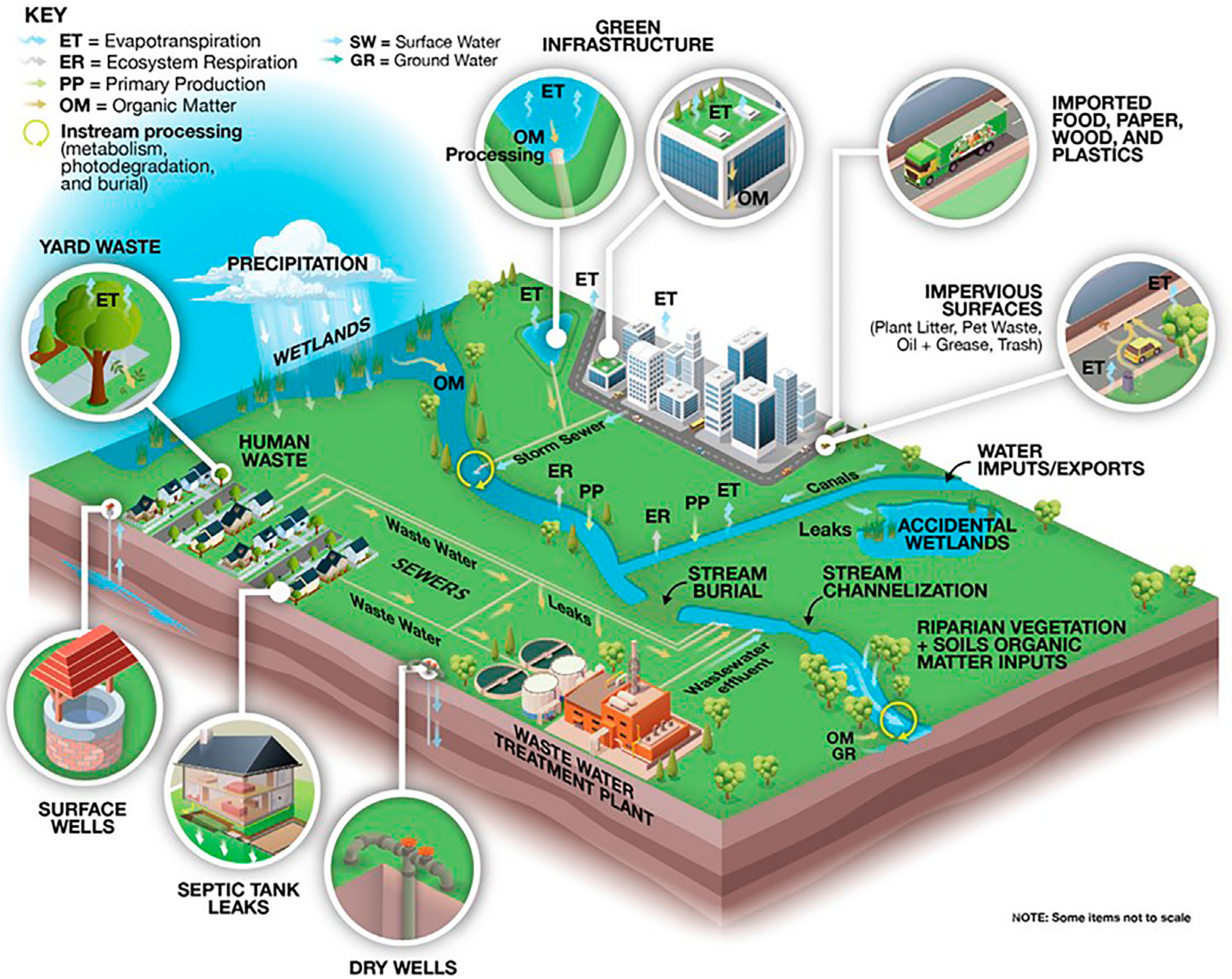


Fig. 1. Sources and transport of organic matter in urban watersheds and within and adjacent to urban streams. Concentrations and sources of organic matter in urban streams will vary within and among cities depending on the location of potential natural and anthropogenic organic matter sources in the watershed, the routing of water (the main transport vector for organic matter), and the processing of organic matter along those flow paths. Figure art by Hiram Henriquez.

in urban areas, even with changes in light availability with urbanization.

As illustrated in the above review, urbanization substantially changes the sources, transport, and transformations of DOM through watersheds. Yet, the nature of these changes is likely to vary among cities because of differences in initial conditions (e.g., whether the natural landscape contains forests or wetlands) and patterns of development including land cover changes and the routing and treatment of stormwater and wastewater. In the next section, we characterize macroscale and local scale gradients of urban heterogeneity and consider how these might drive variation in urban DOM sources, transportation, and transformations.

Urban heterogeneity at macro and local scales is likely to affect urban DOM

Macroscale variations in the biophysical, social, and built characteristics of cities alter DOM

At continental scales, freshwater DOM quantity and composition vary across macro scale gradients of land cover (such as forest, grassland, wetland) and precipitation (Jaffé et al. 2012; Kurek et al. 2024; Orlova et al. 2024), and anthropogenic land uses, including agricultural and urbanization, can disrupt these gradients (Wagner et al. 2015; Vaughn et al. 2023). We expect that urbanization will reshape macro scale gradients by changing the sources, transport, and

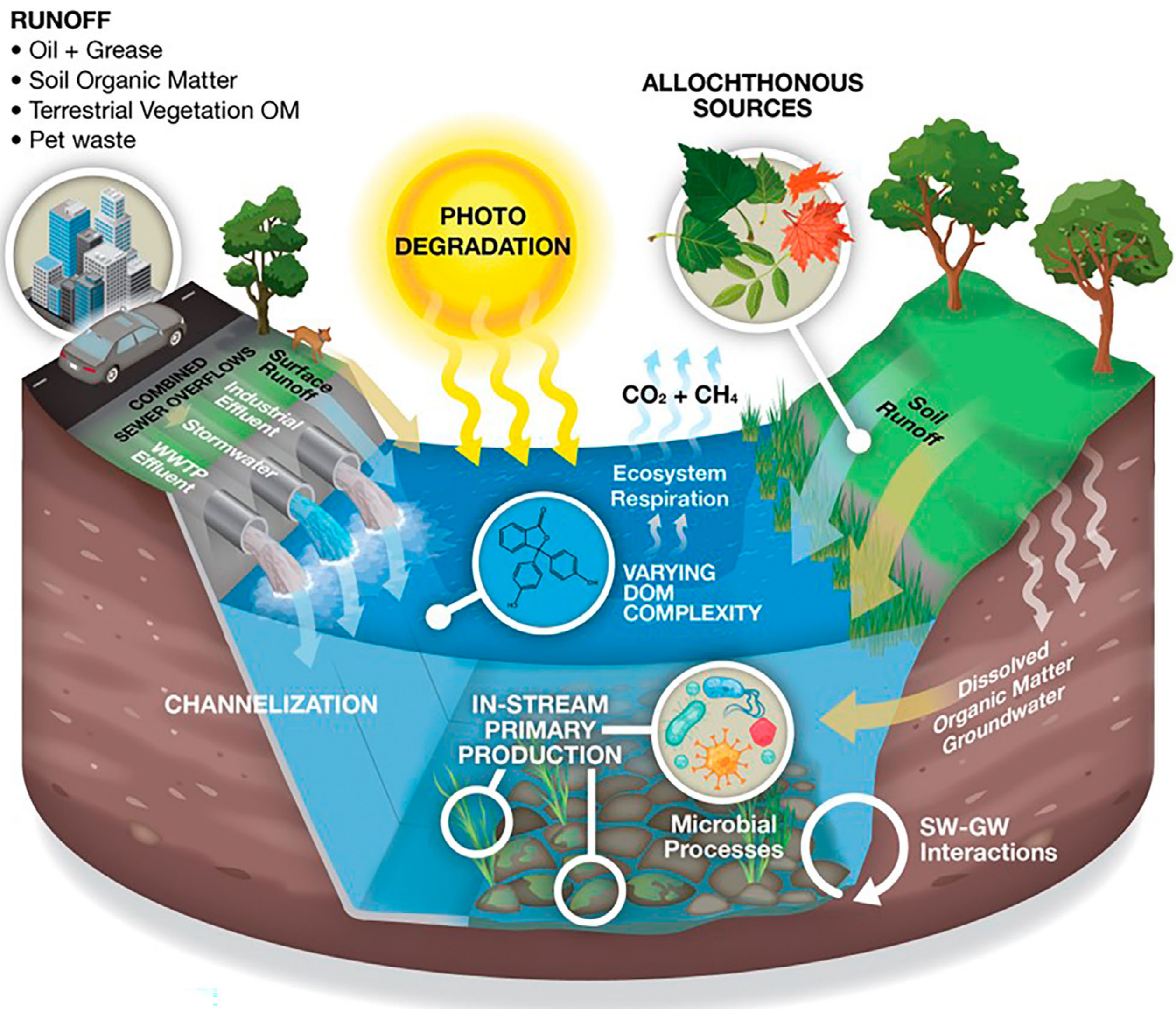


Fig. 2. Sources and transport of organic matter within and adjacent to urban streams. Infrastructure affects connectivity to upstream urban sources, while channelization can disconnect surface and groundwater. Stream biota can affect rates of in-stream processes and respiration. Light exposure can affect photodegradation and rates of primary production. Figure art by Hiram Henriquez.

transformations of DOM, and that variation in patterns of urbanization, for example, variation in wastewater infrastructure, could create new macroscale gradients.

To describe continental gradients in urban heterogeneity, we compiled national-scale datasets for biophysical, social, and built characteristics that we hypothesized could shape freshwater DOM (Supporting Information Table S1; Hopkins et al. 2024). These included biophysical variables such as land use and land cover (e.g., forest, wetland cover), climate (mean temperature and precipitation), topography (elevation and slope), and hydrography (e.g., stream drainage density, canalization) that are known to shape DOM quantity and composition (Gergel et al. 1999; Aitkenhead-Peterson et al. 2005; Kothawala et al. 2015; Creed et al. 2018). We also included sociodemographics (e.g., income, race/ethnicity), housing characteristics (e.g., housing density, housing age, availability of indoor plumbing), and wastewater infrastructure (e.g., WWTPs, combined sewer outfalls) that we hypothesized would directly or indirectly shape DOM composition (details in Supporting Information Table S1; Hopkins et al. 2024). We summarized these variables for the 486 largest urban areas in the conterminous United States and used a principal components analysis to identify macro scale gradients of urbanization for the conterminous United States (Supporting Information, Detailed Methods, Table S2).

Our goal in this analysis was to generate hypotheses for how urban freshwater DOM composition might vary at macroscales. The specific gradients we observed are influenced by the boundaries used to define cities (we use census urban areas for this analysis), as well as the datasets used to describe those cities. We used national-scale datasets, yet stormwater management, including both infrastructure and behavioral practices such as street sweeping, for example, is a very important control on urban DOM for which national datasets do not exist and for which local datasets are not comparable (Choat et al. 2023; Hopkins et al. 2025). As a result, measures such as drainage density do not include stormwater infrastructure (which can represent most of the drainage network in cities). While these data considerations shape the specifics of the gradients described here, the core value of this approach is to develop hypotheses that can later be tested with field observations.

How the sources, transport, and processing of DOM manifest in each city depends on the background ecological conditions coupled with patterns of urban development. We identified five significant macroscale gradients along which large US cities vary (Fig. 3; Supporting Information Table S2). Notably, the gradients highlight the need to consider urban environments as social–ecological–technical systems, as each gradient represents a combination of social, built, and biophysical characteristics that co-vary across the landscape. Here, we describe these gradients and hypothesize how they could shape DOM composition in urban freshwaters.

Among cities, we expect that dominant DOM sources should vary across macroscale gradients. The first macroscale gradient, which explained ~ 22% of the variation among cities, primarily represents the East–West gradient of climate (wetter in the East and along the West Coast, drier in the Intercontinental West), tree canopy cover (higher in the East and coastal West, lower in the West), and population density and imperviousness (because of the urban area boundaries and patterns of urbanization, these are higher in the West and lower in the East and coastal West). Along this East–West US gradient of precipitation and canopy cover (gradient 1), we expect higher DOM concentrations and greater terrestrial, humic DOM in areas with greater canopy cover and precipitation and lower imperviousness, aligning with previous work on nonurban freshwater DOM (Jaffé et al. 2012) (Fig. 4a). The second gradient (12% of variation) primarily describes the North–South gradient in temperature and is also associated with newer housing in the South, greater proportions of minority populations (people of color and Hispanic), and fewer combined sewer outfalls. Along this gradient (gradient 2), we expect that newer cities without combined sewers will have generally lower inputs of raw wastewater from failing sanitary systems, while older cities with older combined sewer systems are more likely to have higher inputs of microbial, wastewater-derived DOM (Fig. 4b). In contrast, warmer temperatures are often associated with greater degradation of soil OM (Orlova et al. 2024), which could provide a natural source of microbial OM for cities with higher gradient 2 values.

The third gradient (9% of variation) has a more complex spatial pattern, in which areas with reduced forest cover, less steep slopes, and lower household incomes are concentrated in the middle part of the country, as well as central California and Florida. Along this gradient (3), we might expect to find generally lower DOM from cities with low slopes and lower forest cover (high values for gradient 3) due to reduced DOM inputs and greater landscape retention (Fig. 1). Overall, we expect that household income is associated with municipal resources for infrastructure to manage anthropogenic DOM inputs (Elliott et al. 2023), and therefore we might expect that increased (generally microbial) anthropogenic DOM inputs would strengthen a gradient from more terrestrial and humic DOM (higher slopes and forest cover, higher incomes) to more microbial (lower slopes and forest cover, lower incomes).

The fourth gradient (8% of variation) is associated with cities with higher canal drainage density, a greater proportion of homeownership, and higher elevation. While canal density drives higher values of this gradient for some low-lying areas (South Florida is a notable area where canals provide flood control and navigation), the overall association between canal density and elevation is driven by greater canal densities in the intermountain West, where canals are primarily used to distribute surface water. Regardless of the type of canals, along this gradient we expect autochthonous DOM to be positively associated with high-light availability and canal infrastructure, which is expected to promote high rates of primary production (Bernot et al. 2010) (gradient 4).

Finally, the fifth gradient (8% of variation) describes areas with greater wetland and surface water cover, higher incomes, higher rates of home ownership, higher rates of complete plumbing (i.e., housing with hot and cold running water, a flush toilet, a bathtub or shower, and a sink with a faucet), and lower forest cover. Areas with high values tend to be in coastal and glacial-impacted landscapes. Along gradient 5, we hypothesize that wetland cover will be associated with higher DOM concentrations overall and greater humic-like DOM, given the well-known role of wetlands as humic DOM sources (Gergel et al. 1999; Kothawala et al. 2015). As in gradient 3, human dimensions gradient 5 is likely to exacerbate the biophysical sources of DOM variation, in this case due to wetlands, since cities with greater availability of plumbing will be expected to have less microbial wastewater DOM compared to cities with lower values.

Within cities, local biophysical and social gradients provide local controls on DOM

Gradients of urban conditions vary among and within cities. To better understand local gradients of urbanization, we compared seven focal cities across the continental United States (Atlanta, GA; Boston, MA; Phoenix, AZ; Miami, FL; Portland, OR; Salt Lake City, UT; San Francisco, CA). We chose these cities because they represent a range of conditions across the macro scale gradients (Supporting Information

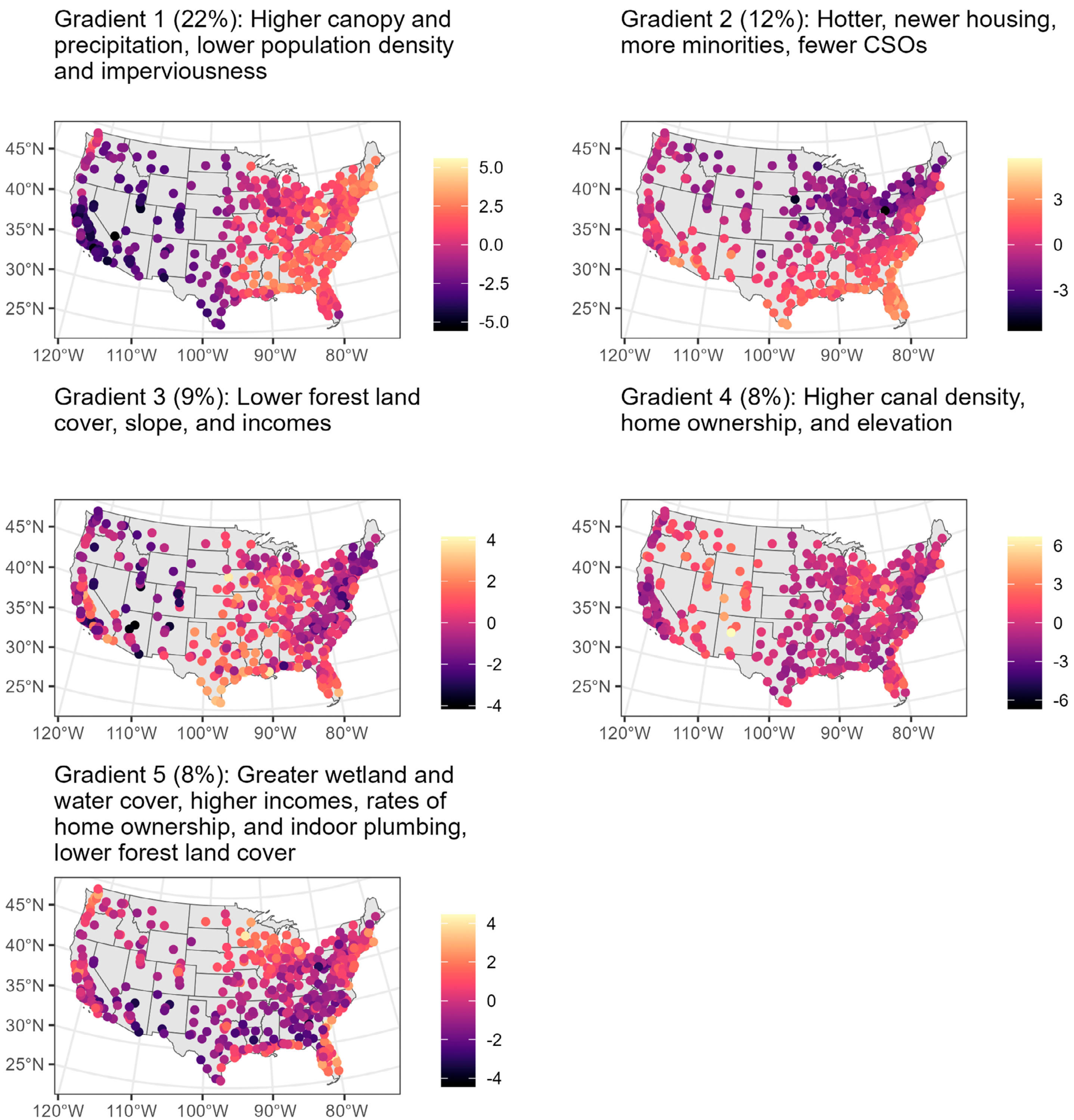
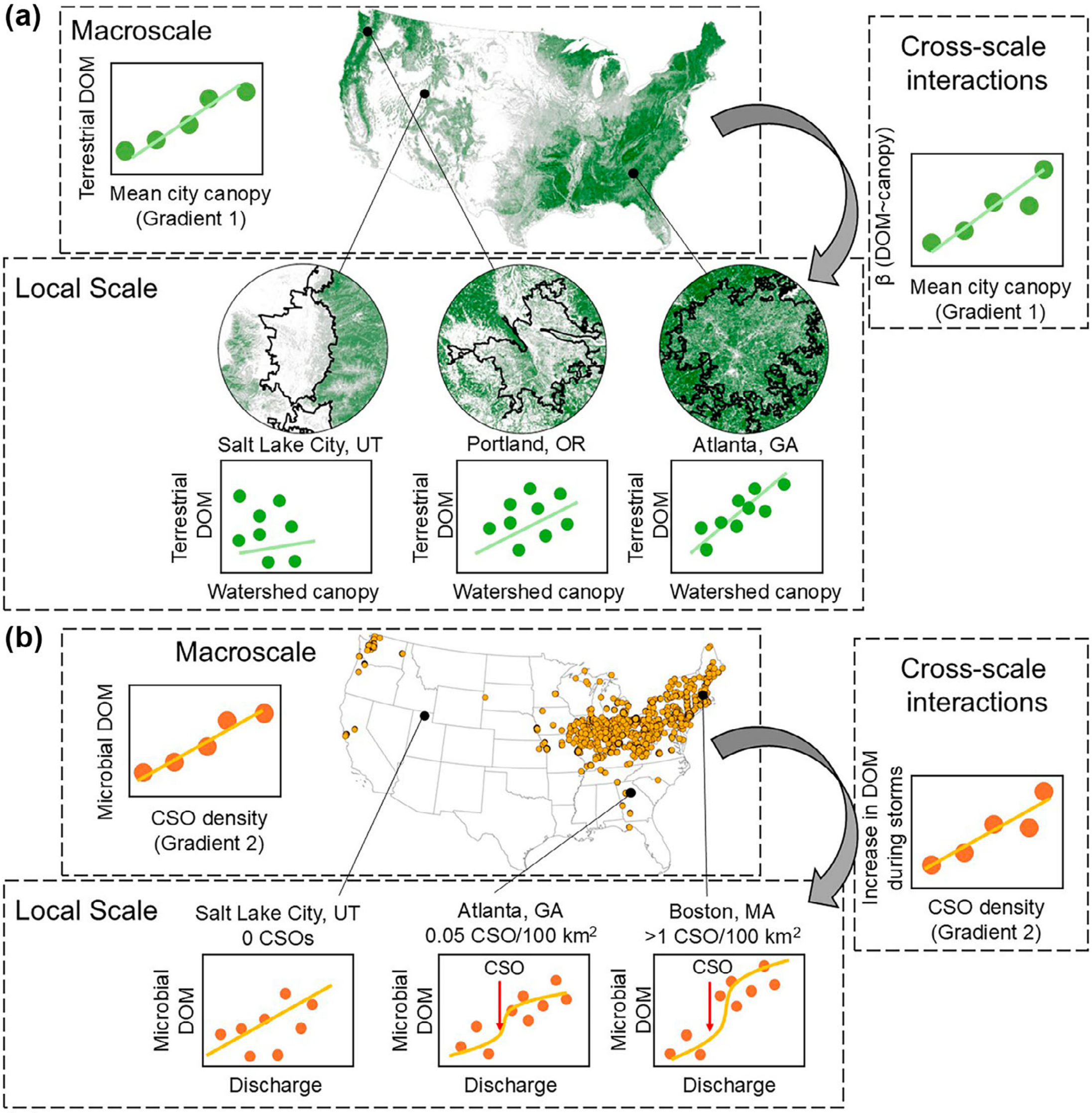
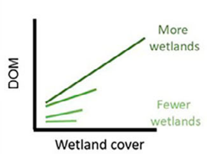
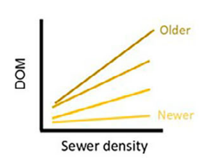
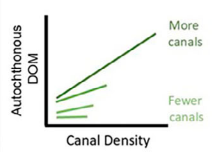
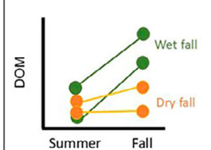


Fig. 3. Five macroscale gradients along which urban areas vary in the continental United States, identified through a principal components analysis (PCA). % represents percent of variation explained by each PCA axis. Subtitles describe characteristics of high values of each gradient (light colors), low values of each gradient have opposite characteristics. Colors represent values on each PCA axis. CSO, combined sewer outfall.

Fig. S1). Focusing on relatively large cities also provided the data resolution needed to identify within-city gradients (i.e., because Census tracts are based on population, smaller cities may only have a few Census tracts). Within cities, there are three local scale sources of variation: (1) local-scale urban gradients, (2) stream network structure, and (3) seasonal



(c)

Hypothesized effect on DOM	**Wetland Cover (Gradient 5)** Cities built on wetlands are more likely to have strong relationships between DOM and wetland cover and more humic DOM	**Housing Age (Gradient 2)** Older areas are more likely to have leaking or failing wastewater infrastructure, and therefore stronger relationships between the density of sewers and DOM in older cities compared to younger cities.	**Canal Density (Gradient 4)** High-elevation cities with greater canal density are likely to have more autochthonous DOM due to the high-light environment of canals, and a stronger control of canal density on DOM quality.	**Seasonal synchrony** Cities with synchronous precipitation and leaf fall will have stronger seasonal variation in DOC than cities with asynchronous precipitation and leaf fall.
Cross-scale Interactions				

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climate and phenology. Here we discuss these three sources of local heterogeneity as well as potential cross-scale interactions—that is, where we expect macroscale gradients (such as canopy cover) to predict variation in local gradients (such as the relationship between canopy cover and imperviousness) or relationships between local gradients and DOM (such as the local relationship between DOM and canopy cover).

Imperviousness provides a common benchmark for assessing "degree of urbanization." Yet, among cities, local-scale urban gradients can be quite variable, and imperviousness does not correlate with the same variables in the same way across cities (Fig. 5). To explore local-scale heterogeneity, we used the same national datasets as for the continental-scale gradient analysis summarized for Census tracts within each urban area and identified gradients with principal components analysis independently for each of the seven focal urban areas. A substantial portion of the local variation within cities was explained by a common pattern of urbanization in which impervious surface cover and population density were positively associated with minority populations and negatively associated with household income, elevation, tree canopy cover, and stream density (Fig. 5; Supporting Information Table S3 and Fig. S2). As a result, we might expect some consistency in patterns in DOM quality along a gradient of increased imperviousness, such as a loss of soil DOM inputs and higher bioavailability (Hosen et al. 2014; Parr et al. 2015; Coble et al. 2022).

However, while many characteristics of the urban environment were correlated in similar ways among cities (e.g., imperviousness, population density, and canopy cover; Supporting Information Table S3), the slopes and intercepts of these relationships varied substantially (Fig. 5), suggesting that the ecological and social impacts of the relationships (e.g., between imperviousness and canopy cover) may be heterogeneous among cities. Further, we hypothesize that this heterogeneity can be described by predictable cross-scale relationships (Fig. 4a). For instance, while canopy cover decreased with impervious cover in all cities, the slope of this decline was strongest for cities with overall greater canopy cover, such as Atlanta and Boston (Fig. 5). These differences in canopy cover may moderate DOM responses to urbanization among cities. For example, shifts from more terrestrial humic to more microbial and autochthonous DOM with impervious surface cover have been observed in forested urban watersheds due to declines in canopy cover with urbanization (Hosen et al. 2014; Parr et al. 2015). However, relationships between terrestrial DOM and canopy cover (Fig. 4a) may be weaker in desert cities such as Phoenix and Salt Lake City, which have overall low canopy cover and likely lower background terrestrial DOM. The hypothesized cross-scale interaction suggests that this heterogeneity is predictable: the slopes of the *local scale* relationship between canopy cover and humic DOM are expected to vary predictably along the *macroscale* gradient of canopy cover (Fig. 4a).

Although the dominant urbanization gradient was similar among cities, there was important variation in local gradients (i.e., local PC1s) among cities (Supporting Information Table S3, Fig. 5), and within cities, these local-scale patterns of watershed DOM sources, such as vegetation, wastewater infrastructure, and wetlands, are likely tied to spatial patterns in the quantity and quality of DOM in streams (Hosen et al. 2014). Inconsistent local-scale patterns among cities are likely to drive city-specific gradients of DOM quality. In Miami and Boston, cities built upon existing wetland areas, wetland cover was negatively associated with imperviousness (Supporting Information Table S3). We expect that the loss of wetlands with urbanization will be an important control on local DOM heterogeneity in these cities, and that the local importance of wetlands will be related to macroscale gradients of wetland cover (Fig. 4c). In some cities, development age correlated with a climate gradient, but these varied among cities: in Phoenix, newer development was associated with a cooler and wetter climate, as development moves into higher elevation areas, while in Salt Lake City and San Francisco, newer development was associated with drier and warmer conditions, as development expands into lower elevation areas. These gradients of temperature and precipitation may be important controls on DOM in cities that cover a strong elevation gradient, such as Salt Lake City and San Francisco, since precipitation and temperature are important controls on the production and transport of DOM generally (Creed et al. 2018).

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Fig. 4. Macrosystem approach for understanding urban heterogeneity, considering variation in urban ecosystems across macroscales, local scales, and the role of cross-scale interactions. (**a**) Macroscale differences in watershed canopy cover across cities are related to climate (gradient 1). In cities with low canopy cover (e.g., Salt Lake City, Utah [UT]), canopy may be a poor predictor of dissolved organic matter (DOM), whereas in cities with higher and variable (e.g., Portland, Oregon [OR] and Atlanta, Georgia [GA]) canopy may be a better predictor of DOM, although other factors may also explain variability in DOM (as implied by the greater scatter in the relationship in Portland compared to Atlanta). As a result, we expect cross-scale interactions, such that the local relationship between DOM concentrations and canopy cover within each city (e.g., the slope between DOM and canopy) will be correlated to the mean city canopy (e.g., a macroscale gradient). (**b**) Combined sewer outfalls (CSOs) are primarily located in the Northeast and Pacific Northwest of the United States (gradient 2). The relationships between discharge and DOM quality are expected to vary with CSO density, due to overflow events during high flows. The increase in microbial DOM during storms is expected to be correlated with CSO density among cities. (**c**) Housing age, canal density, wetland cover, and seasonal synchrony, are all expected to have cross-scale interactions that affect DOM quantity and quality. Here lines represent local scale relationships for different cities, with macroscale characteristics indicated by the color of the line.

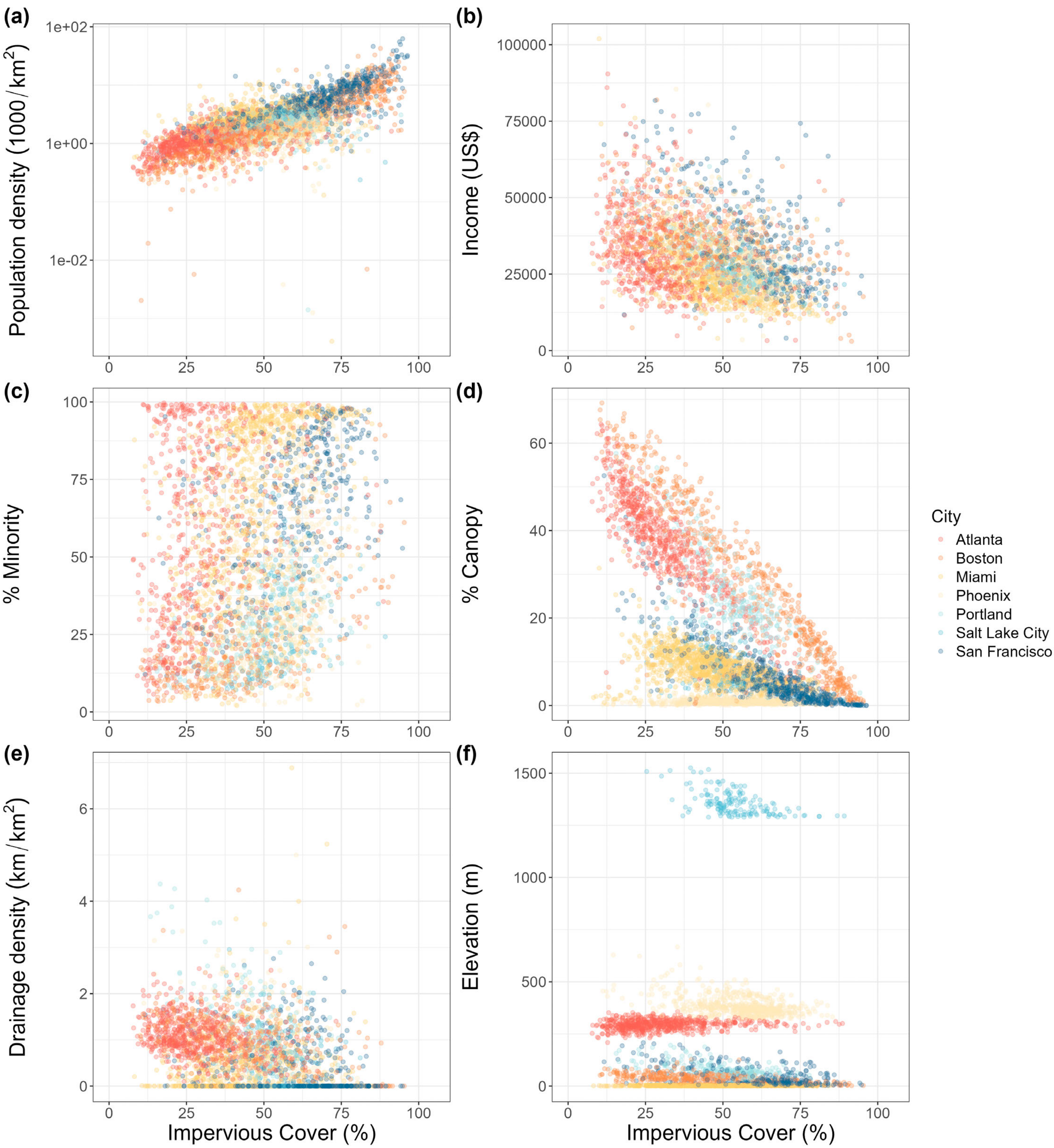

Fig. 5. Relationships between impervious cover and (**a**) population density, (**b**) median household income, (**c**) percent minority population (calculated as difference between total population and non-Hispanic white population), (**d**) percent tree canopy cover, (**e**) stream drainage density, and (**f**) elevation vary among cities. Even though broad associations among variables are consistent among cities, the shapes of these relationships vary among cities, such that impervious surface cover alone is insufficient to characterize urban gradients.

The location of wastewater facilities, and whether they are generally distributed (such as septic systems) or centralized (such as wastewater treatment facilities), as well as their age and condition (Capps 2019) may also influence spatial patterns of sources of nutrients and OM across a city (Smith et al. 2021). For example, septic systems are generally placed in uplands, while sewers are often placed near streams where generally wetter conditions increase connectivity and wastewater leakage to streams (Delesantro et al. 2022). Along the North–South US gradient of housing age and combined sewer systems (gradient 2), we expect that in cities with higher CSO densities, high flows will lead to increases in microbial DOM from sewer overflows, and the increase in microbial DOM during storms will correlate with CSO density among cities (Fig. 4b). Because older infrastructure is more likely to leak, becoming a source of microbial DOM, we expect stronger local effects of sewer density on DOM in older cities than in newer cities (Fig. 4c). In some cities, DOM quality may also be associated with sociodemographic gradients due to historic and ongoing racial segregation that shapes infrastructure investments and maintenance (Parr et al. 2016; Heck 2021; Hendricks and Van Zandt 2021). Inequitable infrastructure investment has been observed for wastewater (Silver 2021), stormwater (Heck 2021), tree canopy (Locke et al. 2021), and green space in general (Nardone et al. 2021), all urban features that shape the concentration and character of DOM. The presence and distribution of other hydrologic infrastructure, such as canals (providing a high-light environment that could support autochthonous DOM production) and concrete-lined streams (reducing terrestrial DOM inputs from riparian zones and promoting the transport of wastewater effluents), are also likely to generate heterogeneity in DOM quality within cities (Duan et al. 2014; Smith et al. 2021), and we expect that canal density will be a stronger predictor of autochthonous DOM in cities with greater overall density of canals (Fig. 4c).

Spatial patterns of urbanization across stream networks

Urban streams and watershed networks interact with urban infrastructure, which adds unique considerations for thinking about scale and heterogeneity beyond spatial patterns of land cover. The dominant flowpaths connecting terrestrial and aquatic habitats in cities likely vary from urban headwaters to urban rivers (Fig. 6a) due to a layering of human activity (Kaushal and Belt 2012) over natural variation across stream networks and the location of the city within the watershed network (Vannote et al. 1980). For example, surface runoff is likely to dominate small headwater streams (which may be zero-order stormsheds) (Fork et al. 2018), with groundwater generally increasing with watershed area (Kaushal et al. 2014; Gabor et al. 2017). Flow contributions from infrastructure, such as stormwater outfalls, combined sewers, and wastewater treatment facilities will increase with watershed area, as will contributions from upstream areas (Kaushal and Belt 2012; Hale et al. 2015). Such changes in dominant flowpaths are expected to be associated with variation in material inputs, such as OM or nutrients, such that urban headwaters are dominated by surface materials, such as leaf litter (Fork et al. 2018), while additional sources, such as groundwater, wastewater, and instream processes become more important downstream (Fig. 6a) (Griffith et al. 2009; Kaushal et al. 2014; Hale et al. 2015).

Scaling relationships are likely to vary substantially among cities depending on the location of the city in the broader stream network, the location of relevant flowpaths, and the network position of important infrastructure such as WWTPs (Fig. 6b, c). For example, Atlanta, GA is located within the upper watersheds and upper reaches of several large rivers (the Altamaha, Chattahoochee, and Flint Rivers) and therefore has fewer upstream inputs. Thus, scaling relationships with watershed area in Atlanta are likely to differ from those in Boston, MA, where the urban core is located near the coast where large rivers meet the ocean, and where there are substantial inputs from upstream of the city. Similarly, the location of infrastructure, such as WWTPs, will also shape the form and function of river networks (Fig. 6c). Even though Boston and Atlanta differ in the location of the city within the watershed, WWTPs in both cities discharge to relatively smaller streams higher up in the network (watershed areas 160–388 km^2), potentially increasing flow heterogeneity among streams within the city. In contrast, WWTPs in Salt Lake City are nearly all located along the Jordan River (watershed area $\sim$ 10,000 km^2), so WWTP impacts are absent from headwaters and are more consistent because there is only one river flowing through the city (Fig. 6c).

Variation in seasonality and temporal patterns among cities

In addition to spatial patterns, heterogeneity within and among urban watersheds is expected due to differences in seasonality that will shape material inputs, transport, and transformations. For example, seasonal patterns of stream discharge vary substantially among the focal cities (Supporting Information Fig. S3a). Some discharge patterns are a direct result of urbanization, such as the flashy hydrology of Peachtree Creek in Atlanta. In other cities, flashy urban discharge overlays a seasonal discharge pattern that might reflect seasonal variation in precipitation or evapotranspiration. In general, we expect greater connectivity to terrestrial DOM sources during higher flow conditions, whether that is seasonal or during storms (Raymond et al. 2016; Fork et al. 2018; Wise et al. 2019), and greater proportions of autochthonous DOM during dry periods. Where WWTP effluent is a dominant source of DOM, seasonal variation in DOM may be lower due to more consistent fluxes (Capps 2019), while combined sewer systems could lead to storm-driven pulses in microbial DOM, in addition to pulses of allochthonous DOM (Fork et al. 2018).

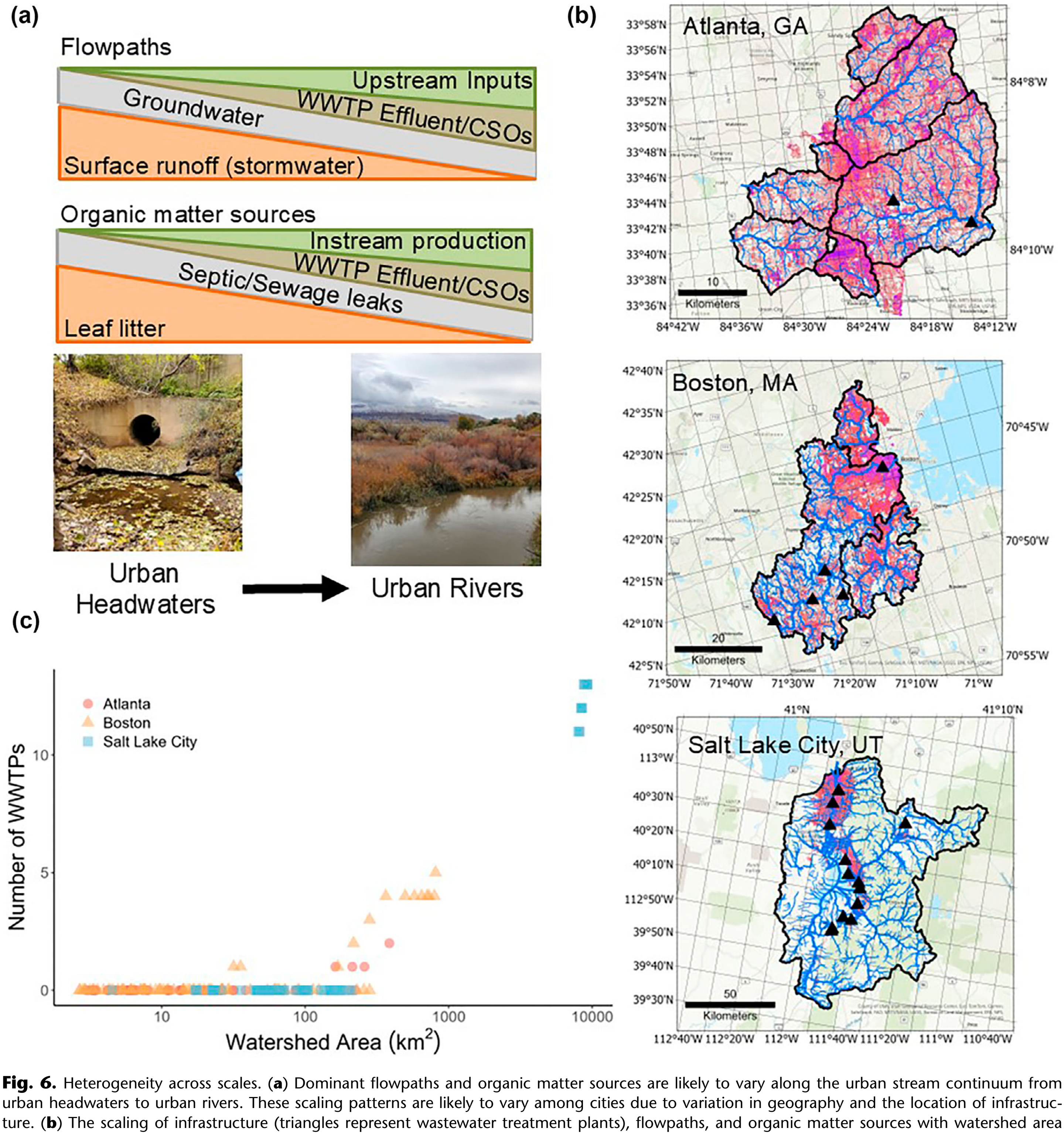

Fig. 6. Heterogeneity across scales. (**a**) Dominant flowpaths and organic matter sources are likely to vary along the urban stream continuum from urban headwaters to urban rivers. These scaling patterns are likely to vary among cities due to variation in geography and the location of infrastructure. (**b**) The scaling of infrastructure (triangles represent wastewater treatment plants), flowpaths, and organic matter sources with watershed area varies among cities due to the interaction between watershed and development geography. Development in Atlanta, Georgia (GA) is in the headwaters of several watersheds, while development in Boston, Massachusetts (MA) is at the mouth of three rivers. In Salt Lake City, Utah (UT), development is centered on a single major river that has a large watershed upstream of the city. Basemap is World Topographic Map (ESRI 2017). (**c**) As a result, wastewater treatment plants discharge into streams with different watershed areas in different cities (points are sampled subwatersheds within each city).

In other systems, such as Miami and Salt Lake City, seasonal patterns may be driven less by variation in the availability of DOM sources on the landscape and more by seasonal variation in water sources and management (Smith et al. 2021). In Salt Lake City, this management consists of water diversions during high spring streamflows for flood control (which are no longer visible in the resulting hydrograph) and interbasin transfers to supplement streamflow during the summer when snowmelt is diverted for water supply. In Miami, the stream network is almost entirely canals, which are managed for flood control, irrigation, recreation, and water supply. In both Salt Lake City and Miami, water management is largely designed to manage and minimize seasonal variation in streamflow and directly impacts seasonal patterns in the sources and quality of water and DOM (Kelso and Baker 2020; Smith et al. 2021).

Seasonality in climate and phenology is also location dependent and is expected to change the relative importance of various DOM sources. In some cities, temperature and precipitation covary (Miami), while others have dry summers and wet winters (Portland and San Francisco), and still others have relatively consistent precipitation throughout the year (Boston and Atlanta) (Supporting Information Fig. S3b). In urban watersheds with substantial tree canopy, seasonal riparian forest phenology drives variation in DOM, where terrestrial, leaf-derived DOM is highest during autumn leaf-off (Arango et al. 2017). The timing of precipitation in relation to leaf-bud and leaf-fall will influence seasonal DOM quality, with greater protein-like DOM expected during wet leaf-bud and leaf-fall seasons (Singh et al. 2014), whereas DOM from leaf-fall that occurs during seasonal dry periods will be less likely to be rapidly transported to streams (Fig. 4c).

Implications: A macrosystems approach to urban functional heterogeneity

Urban watersheds and the impacts of urbanization on stream ecosystems are complex, and disentangling this complexity is essential for effective watershed management (Roy et al. 2016). Responses to urbanization among streams depend on climate (Hale et al. 2016), the built environment (Parr et al. 2016), socioeconomics (Capps et al. 2016), and interactions among these factors. Effective management of urban watersheds thus requires a better understanding of the sources of problems and anticipated patterns, and a macroscale approach provides a pathway for understanding when, where, and how urbanization can shape stream ecosystems. This understanding is essential not only for generalizing scientific results, but also for effectively applying and transferring management activities. We have illustrated the utility of this approach for making predictions about DOM in urban streams, and the approach could be used to generate hypotheses about any indicator of interest.

Urbanization influences DOM through changing the presence and identity of DOM sources (e.g., soils, vegetation, novel anthropogenic sources), the connectivity of sources to streams (e.g., disconnection of soils, connectivity of wastewater), and processing of DOM in streams (e.g., rates of gross primary production and respiration). We have hypothesized that the effects of urbanization on DOM will vary across local and macroscale gradients due to background DOM conditions and sources and the characteristics of urbanization itself. Sources and concentrations of DOM naturally vary across biophysical gradients. For example, the relative importance of forests, wetlands, or instream primary production as DOM sources varies among ecosystems. We hypothesize that these background conditions shape ecosystem responses to urbanization, which may result in loss of DOM sources if forests and wetlands are converted to urban land or may fuel DOM sources by stimulating instream primary production. The second key set of factors shaping DOM responses to urbanization is the characteristics of urbanization itself, including the nature and location of anthropogenic DOM inputs such as wastewater, and how water and DOM are routed through cities. We expect that these variables at the macroscale will help understand and predict local scale patterns (Fig. 4). For example, with strong terrestrial DOM sources, such as wetlands or forests, we expect that local gradients will be based on the loss of these sources with urbanization. Similarly, with very connected wastewater systems such as CSOs, we expect that gradients of this infrastructure will drive local variation in microbial DOM.

Importantly, these are hypotheses that need to be tested, and additional research will likely identify additional sources of DOM variation at local to macro scales. Testing these hypothesized cross-scale interactions could enable a better understanding of how urbanization shapes watershed function differently at local to macro scales. As DOM integrates many elements of urbanization and water quality, it may offer insight into other urban stream responses. For example, changes in the dominant sources of DOM with urbanization are likely to influence stream biogeochemical processes (Fuß et al. 2017; Demars et al. 2020; Xenopoulos et al. 2021) and stream food webs (Demars et al. 2020), and microbial DOM signatures can be useful indicators of wastewater pollution (Smith et al. 2021; Batista-Andrade et al. 2024), which has far-reaching consequences beyond DOM. A macrosystems approach may also facilitate more effective translation of management approaches among cities by identifying cities with similar challenges where related management approaches are likely to be successful.

Author Contributions

Rebecca L. Hale led the manuscript effort and conducted the statistical analyses. Rebecca L. Hale, Kristina G. Hopkins, Krista A. Capps, John S. Kominoski, Jennifer L. Morse, and

Allison H. Roy developed the research questions and conceptual figures. All authors reviewed the literature, provided input for the conceptual figures, and wrote the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are published in Hopkins K. G, R Hale, K. Capps., et al. 2024. "Landscape characteristics for urban gradients in United States cities across multiple scales: U.S. Geological Survey data release." (https://doi.org/10.5066/P13UZYZF)

References

Aitkenhead-Peterson, J. A., J. E. Alexander, and T. A. Clair. 2005. "Dissolved Organic Carbon and Dissolved Organic Nitrogen Export from Forested Watersheds in Nova Scotia: Identifying Controlling Factors." *Global Biogeochemical Cycles* 19: GB4016. https://doi.org/10.1029/2004GB002438.

Alberts, J. M., J. J. Beaulieu, and I. Buffam. 2017. "Watershed Land Use and Seasonal Variation Constrain the Influence of Riparian Canopy Cover on Stream Ecosystem Metabolism." *Ecosystems* 20: 553–567. https://doi.org/10.1007/s10021-016-0040-9.

Arango, C. P., J. J. Beaulieu, K. M. Fritz, et al. 2017. "Urban Infrastructure Influences Dissolved Organic Matter Quality and Bacterial Metabolism in an Urban Stream Network." *Freshwater Biology* 62: 1917–1928. https://doi.org/10.1111/fwb.13035.

Armstrong, A., and D. Jackson-Smith. 2017. "Connections and Collaborations of Local Water Management Organizations of Utah." *Society & Natural Resources* 30: 1343–1357. https://doi.org/10.1080/08941920.2017.1347972.

Batista-Andrade, J. A., C. Welty, D. Iglesias Vega, A. McClain, and L. Blaney. 2024. "Geospatial Variability of Fluorescent Dissolved Organic Matter in Urban Watersheds: Relationships with Land Cover and Wastewater Infrastructure." *Environmental Science & Technology* 58: 7529–7542. https://doi.org/10.1021/acs.est.3c07925.

Beaulieu, J. J., P. M. Mayer, S. S. Kaushal, et al. 2014. "Effects of Urban Stream Burial on Organic Matter Dynamics and Reach Scale Nitrate Retention." *Biogeochemistry* 121: 107–126. https://doi.org/10.1007/s10533-014-9971-4.

Bernhardt, E. S., and G. E. Likens. 2002. "Dissolved Organic Carbon Enrichment Alters Nitrogen Dynamics in a Forest Stream." *Ecology* 83: 1689–1700. https://doi.org/10.1890/0012-9658(2002)083[1689:DOCEAN]2.0.CO;2.

Bernhardt, E. S., P. Savoy, M. J. Vlah, et al. 2022. "Light and Flow Regimes Regulate the Metabolism of Rivers." *Proceedings of the National Academy of Sciences of the United States of America* 119: e2121976119. https://doi.org/10.1073/pnas.2121976119.

Bernot, M. J., D. J. Sobota, R. O. Hall JR., et al. 2010. "Inter-Regional Comparison of Land-Use Effects on Stream Metabolism." *Freshwater Biology* 55: 1874–1890. https://doi.org/10.1111/j.1365-2427.2010.02422.x.

Bhattacharya, R., and C. L. Osburn. 2020. "Spatial Patterns in Dissolved Organic Matter Composition Controlled by Watershed Characteristics in a Coastal River Network: The Neuse River Basin, USA." *Water Research* 169: 115248. https://doi.org/10.1016/j.watres.2019.115248.

Blaszczak, J. R., J. M. Delesantro, D. L. Urban, M. W. Doyle, and E. S. Bernhardt. 2019*a*. "Scoured or Suffocated: Urban Stream Ecosystems Oscillate between Hydrologic and Dissolved Oxygen Extremes." *Limnology and Oceanography* 64: 877–894. https://doi.org/10.1002/lno.11081.

Blaszczak, J. R., J. M. Delesantro, Y. Zhong, D. L. Urban, and E. S. Bernhardt. 2019*b*. "Watershed Urban Development Controls on Urban Streamwater Chemistry Variability." *Biogeochemistry* 144: 61–84. https://doi.org/10.1007/s10533-019-00572-7.

Booth, D., and C. Jackson. 1997. "Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation." *Journal of the American Water Resources Association* 33: 1077–1090. https://doi.org/10.1111/j.1752-1688.1997.tb04126.x.

Bratt, A. R., J. C. Finlay, S. E. Hobbie, B. D. Janke, A. C. Worm, and K. L. Kemmitt. 2017. "Contribution of Leaf Litter to Nutrient Export during Winter Months in an Urban Residential Watershed." *Environmental Science & Technology* 51: 3138–3147. https://doi.org/10.1021/acs.est.6b06299.

Brown, R. R., N. Keath, and T. H. F. Wong. 2009. "Urban Water Management in Cities: Historical, Current and Future Regimes." *Water Science and Technology* 59: 847–855. https://doi.org/10.2166/wst.2009.029.

Burchfield, M., H. G. Overman, D. Puga, and M. A. Turner. 2006. "Causes of Sprawl: A Portrait from Space*." *The Quarterly Journal of Economics* 121: 587–633. https://doi.org/10.1162/qjec.2006.121.2.587.

Butman, D., S. Stackpoole, E. Stets, C. P. McDonald, D. W. Clow, and R. G. Striegl. 2016. "Aquatic Carbon Cycling in the Conterminous United States and Implications for Terrestrial Carbon Accounting." *Proceedings of the National Academy of Sciences* 113: 58–63. https://doi.org/10.1073/pnas.1512651112.

Cadenasso, M. L., S. T. A. Pickett, and K. Schwarz. 2007. "Spatial Heterogeneity in Urban Ecosystems: Reconceptualizing Land Cover and a Framework for Classification." *Frontiers in Ecology and the Environment* 5: 80–88. https://doi.org/10.1890/1540-9295(2007)5[80:SHIUER]2.0.CO;2.

Capps, K. A. 2019. "Wastewater Infrastructure and the Ecology and Management of Freshwater Systems." *Acta Limnologica Brasiliensia* 31: e104. https://doi.org/10.1590/S2179-975X3719.

Capps, K. A., C. N. Bentsen, and A. Ramírez. 2016. "Poverty, Urbanization, and Environmental Degradation: Urban Streams in the Developing World." *Freshwater Science* 36: 429–435. https://doi.org/10.1086/684945.

Chen, S., Y. Lu, P. Dash, et al. 2019. "Hurricane Pulses: Small Watershed Exports of Dissolved Nutrients and Organic Matter during Large Storms in the Southeastern USA." *Science of the Total Environment* 689: 232–244. https://doi.org/10.1016/j.scitotenv.2019.06.351.

Choat, B., A. Pulido, A. S. Bhaskar, et al. 2023. "Assessing Stormwater Control Measure Inventories from 23 Cities in the United States." *Environmental Research: Infrastructure and Sustainability* 3: 025003. https://doi.org/10.1088/2634-4505/acc759.

Coble, A. A., A. S. Wymore, J. D. Potter, and W. H. McDowell. 2022. "Land Use Overrides Stream Order and Season in Driving Dissolved Organic Matter Dynamics Throughout the Year in a River Network." *Environmental Science & Technology* 56: 2009–2020. https://doi.org/10.1021/acs.est.1c06305.

Cory, R. M., and G. W. Kling. 2018. "Interactions between Sunlight and Microorganisms Influence Dissolved Organic Matter Degradation along the Aquatic Continuum." *Limnology and Oceanography Letters* 3: 102–116. https://doi.org/10.1002/lol2.10060.

Creed, I. F., A.-. K. Bergström, C. G. Trick, et al. 2018. "Global Change-Driven Effects on Dissolved Organic Matter Composition: Implications for Food Webs of Northern Lakes." *Global Change Biology* 24: 3692–3714. https://doi.org/10.1111/gcb.14129.

Cuffney, T. F., R. Kashuba, S. S. Qian, et al. 2011. "Multilevel Regression Models Describing Regional Patterns of Invertebrate and Algal Responses to Urbanization across the USA." *Journal of the North American Benthological Society* 30: 797–819. https://doi.org/10.1899/10-140.1.

Delesantro, J. M., J. M. Duncan, D. Riveros-Iregui, et al. 2021. "Characterizing and Classifying Urban Watersheds with Compositional and Structural Attributes." *Hydrological Processes* 35: e14339. https://doi.org/10.1002/hyp.14339.

Delesantro, J. M., J. M. Duncan, D. Riveros-Iregui, et al. 2022. "The Nonpoint Sources and Transport of Baseflow Nitrogen Loading Across a Developed Rural–Urban Gradient." *Water Resources Research* 58: e2021WR031533. https://doi.org/10.1029/2021WR031533.

Delesantro, J. M., J. M. Duncan, D. Riveros-Iregui, K. M. Whitmore, and L. E. Band. 2024. "High Frequency Monitoring and Nitrate Sourcing Reveals Baseflow and Stormflow Controls on Total Dissolved Nitrogen and Carbon Export Along a Rural–Urban Gradient." *Water Resources Research* 60: e2023WR036750. https://doi.org/10.1029/2023WR036750.

Demars, B. O. L., N. Friberg, and B. Thornton. 2020. "Pulse of Dissolved Organic Matter Alters Reciprocal Carbon Subsidies Between Autotrophs and Bacteria in Stream Food Webs." *Ecological Monographs* 90: e01399. https://doi.org/10.1002/ecm.1399.

Dewitz, J. A. 2023. National Land Cover Database (NLCD) 2021 Products. Earth Resources Observation and Science (EROS) Center. https://doi.org/10.5066/P9JZ7AO3.

Dodds, W. K., L. Bruckerhoff, D. Batzer, et al. 2019. "The Freshwater Biome Gradient Framework: Predicting Macroscale Properties Based on Latitude, Altitude, and Precipitation." *Ecosphere* 10: e02786. https://doi.org/10.1002/ecs2.2786.

Dodds, W. K., K. C. Rose, S. Fei, and S. Chandra. 2021. "Macrosystems Revisited: Challenges and Successes in a New Subdiscipline of Ecology." *Frontiers in Ecology and the Environment* 19: 4–10. https://doi.org/10.1002/fee.2286.

Duan, S., R. M. W. Amon, and R. L. Brinkmeyer. 2014. "Tracing Sources of Organic Matter in Adjacent Urban Streams Having Different Degrees of Channel Modification." *Science of the Total Environment* 485: 252–262. https://doi.org/10.1016/j.scitotenv.2014.03.066.

Eger, C. G., D. G. Chandler, and C. T. Driscoll. 2017. "Hydrologic Processes that Govern Stormwater Infrastructure Behaviour." *Hydrological Processes* 31: 4492–4506. https://doi.org/10.1002/hyp.11353.

Elliott, M. A., A. Bakchan, J. Maxcy-Brown, et al. 2023. "Sustainable Wastewater Management for Underserved Communities Using Federal Infrastructure Funds: Barriers, Bottlenecks, and Tradeoffs." *Water Security* 20: 100152. https://doi.org/10.1016/j.wasec.2023.100152.

ESRI. 2017. World Topographic Map. World Topographic Map.

Fork, M. L., J. R. Blaszczak, J. M. Delesantro, and J. B. Heffernan. 2018. "Engineered Headwaters Can Act as Sources of Dissolved Organic Matter and Nitrogen to Urban Stream Networks." *Limnology and Oceanography Letters* 3: 215–224. https://doi.org/10.1002/lol2.10066.

Fuß, T., B. Behounek, A. J. Ulseth, and G. A. Singer. 2017. "Land Use Controls Stream Ecosystem Metabolism by Shifting Dissolved Organic Matter and Nutrient Regimes." *Freshwater Biology* 62: 582–599. https://doi.org/10.1111/fwb.12887.

Gabor, R. S., S. J. Hall, D. P. Eiriksson, et al. 2017. "Persistent Urban Influence on Surface Water Quality Via Impacted Groundwater." *Environmental Science & Technology* 51: 9477–9487. https://doi.org/10.1021/acs.est.7b00271.

Gergel, S. E., M. G. Turner, and T. K. Kratz. 1999. "Dissolved Organic Carbon as an Indicator of the Scale of Watershed Influence on Lakes and Rivers." *Ecological Applications* 9: 1377–1390. https://doi.org/10.1890/1051-0761(1999)009[1377:DOCAAI]2.0.CO;2.

Griffith, D. R., R. T. Barnes, and P. A. Raymond. 2009. "Inputs of Fossil Carbon from Wastewater Treatment Plants to U.S. Rivers and Oceans." *Environmental Science & Technology* 43: 5647–5651. https://doi.org/10.1021/es9004043.

Grove, M., L. Ogden, S. Pickett, et al. 2018. "The Legacy Effect: Understanding How Segregation and Environmental Injustice Unfold over Time in Baltimore." *Annals of the American Association of Geographers* 108: 524–537. https://doi.org/10.1080/24694452.2017.1365585.

Hale, R. L., M. Scoggins, N. J. Smucker, and A. Suchy. 2016. "Effects of Climate on the Expression of the Urban Stream Syndrome." *Freshwater Science* 35: 421–428. https://doi.org/10.1086/684594.

Hale, R. L., L. Turnbull, S. R. Earl, D. L. Childers, and N. B. Grimm. 2015. "Stormwater Infrastructure Controls Runoff and Dissolved Material Export from Arid Urban Watersheds." *Ecosystems* 18: 62–75. https://doi.org/10.1007/s10021-014-9812-2.

Heck, S. 2021. "Greening the Color Line: Historicizing Water Infrastructure Redevelopment and Environmental Justice in the St. Louis Metropolitan Region." *Journal of Environmental Policy & Planning* 23: 565–580. https://doi.org/10.1080/1523908X.2021.1888702.

Heffernan, J. B., P. A. Soranno, M. J. Angilletta Jr., et al. 2014. "Macrosystems Ecology: Understanding Ecological Patterns and Processes at Continental Scales." *Frontiers in Ecology and the Environment* 12: 5–14. https://doi.org/10.1890/130017.

Hendricks, M. D., and S. Van Zandt. 2021. "Unequal Protection Revisited: Planning for Environmental Justice, Hazard Vulnerability, and Critical Infrastructure in Communities of Color." *Environmental Justice* 14: 87–97. https://doi.org/10.1089/env.2020.0054.

Hill, R. A., M. H. Weber, S. G. Leibowitz, A. R. Olsen, and D. J. Thornbrugh. 2016. "The Stream-Catchment (StreamCat) Dataset: A Database of Watershed Metrics for the Conterminous United States." *JAWRA Journal of the American Water Resources Association* 52: 120–128. https://doi.org/10.1111/1752-1688.12372.

Hobbie, S. E., L. A. Baker, C. Buyarski, D. Nidzgorski, and J. C. Finlay. 2014. "Decomposition of Tree Leaf Litter on Pavement: Implications for Urban Water Quality." *Urban Ecosystem* 17: 369–385. https://doi.org/10.1007/s11252-013-0329-9.

Hobbie, S. E., R. A. King, T. Belo, et al. 2023. "Sources of Variation in Nutrient Loads Collected through Street Sweeping in the Minneapolis-St. Paul Metropolitan Area, Minnesota, USA." *Science of the Total Environment* 905: 166934. https://doi.org/10.1016/j.scitotenv.2023.166934.

Hopkins, K. G., R. Hale, K. Capps, et al. 2024. Landscape Characteristics for Urban Gradients in United States Cities across Multiple Scales. U.S. Geological Survey. https://doi.org/10.5066/P13UZYZF.

Hopkins, K. G., R. L. Hale, K. A. Capps, et al. 2025. "Overcoming Challenges in Mapping Hydrography and Heterogeneity in Urban Landscapes." *Hydrological Processes* 39: e70221. https://doi.org/10.1002/hyp.70221.

Hopkins, K. G., N. B. Morse, D. J. Bain, et al. 2015. "Assessment of Regional Variation in Streamflow Responses to Urbanization and the Persistence of Physiography." *Environmental Science & Technology* 49: 2724–2732. https://doi.org/10.1021/es505389y.

Hosen, J. D., O. T. McDonough, C. M. Febria, and M. A. Palmer. 2014. "Dissolved Organic Matter Quality and Bioavailability Changes Across an Urbanization Gradient in Headwater Streams." *Environmental Science & Technology* 48: 7817–7824. https://doi.org/10.1021/es501422z.

Jaffé, R., Y. Yamashita, N. Maie, et al. 2012. "Dissolved Organic Matter in Headwater Streams: Compositional Variability across Climatic Regions of North America." *Geochimica et Cosmochimica Acta* 94: 95–108. https://doi.org/10.1016/j.gca.2012.06.031.

Kaushal, S., and K. Belt. 2012. "The Urban Watershed Continuum: Evolving Spatial and Temporal Dimensions." *Urban Ecosystems* 15: 409–435. https://doi.org/10.1007/s11252-012-0226-7.

Kaushal, S. S., K. Delaney-Newcomb, S. E. G. Findlay, et al. 2014. "Longitudinal Patterns in Carbon and Nitrogen Fluxes and Stream Metabolism along an Urban Watershed Continuum." *Biogeochemistry* 121: 23–44. https://doi.org/10.1007/s10533-014-9979-9.

Kelso, J. E., and M. A. Baker. 2020. "Organic Matter Is a Mixture of Terrestrial, Autochthonous, and Wastewater Effluent in an Urban River." *Frontiers in Environmental Science* 7: 202. https://doi.org/10.3389/fenvs.2019.00202.

Khamis, K., C. Bradley, and D. m. Hannah. 2017. "Understanding Dissolved Organic Matter Dynamics in Urban Catchments: Insights from In Situ Fluorescence Sensor Technology." *WIREs Water* 5: e1259. https://doi.org/10.1002/wat2.1259.

King, R. S., M. E. Baker, P. F. Kazyak, and D. E. Weller. 2011. "How Novel Is Too Novel? Stream Community Thresholds at Exceptionally Low Levels of Catchment Urbanization." *Ecological Applications* 21: 1659–1678. https://doi.org/10.1890/10-1357.1.

Kothawala, D. N., X. Ji, H. Laudon, et al. 2015. "The Relative Influence of Land Cover, Hydrology, and in-Stream Processing on the Composition of Dissolved Organic

Matter in Boreal Streams." *Journal of Geophysical Research: Biogeosciences* 120: 1491–1505. https://doi.org/10.1002/2015JG002946.

Kurek, M. R., K. P. Wickland, N. A. Nichols, et al. 2024. "Linking Dissolved Organic Matter Composition to Landscape Properties in Wetlands across The United States of America." *Global Biogeochemical Cycles* 38: e2023GB007917. https://doi.org/10.1029/2023GB007917.

Ledford, S. H., J. S. Diamond, and L. Toran. 2021. "Large Spatiotemporal Variability in Metabolic Regimes for an Urban Stream Draining Four Wastewater Treatment Plants with Implications for Dissolved Oxygen Monitoring." *PLoS One* 16: e0256292. https://doi.org/10.1371/journal.pone.0256292.

Ledford, S. H., M. Zimmer, and D. Payan. 2020. "Anthropogenic and Biophysical Controls on Low Flow Hydrology in the Southeastern United States." *Water Resources Research* 56: e2020WR027098. https://doi.org/10.1029/2020WR027098.

Locke, D. H., B. Hall, J. M. Grove, et al. 2021. "Residential Housing Segregation and Urban Tree Canopy in 37 US Cities." *Npj Urban Sustainability* 1: 1–9. https://doi.org/10.1038/s42949-021-00022-02021.

McCluney, K. E., N. L. Poff, M. A. Palmer, et al. 2014. "Riverine Macrosystems Ecology: Sensitivity, Resistance, and Resilience of Whole River Basins with Human Alterations." *Frontiers in Ecology and the Environment* 12: 48–58. https://doi.org/10.1890/120367.

Nardone, A., K. E. Rudolph, F. R. Morello, and J. A. Casey. 2021. "Redlines and Greenspace: The Relationship between Historical Redlining and 2010 Greenspace across the United States." *Environmental Health Perspectives* 129: 017006. https://doi.org/10.1289/EHP7495.

Orlova, J., F. Amiri, A. K. Bourgeois, et al. 2024. "Composition of Stream Dissolved Organic Matter across Canadian Forested Ecozones Varies in Three Dimensions Linked to Landscape and Climate." *Water Resources Research* 60: e2023WR035196. https://doi.org/10.1029/2023WR035196.

Ortiz Muñoz, L. D., and J. S. Kominoski. 2025. "Forecasting Climate and Human Alterations to Coastal and Estuarine Dissolved Organic Matter." *Limnology and Oceanography Letters* 10: 265–286. https://doi.org/10.1002/lol2.70002.

Parr, T. B., C. S. Cronan, T. Ohno, S. E. Findlay, S. Smith, and K. S. Simon. 2015. "Urbanization Changes the Composition and Bioavailability of Dissolved Organic Matter in Headwater Streams." *Limnology and Oceanography* 60: 885–900. https://doi.org/10.1002/lno.10060.

Parr, T. B., N. J. Smucker, M. W. Neale, and C. N. Bentsen. 2016. "Potential Roles of Past, Present, and Future Urbanization Characteristics in Producing Varied Stream Responses." *Freshwater Science* 35: 436–443. https://doi.org/10.1086/685030.

Pisani, O., D. D. Bosch, A. W. Coffin, D. M. Endale, D. Liebert, and T. C. Strickland. 2020. "Riparian Land Cover and Hydrology Influence Stream Dissolved Organic Matter Composition in an Agricultural Watershed." *Science of the Total Environment* 717: 137165. https://doi.org/10.1016/j.scitotenv.2020.137165.

Raymond, P. A., J. E. Saiers, and W. V. Sobczak. 2016. "Hydrological and Biogeochemical Controls on Watershed Dissolved Organic Matter Transport: Pulse-Shunt Concept." *Ecology* 97: 5–16. https://doi.org/10.1890/14-1684.1.

Roy, A. H., K. A. Capps, R. W. El-Sabaawi, et al. 2016. "Urbanization and Stream Ecology: Diverse Mechanisms of Change." *Freshwater Science* 35: 272–277. https://doi.org/10.1086/685097.

Schueler, T. R., L. Fraley-McNeal, and K. Cappiella. 2009. "Is Impervious Cover Still Important? Review of Recent Research." *Journal of Hydrologic Engineering* 14: 309–315. https://doi.org/10.1061/(ASCE)1084-0699(2009)14:4(309).

Silver, J. 2021. "Decaying Infrastructures in the Post-Industrial City: An Urban Political Ecology of the US Pipeline Crisis." *Environment and Planning E: Nature and Space* 4: 756–777. https://doi.org/10.1177/2514848619890513.

Singh, S., S. Inamdar, M. Mitchell, and P. McHale. 2014. "Seasonal Pattern of Dissolved Organic Matter (DOM) in Watershed Sources: Influence of Hydrologic Flow Paths and Autumn Leaf Fall." *Biogeochemistry* 118: 321–337. https://doi.org/10.1007/s10533-013-9934-1.

Smith, M. A., J. S. Kominoski, E. E. Gaiser, R. M. Price, and T. G. Troxler. 2021. "Stormwater Runoff and Tidal Flooding Transform Dissolved Organic Matter Composition and Increase Bioavailability in Urban Coastal Ecosystems." *Journal of Geophysical Research: Biogeosciences* 126: e2020JG006146. https://doi.org/10.1029/2020JG006146.

Soranno, P. A., K. S. Cheruvelil, E. G. Bissell, et al. 2014. "Cross-Scale Interactions: Quantifying Multi-Scaled Cause–Effect Relationships in Macrosystems." *Frontiers in Ecology and the Environment* 12: 65–73. https://doi.org/10.1890/120366.

Steele, M. K., and H. Wolz. 2019. "Heterogeneity in the Land Cover Composition and Configuration of US Cities: Implications for Ecosystem Services." *Landscape Ecology* 34: 1247–1261. https://doi.org/10.1007/s10980-019-00859-y.

Tank, J. L., E. J. Rosi-Marshall, N. A. Griffiths, S. A. Entrekin, and M. L. Stephen. 2010. "A Review of Allochthonous Organic Matter Dynamics and Metabolism in Streams." *Journal of the North American Benthological Society* 29: 118–146. https://doi.org/10.1899/08-170.1.

Thorp, J. H., M. C. Thoms, M. D. Delong, and A. Maasri. 2023. "The Ecological Nature of Whole River Macrosystems: New Perspectives from the Riverine Ecosystem Synthesis." *Frontiers in Ecology and Evolution* 11: 1184433. https://doi.org/10.3389/fevo.2023.1184433.

U.S. Census Bureau. 2022. MAF/TIGER Feature Class Code Definitions. Census.gov.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. "River Continuum Concept." *Canadian Journal of Fisheries and Aquatic Sciences* 37: 130–137. https://doi.org/10.1139/f80-017.

Vaughn, D. R., A. M. Kellerman, K. P. Wickland, et al. 2023. "Anthropogenic Landcover Impacts Fluvial Dissolved

Organic Matter Composition in the Upper Mississippi River Basin." *Biogeochemistry* 164: 117–141. https://doi.org/10.1007/s10533-021-00852-1.

Wagner, S., T. Riedel, J. Niggemann, A. V. Vähätalo, T. Dittmar, and R. Jaffé. 2015. "Linking the Molecular Signature of Heteroatomic Dissolved Organic Matter to Watershed Characteristics in World Rivers." *Environmental Science & Technology* 49: 13798–13806. https://doi.org/10.1021/acs.est.5b00525.

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. P. Morgan. 2005. "The Urban Stream Syndrome: Current Knowledge and the Search for a Cure." *Journal of the North American Benthological Society* 24: 706–723. https://doi.org/10.1899/04-028.1.

Wise, J. L., D. J. Van Horn, A. F. Diefendorf, P. J. Regier, T. V. Lowell, and C. N. Dahm. 2019. "Dissolved Organic Matter Dynamics in Storm Water Runoff in a Dryland Urban Region." *Journal of Arid Environments* 165: 55–63. https://doi.org/10.1016/j.jaridenv.2019.03.003.

Wohl, E. 2019. "Forgotten Legacies: Understanding and Mitigating Historical Human Alterations of River Corridors." *Water Resources Research* 55: 5181–5201. https://doi.org/10.1029/2018WR024433.

Xenopoulos, M. A., R. T. Barnes, K. S. Boodoo, et al. 2021. "How Humans Alter Dissolved Organic Matter Composition in Freshwater: Relevance for the Earth's Biogeochemistry." *Biogeochemistry* 154: 323–348. https://doi.org/10.1007/s10533-021-00753-3.

Supporting Information

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

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