Received: 2 June 2025 | Accepted: 11 August 2025

DOI: 10.1002/jeq2.70080

Journal of Environmental Quality

REVIEW & ANALYSIS

Surface Water Quality

Defining stream riparian zones across multidimensional environmental gradients

Walter K. Dodds[1] | **Leon A. Barmuta**[2] | **Susana Bernal**[3] | **Jessica Corman**[4] | **Tamara K. Harms**[5] | **Sherri L. Johnson**[6] | **Li Li**[7] | **Davi Gasparini Fernandes Cunha**[8] | **Julian D. Olden**[9,10] | **Tenna Riis**[11] | **Lucas C. R. Silva**[12] | **John C. Stella**[13] | **Pamela Sullivan**[14] | **Ellen Wohl**[15]

[1]Division of Biology, Kansas State University, Manhattan, Kansas, USA

[2]Biological Sciences, School of Natural Sciences, University of Tasmania, Hobart, Tasmania, Australia

[3]Center of Advanced Studies of Blanes (CEAB-CSIC), Girona, Spain

[4]School of Natural Resources, University of Nebraska-Lincoln, Lincoln, Nebraska, USA

[5]Department of Environmental Sciences, University of California Riverside, Riverside, California, USA

[6]US Forest Service, Pacific Northwest Research Station, Corvallis, Oregon, USA

[7]Department of Civil and Environmental Engineering, Penn State University, University Park, Pennsylvania, USA

[8]Departamento de Hidráulica e Saneamento, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Paulo, Brazil

[9]School of Aquatic and Fishery Sciences, Department of Wildlife, Fish & Environmental Studies, University of Washington, Seattle, Washington, USA

[10]Swedish University of Agricultural Sciences, Umeå, Sweden

[11]Department of Biology, Arctic Center, Aarhus University, Aarhus, Denmark

[12]Environmental Studies Program, Department of Biology, Institute of Ecology and Evolution, University of Oregon, Eugene, Oregon, USA

[13]Department of Sustainable Resources Management, State University of New York College of Environmental Science and Forestry, Syracuse, New York, USA

[14]College of Earth Ocean and Atmospheric Science, Oregon State University, Corvallis, Oregon, USA

[15]Department of Geosciences, Colorado State University, Fort Collins, Colorado, USA

Correspondence
Walter K. Dodds, Division of Biology, Kansas State University, Manhattan, KS, USA.
Email: wkdodds@ksu.edu

Assigned to Associate Editor Rob Jamieson.

Funding information
Department of Agriculture, Fisheries and Forestry, Australian Government; Future Drought-Fund, TAS FARM Innovation Hub; Fulbright Program; Ministerio de Ciencia e Innovación, Grant/Award

Abstract

Riparian zones are a critical terrestrial-aquatic ecotone. They play important roles in ecosystems including (1) harboring biodiversity, (2) influencing light and carbon fluxes to aquatic food webs, (3) maintaining water quality and streamflow, (4) enhancing aquatic habitat, (5) influencing greenhouse gas production, and (6) sequestering carbon. Defining what qualifies as a riparian zone is a first step to delineation. Many definitions of riparian boundaries focus on static attributes or a subset of potential functions without recognizing that they are spatially continuous, temporally dynamic, and multi-dimensional. We emphasize that definitions should consider multiple ecological and biogeochemical functions and physical gradients,

Number: PID2021-122817-NB-100;
Division of Environmental Biology,
Grant/Award Number: DEB-2025849;
Next Generation EU, Grant/Award Number:
CNS2023-144737

and explore how this approach influences spatial characterization of riparian zones. One or more of the following properties can guide riparian delineation: (1) distinct species, elevated biodiversity, or species with specific adaptations to flooding and inundation near streams relative to nearby upland areas; (2) unique vegetation structure directly influencing irradiance or organic material inputs to aquatic ecosystems; (3) hydrologic and geomorphic features or processes maintaining floodplains; (4) hydric soil properties that differ from the uplands; and/or (5) elevated retention of dissolved and suspended materials relative to adjacent uplands. Considering these properties for an operational and dynamic definition of riparian zones recognizes that riparian boundaries vary in space (e.g., variation of riparian corridor widths within or among watersheds) and time (e.g., responses to hydrological variance and climate change). Inclusive definitions addressing multiple riparian functions could facilitate attainment of research and management goals by linking properties of interest to specific outcomes.

1 | INTRODUCTION

Defining riparian zones is required for effective and durable protection of these valuable ecosystems (Riis et al., 2020). Riparian zones comprise a control point (Bernhardt et al., 2017) of material fluxes and are disproportionately important to interactions between land and freshwaters, and ultimately hydrological and material transport from freshwaters to oceans. Riparian protection will help ensure the provision of key ecosystem functions that provide or support important services, including harboring biodiversity, maintaining water quality, and decreasing erosion and other flood disturbance.

Managing riparian habitats and understanding their ecological importance requires an objective definition that links to specific ecosystem functions of interest and that links disparate approaches and goals globally (Rodríguez-González et al., 2022). Yet, defining the riparian zone as a single category distinct from the uplands or adjacent stream is difficult because these ecotones span gradients of spatiotemporally variable physical, chemical, and ecological characteristics at the interface between terrestrial and aquatic ecosystems (Naiman & Décamps, 1997) and those gradients influence different functions in various ways.

Spatial and temporal heterogeneity in physical and ecological features within riparian zones and corridors complicates the delineation of riparian boundaries. The properties that distinguish riparian zones from adjacent uplands and streams often result from wetter conditions nearer to streams that interact with terrestrial vegetation and soils differently than in the drier uplands nearby. The spatial distribution of shallow groundwater and saturated soils in riparian zones is determined by the interactions of geology and hydrogeomorphology (Gurnell et al., 2016). Geomorphological processes influencing riparian zones include river erosion, deposition, lateral channel movement (Bendix & Hupp, 2000; Gregory et al., 1991), movement of sediment and particulate organic matter by currents and waves, and interception of surface and subsurface hydrological flow paths. These processes result from catchment configuration such as the coalescence of small streams into large rivers downstream (Benda et al., 2004). Hydrological influences on riparian processes include spatial extent of flooding, groundwater interactions with terrestrial vegetation and nearby freshwater (e.g., evapotranspiration), and bidirectional movement of water across aquatic-terrestrial boundaries via surface, shallow subsurface, and deeper groundwater flowpaths.

Riparian zones are variously defined by a suite of ecological attributes, including species composition and structure of riparian vegetation (herbs, lianas, shrubs, and trees), organic matter contribution to streams, biodiversity, and material retention. The heterogeneity of these zones arises from the aforementioned factors and the bidirectional resource exchange with adjacent streams (Bartels et al., 2012; Schindler & Smits, 2017). This exchange, modulated by riparian width and proximity to the channel, affects the movement of matter and energy (Muehlbauer et al., 2014). Additionally, riparian-terrestrial interactions, such as stream shading by vegetation, regulate solar radiation and energy fluxes into aquatic habitats. These dynamics also foster environmental conditions conducive to the establishment of unique riparian species, thereby influencing local and regional biodiversity (Sabo et al., 2005).

Multiple gradients (ecological and physical) within riparian zones regulate the riparian functions that are often targets for conservation and management. A multi-gradient approach could align definitions of riparian boundaries with these targets, as demonstrated empirically by Sweeney and Newbold (2014) and Lind et al. (2019). Here, we highlight the nested nature of riparian functions and how they might align with each other. This could allow managers or policymakers an avenue to prioritize various functions and consider actions that could accrue benefits from multiple functions. Given the diversity of potential riparian functions, we summarize historical and current definitions of riparian zones and identify how a multi-gradient viewpoint could facilitate new insights into relationships between riparian structure and function. Where possible, we identify measurable parameters that can be used to delineate riparian zones and attain management goals that are specific to the function of interest (Kuglerová et al., 2024).

Core Ideas

- Functional properties determine effective riparian widths.
- Multiple physical gradients independently affect functional properties.
- Sharp and heterogeneous physical gradients near streams dictate variable widths.
- A multi-function approach will better inform riparian science and management.

2 | PRIOR DEFINITIONS OF RIPARIAN ZONES

The scientific definition of riparian zones has varied, and the attributes or components studied have shifted as interests in functions and regulatory objectives have changed (see Table 1 for representative definitions). Riparian zones were initially defined as integral parts of freshwater ecosystems (e.g., Hynes, 1975) or as ecotones occupying the transition between terrestrial and freshwater ecosystems (e.g., Gregory et al., 1991; Holland & Risser, 1991). Definitions recognizing riparian zones as interfaces have focused on their transitional nature and emphasized gradients in physical and biological structure (National Research Council, 2002).

Gregory et al. (1991) defined riparian zones by focusing on flood extent, vegetative structure, and the implications for specific ecosystem processes such as material retention. This definition recognizes that riparian structure and function vary over space and time with changing external drivers (i.e., climate and the intensity and frequency of extreme hydrological events) and internal features (i.e., topography and geomorphology). Subsequently, Naiman and Décamps (1997) emphasized that the diversity of geomorphic and hydrological features within riparian zones supports a varied set of functions and suggested that the physical boundaries of riparian zones extended from the edge of the stream at low water levels out to the extent of elevated water table or hydric soils. The National Research Council (2002) of the United States defined riparian zones by their influences on aquatic habitats, highlighting them as interfaces between terrestrial and aquatic environments with emphasis on management implications and disproportional importance with respect to ecosystem functions per unit area.

Research on riparian zones has proliferated since the late 20th century, characterizing numerous riparian processes supporting water quality and aquatic habitat. These included the capacity to remove nutrients and sediments from runoff, particularly in agricultural lands. Early studies (Lowrance et al., 1984; Peterjohn & Correll, 1984) spurred interest and future progress in this area (Mayer et al., 2007; Sweeney & Newbold, 2014). Studies also documented the role of riparian vegetation in regulating stream temperature (Brown & Krygier, 1970; T. M. Burton & Likens, 1973) and providing large woody material as aquatic habitat (Pusey & Arthington, 2003). As the field of riparian science developed, federal and local (state, provincial, tribal, conservational, etc.) entities in North America, Brazil, Europe, and elsewhere began to implement policies to protect and restore riparian zones. These policies required defining riparian zones with easily applied spatial criteria; consequently, regulatory definitions tended to identify specific widths required to perform desired functions or were based on obvious observable features such as type of vegetation or presence of hydric soils (Table 1). However, a patchwork of definitions has been employed by different agencies within regions, across states or other jurisdictions, which will be discussed here and in more detail in Section 5.

Fixed-width buffers, adopted by many regulatory agencies, are conceptually simple, easily implemented, and can protect specific riparian functions. The ease of identification and implementation across broad landscapes has been an attractive feature of fixed-width regulatory buffers, with widths prescribed relative to stream size and varying with land cover (Boisjolie et al., 2019). The Brazilian Forest Code prescribed nationwide protection of riparian zones within boundaries based on stream channel widths. Under this policy, stream channels less than 10 m wide should have a 30-m buffer on each bank, and channels greater than 600 m wide would have a 500-m buffer on each side (da Silva et al., 2017). However, modifications of the code allow agriculture within 8 m of streams (Guidotti et al., 2020) and enforcement of the code is inconsistent.

Width-based definitions of riparian zones often focus on single functions in contrast with those that emphasize spatial heterogeneity, environmental gradients, and multiple functions (e.g., Ilhardt et al., 2000). Assigning a specific width can be problematic because riparian zones are characterized by

TABLE 1 Representative definitions of riparian zones

Defining features	Definition of riparian zone	Citation
Aquatic-terrestrial interaction	• Three-dimensional zones of direct interaction between terrestrial and aquatic ecosystems	Gregory et al., 1991
Aquatic-terrestrial interaction; hydrology	• Assemblage of plants and other organisms in an environment adjacent to water • Without definite boundaries, may include streambanks, floodplain, and wetlands, [. . .] forming a transitional zone between upland and aquatic habitat • Characterized by laterally flowing water that rises and falls at least once within a growing season	Lowrance et al., 1984
Aquatic-terrestrial interaction; hydrology	• Transitional between terrestrial and aquatic ecosystems distinguished by gradients in biophysical conditions, ecological processes, and biota • Areas through which surface and subsurface hydrology connect streams with their adjacent upland • Portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems	National Research Council, 2002
Hydrology	• Stream channel between the low and high-water marks and that portion of the terrestrial landscape from the high water mark toward the uplands where vegetation may be influenced by elevated water tables or flooding and by the ability of the soils to hold water	Naiman & Decamps, 1997
Hydrology	• A vegetated ecosystem along a water body through which energy, materials, and water pass. • Characteristic shallow water table and subject to periodic flooding and influence from the adjacent water body	US Environmental Protection Agency, 2005
Aquatic- terrestrial interaction; hydrology; geomorphology	• Three-dimensional space of interaction that includes terrestrial and aquatic ecosystems that extend down into the groundwater, up above the canopy, outward across the floodplain, up the near-slopes that drain to the water, laterally into the terrestrial ecosystem, and along the water course at a variable width • Width of the valley (its flood prone area width) plus 30 m on each side to encompass the important adjacent riparian functions, and 15 m around obvious landslides	(Ilhardt et al., 2000; Verry et al., 2004)
Hydrology; vegetation; soil properties	• Ecotones that occur along watercourses or streams • Distinctly different from the surrounding lands because of unique soil and vegetation characteristics that are strongly influenced by free or unbound water in the soil	US Department of Agriculture, 2010
Hydrology; vegetation	• Wetland transition between permanently saturated wetlands and upland areas • Vegetation or physical characteristics reflective of permanent surface or subsurface water influence • Lands along, adjacent to, or contiguous with perennially and intermittently flowing rivers and streams, glacial potholes, and the shores of lakes and reservoirs with stable water levels • Excludes ephemeral streams or washes that do not exhibit the presence of vegetation dependent upon free water in the soil.	US Bureau of Land Management, 2017
Vegetation	• Plant communities contiguous to and affected by surface and subsurface hydrological features of perennial or intermittent lotic and lentic streams (rivers, streams, lakes, or drainage ways) • Transitional between wetland and upland with one or both of the following characteristics: (1) Distinctly different vegetative species than adjacent areas. (2) Species similar to adjacent areas but exhibiting more vigorous or robust growth forms.	US Fish and Wildlife Service, 2023

habitat transitions (ecotonal) and physical or ecological gradients, rather than sharp boundaries (Muehlbauer et al., 2014; Richardson et al., 2012). Furthermore, the width required to support one or several functions can vary based on the catchment setting (e.g., constrained versus open valleys, small versus large streams) and specific conditions that change over time (e.g., changing vegetation with climate change or streamflow patterns with seasonal to decadal climate oscillations). While fixed-width definitions based on single functions can be simple to apply and enforce, they can be potentially ineffective for some management objectives.

The complex spatial and temporal gradients comprising riparian zones suggest that definitions of riparian zones should be flexible and accommodate the specific characteristics or processes of interest. For example, based on a literature review, Sweeney and Newbold (2014) defined riparian width from multiple functions: (1) nitrate removal, (2) sediment trapping, (3) stream channel width, (4) geomorphological stability, (5) stream temperature protection, (6) input of large wood, and (7) protection of habitat for fish and invertebrates. They concluded that 30 m wide buffers would largely protect many of these functions. A more recent meta-analysis

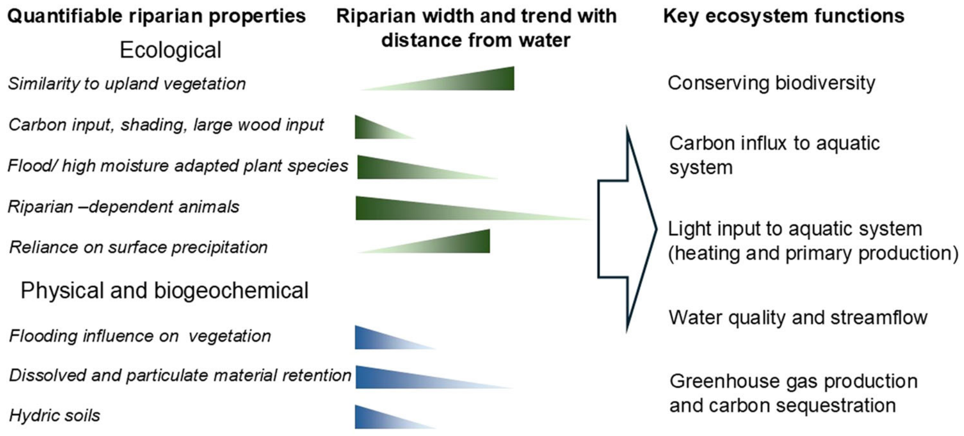

FIGURE 1 Some quantifiable riparian properties that can delineate riparian areas, their generalized changes with distance from a stream, and key ecosystem functions that can be influenced by the riparian properties. The taller edge of the wedges indicates where the properties are maximized, and the relative widths are signified by the length of the wedges based on arguments in text and data from Lind et al. (2019). The text and Tables 2 and 3 expand on quantifiable properties and links to ecosystem functions. The ecosystem functions in column 3 can depend upon multiple aspects listed in column 1.

recommended criteria defining "ecologically functional riparian zones" in agricultural landscapes that might differ in width due to the biological or physical attribute of interest (Lind et al., 2019). Data summarized by Lind et al. (2019) indicated that riparian widths designed to support conservation of terrestrial vertebrates tended to be three to five times wider than those required for other biota or for nutrient retention functions. This approach was parallel to that proposed by Nelson et al. (2024), who suggest that including multiple functions of river corridors (defined by the channel migration zone and including riparian habitat) could help managers simultaneously protect key functions while planning for desired floodplain rejuvenation, with the potential to lead to restoration of natural channel morphology and natural habitat heterogeneity near rivers.

Recent advances in applying remote sensing tools combined with modeling and other methods to delineate riparian zones (e.g., C. A. McMahon et al., 2024; Rusnák et al., 2022) suggest a more flexible approach to delineation could be implemented in some cases based on existing technology. For example, these methods have helped in defining variable width riparian zones based on unevenness in valley topography, as suggested by Ilhardt et al. (2000). Remote sensing can also support multi-dimensional definition of riparian zones by integrating across multiple data layers and data products to identify riparian zones based on their primary function or dominant feature extrapolating from finer grained ground surveys. Such an approach is exemplified in several inventories and models across the European Union (e.g., Clerici et al., 2011).

Here, we review how riparian boundaries can be defined by various ecological and physical properties, and how these properties support important riparian ecosystem functions (Figure 1, Table 2). We have grouped the riparian properties as ecological, biogeochemical, and physical. We take the explicit view that riparian zones are ecotones encompassing multiple gradients. Describing attributes of the spatial and temporal gradients that influence riparian functions will provide context for delineating riparian zones by scientists, managers, or policymakers.

3 | PROPERTIES THAT CAN BE USED TO DELINEATE RIPARIAN ZONES

3.1 | Vegetation structure

Definitions of riparian zones often distinguish them from uplands based on species composition or structure of vegetation (Naiman et al., 2005) because of sharp transitions between upland plants and species adapted to wetter conditions. Flood-resistant species or those that require or tolerate continuous inundation of roots near a stream would clearly be considered riparian species. In more arid regions, trees or shrubs might only occur near streams, or plants may be larger or denser in the riparian zone, and sequester greater amounts of carbon compared to upland ecosystems (Dybala et al., 2019; Matzek et al., 2018). Leaf traits of riparian vegetation can also differentiate riparian zones from uplands, because relatively nutrient-rich, wet soils in riparian zones result in tradeoffs between resource use-efficiency and primary productivity (i.e., supporting highly productive vegetation that uses large amounts of water and nutrients; Paiva et al., 2015). These traits may be distinguishable via remote sensing (Ladd et al., 2013, 2014; Mello et al., 2023). Therefore, the width of the riparian zone could be defined based on the

TABLE 2 Ecological properties that could be used to delineate the spatial extent of the riparian zone and associated approaches to measuring riparian width.

Property	Quantitative criteria that could be used as targets and metrics of success for management goals	Area or width determination	Potential methodological approaches
[1] Vegetation structure	Vegetation height and density	Area where vegetation structure is distinct from uplands	LiDAR, satellite or aerial imagery with ground truthing (Bertoldi et al., 2011)
[2] Vegetation structure influencing primary production in stream	Light (photosynthetically active radiation [PAR]) reaching stream	Width supporting terrestrial vegetation shading (reducing PAR) the adjacent stream	Stream width and tree height (LiDAR and other remote sensing tools) (Kałuża et al., 2020)
[3] Vegetation structure influencing aquatic habitat temperature	Physical characteristics influencing influx rates of PAR and near-infrared radiation (NIR) inputs	Width supporting terrestrial vegetation that reduces PAR and NIR entering the adjacent stream	Water body width and tree height (LiDAR and other remote sensing and Geographic Information System (GIS) tools) (Dugdale et al., 2020)
[4] Vegetation structure influencing carbon export to stream	Particulate carbon flux to stream	Width from within which most of the terrestrial detritus entering the adjacent stream originates	Similar methods as [2] and [3] plus direct field measurements of all other plant parts and sediment input in representative areas
[5] Vegetation structure influencing channel geomorphology	Influx rates of large wood; bank stabilization by plant roots	Distance within which most large wood found in a stream originates; horizontal distance of plant rooting	Remote sensing or LiDAR for vegetation height combined with GIS analysis and modeling (MacNally et al., 2002; J. M. McMahon et al., 2020; Meleason et al., 2003) and functional plant databases
[6] Riparian-adapted species	Species composition matching native riparian vegetation assemblage; specific riparian-related traits	Area inhabited by species unique to the aquatic-terrestrial interface or water saturated soils	Ground-based vegetation surveys; remote sensing using phenology differences to find unique species (Jayasuriya et al., 2021; C. A. McMahon et al., 2024)
[7] Riparian-dependent species	Vertebrate species such as birds, amphibians, and reptiles strongly depending on riparian habitats	Area inhabited by endangered and unique animals linked to the aquatic-terrestrial interface	Ground-based surveys of animal diversity and plant composition (Hagar et al., 2012; Olson et al., 2007)

Abbreviations: GIS, Geographic Information System; LiDAR, Light Detection and Ranging.

spatial distributions of plant communities established near the stream (Table 2 [1,6,7]). However, riparian areas in wetter climates may not have unique species compositions (Baker et al., 2007).

The physical structure of riparian plant communities contributes to many functions of riparian zones. These include influences on habitat structure and ecosystem processes in adjacent streams. For example, riparian vegetation height influences solar radiation entering streams (Caissie, 2006), though the magnitude of shading depends on the type of radiation and the physical structure of the vegetation (Boisjolie et al., 2019). Plant leaves efficiently intercept photosynthetically active radiation (PAR, 400–700 nm) and riparian forests can strongly reduce the PAR available to aquatic primary producers as well as intercept radiation of other wavelengths such as near infrared (Davies-Colley & Payne, 2023). The influence of riparian vegetation on light and temperature in aquatic ecosystems will depend on the height and density of the riparian canopy, local topography, and the width of the stream. If management is focused on water temperature or aquatic primary production, riparian zones could be defined based on the distance from the stream over which terrestrial vegetation significantly reduces irradiance input into the stream (Table 2 [2,3]).

Light inputs together with terrestrial detritus reaching streams are also essential to energy flow and productivity in aquatic food webs. Specifically, the proportion of terrestrial carbon inputs determines whether external sources (allochthonous) or aquatic primary production (autochthonous) predominate as a carbon source (Fisher & Likens, 1973). Thus, riparian width could be defined by the average distance over which vegetation influences light input into the stream (Kiffney et al., 2004). Likewise, the influence of riparian vegetation on coarse organic matter inputs into the stream could be determined from litter deposition rates from various riparian species and estimates of lateral input distance (see Section 3.3.3, Table 2 [4]). In addition, where there are distinct riparian plant species, identity of undecomposed leaves could be used to assess the degree of influence of various riparian species.

Finally, large wood and plant roots can form habitat for aquatic biota (Fritz & Feminella, 2011) and influence characteristics of riparian functions (Dodds et al., 2017; Treadwell et al., 1999). Large wood and roots shape channel, floodplain, and shoreline morphology (Ardón et al., 2021; Czarnecka, 2016; Hawley & MacMannis, 2019; Kramer & Wohl, 2015; Wohl, 2017), thereby influencing riparian width and establishing physical gradients within riparian zones. The presence of trees, their size, floodplain forest age, and other factors such as slope moving from the uplands to the stream all influence the rates of input of large wood (J. I. Burton et al., 2016; Stella et al., 2021). Therefore, the width of the riparian zone could be defined as the area from within which some proportion of large wood in the channel originates or where the roots of riparian vegetation can establish in the stream (Table 2 [5]). Generally, maximal lateral rooting distances are around 15 m (Schwarz et al., 2010), and remote sensing (e.g., aerial photography and imagery from drones) can be used to estimate rates of large wood accumulation within the stream (MacNally et al., 2002; C. A. McMahon et al., 2024).

3.2 | Species adaptations and biodiversity

Contrasts in the physicochemical attributes of riparian zones relative to adjacent uplands and streams can contribute to distinct biotic assemblages in riparian zones that augment regional species diversity (Sabo et al., 2005). General ecological synthesis suggests that species diversity is often, though not always, greater in ecotones than in the areas they connect (Kark, 2013). Relative to uplands, riparian zones are generally characterized by wetter conditions, frequent exposure to floods, greater potential for seasonal waterlogging, reduced temporal variance in microclimate, and greater accumulation of organic matter and nutrients (Lopez et al., 2023). Spatial patterns in species composition of riparian zones might therefore correspond with environmental gradients established by hydrological conditions, microclimate, or resource availability. These gradients could lead to quantifiable diversity differences among riparian zones, uplands, and streams (Corenblit et al., 2009; Polvi, 2009).

As an example of riparian conditions contributing to distinct species assemblages of plants, waterlogging and flooding can restrict plant species present in riparian zones to those that can establish in such conditions (Catford & Jansson, 2014; Cronk & Fennessy, 2016). Adaptations to hydrological conditions can establish gradients in plant communities across riparian zones from species adapted to conditions that are (1) always waterlogged, near the stream; (2) seasonally waterlogged; (3) not water-limited (roots can access groundwater); (4) seasonally variable in water source (surface soil water vs. groundwater); or (5) limited to surface soil water (Figure 2). For example, distance to groundwater can rapidly increase with distance from the stream in mountainous areas, leading to very narrow riparian zones with saturated soils that are subject to intense seasonal flooding, and potentially unique plant species adapted to these conditions that are rare or absent in uplands. In some deserts, the riparian zone can support different plant species than the uplands (Sabo et al., 2005) because of unique environmental conditions near stream channels such as flooding, wetter conditions, and anoxic soils.

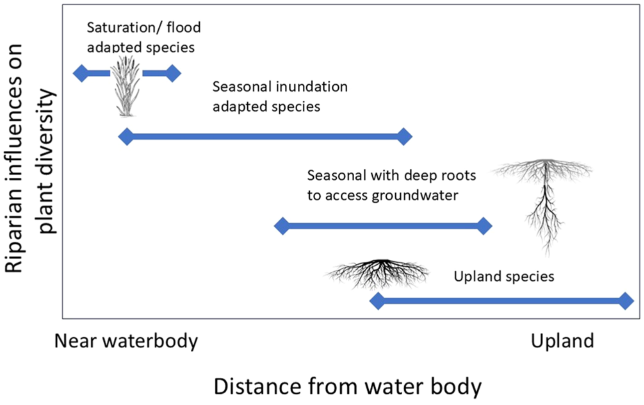

FIGURE 2 Functional characteristics of vegetation (blue lines) that could drive distribution of plant species adaptations across a gradient of flood influence and moisture availability in a mesic environment moving from waterbody to uplands with a moderate slope. Plant species composition has often been used to define riparian width, and the relative influence of a nearby water body can vary depending upon context. Upland species far from groundwater rely only on precipitation, but those that can use groundwater have deeper roots for dry periods and shallow roots for wetter conditions. Characterizing diversity across the ecotone could provide insight into unique conditions and habitats associated with a riparian area that differ from surrounding areas. Plant trait categories based on Fan et al. (2017).

Maximum vascular plant diversity could occur somewhere along the riparian gradient from the stream to the uplands if plants respond to the interplay between flooding effects and moisture gradients, as well as nutrient and light availability. In regions with substantial precipitation, for instance, diversity may be lower in areas that are periodically flooded, but the lack of water limitation of upland species means that diversity may not decrease with increasing distance from the stream (Baker et al., 2007; Clinton et al., 2010). In small streams of wetter temperate habitats where flooding effects are not intense, understory diversity can be greater immediately next to the stream where light availability may be highest (Dieterich & Anderson, 1998; Jayasuriya et al., 2021), but tree diversity may not differ from uplands (Hagan et al., 2006). In dry biomes, where waterlogged conditions are infrequent and water strongly limits species diversity, maximum diversity could occur immediately adjacent to the stream (Stromberg et al., 2017). Distribution patterns of species can provide one type of gradient across which a riparian zone could be delineated, particularly if unique species in need of conservation occur only within riparian zones, offering yet another target for managers of riparian zones.

The influence of abiotic gradients also manifests in the inter- and intraspecific variation in species traits as well as evolutionary adaptations of individual congeneric species. For example, members of the same genus adapted to either riparian forests or adjacent savannas display distinct functional traits such as morphology and phenology. For example, riparian species typically exhibit greater specific leaf area than vegetation in the uplands, which enhances light capture and photosynthetic efficiency and in turn is negatively correlated with water- and nutrient-use efficiency (Hoffmann et al., 2005). Increased resolution and frequency of remotely sensed imagery allows clearer and broader scale identification of differences in riparian areas from uplands based on differing phenology. This phenology approach distinguished deciduous riparian vegetation in three California watersheds (C. A. McMahon et al., 2024). In regions disturbed by fire, riparian plants often have thinner bark than upland species due to the lesser need for protective structures in less fire-prone, moist environments (Hoffmann et al., 2012). Spatial distribution of physiological and morphological traits (Silva & Lambers, 2021) could be used to delineate the width of riparian zones and distinguish them from nearby uplands. Practically, managers would need a list of common plant species and their functional characteristics and could use trait distribution to establish the extent of the riparian zone. This approach is embedded in the approach most commonly used to delineate jurisdictional wetlands in the United States (US Army Corps of Engineers, 1987), but could be expanded for regionally specific use in riparian zones.

Species composition can also influence the functions of riparian zones. For example, greater functional and phylogenetic diversity of riparian trees can increase overall leaf litter decomposition rates (e.g., Zhou et al., 2020). Although restoration activities often target reforestation with a limited subset of species (González et al., 2015), functions such as decomposition and energy fluxes might be best supported by considering relationships between biodiversity and key functions. In particular, ecosystem processes mediated by soil microbes might follow similar spatial patterns to plant species distributions because microbial communities respond to plant functional traits and host-specific symbioses that in turn vary with soil age and nutrient availability (Silva & Lambers, 2021). For example, Veach et al. (2016) demonstrated decreasing soil bacterial evenness and species richness moving from upland grasslands to intermittent stream channels, but patterns of fungal diversity were not as strong. In contrast, edaphic parameters, ecosystem productivity, and water availability can be more important predictors of saprotrophic fungi, while plant species composition is the most important predictor of distributions of mycorrhizal fungi (Mikryukov et al., 2023). Thus, species composition of plants as well as other associated organisms could be used to delineate riparian zones.

Regional animal diversity can also be highly dependent upon riparian habitat. Naiman et al. (2000) estimated that 30% of wildlife species in the US Pacific Coast Ecoregion require riparian habitat. Olson et al. (2007) noted that 32% of amphibian populations in the same ecoregion require riparian habitat, and the remaining species are facultatively associated with riparian zones due to cooler and wetter conditions compared to uplands. Wetter conditions in riparian zones are essential for amphibians and reptiles (Semlitsch & Bodie, 2003), especially in agricultural landscapes and dry lands, and thus, the home range of these species could be used to delineated the width of riparian zones (Table 2 [7]). Olson et al. (2007) also found amphibians have high reliance on headwater habitats. Thus, effective management plans could consider accounting for heterogeneity within riparian zones, particularly contrasting first-order streams to larger downstream rivers and conditions specific to the smaller streams (e.g., presence or absence of fish).

Streams can be important sources of food for animals, enhancing occasional or obligate use of riparian zones by large carnivores foraging on fish and birds, and predators of emerging aquatic insects (e.g., Gray, 1993; Sabo & Power, 2002; Sanzone et al., 2003). The width of suitable habitat for animals foraging in riparian zones would then be defined by the distance over which aquatic resources (e.g., stream-derived nitrogen; Helfield & Naiman, 2001) are dispersed into adjacent terrestrial ecosystems. In river networks, transport distances of these aquatic-terrestrial fluxes are influenced by network structure, watershed slope, and channel shape in addition to dispersal attributes of aquatic organisms (Sabo & Hagen, 2012). In drylands or during episodic dry periods, elevated primary production in riparian zones compared to adjacent uplands can provide food sources that sustain populations of consumers (Sabo et al., 2008; Soykan & Sabo, 2009). In addition to riparian specialists, riparian zones are corridors for animals, especially in areas where humans have fragmented natural upland vegetation and in dry climates (Gillies & St. Clair, 2008; Naiman et al., 1993).

Summarizing, organismal abundance or diversity can be used to define riparian width in support of managing biodiversity. This approach would encompass the area required to maintain reference conditions or achieve targets in species richness or community composition. Such goals might address plants, animals, and even microbes. As each group of organisms has different ranges of adaptations and mobility, the width of the riparian zone is expected to vary depending upon organismal attributes (Marczak et al., 2010). Mobile animals such as reptiles and birds are expected to need wide riparian zones (e.g., greater than 100 m) because they have large home ranges (Lind et al., 2019; Semlitsch & Bodie, 2003). Thus, width definition based on animal diversity could yield greater widths than other approaches such as interception of sediments and nutrients (Lind et al., 2019).

3.3 | Hydrological and geomorphological gradients

Hydrology and geology interact to form much of the basis of riparian structure and function as they determine aboveground and belowground vegetation characteristics and the degree of groundwater–surface water interactions near streams. Thus, defining riparian zones requires consideration of hydrology shaped by geology and geomorphology. Here, we include the relationship of riparian structure and function with (1) flooding, (2) groundwater depth, (3) material transport and retention, and (4) bank stability.

3.3.1 | Flooding

Riparian zones can be delineated by the maximum area of flooding based on the geomorphic features (Polvi et al., 2011; Verry et al., 2004). Definitive delineation is, however, difficult unless geological features constrain the elevation with steep valleys such that even very large floods influence only a specific distance from the water's edge. Furthermore, some aquatic habitats (e.g., spring-fed streams and sand-dominated rivers) rarely flood or have relatively stable banks. Here, we specifically concentrate on areas influenced by flooding without geological constraints such as steep valleys.

The probability of hydrological effects, in the form of inundation, decreases as elevation rises moving away from the aquatic habitat such that only the largest floods will reach greater elevations. The basic principles discussed here have been used to create detailed flood maps for large areas. For example, the US Federal Emergency Management Agency has high-resolution maps for many areas in the United States based on hydrological models and topographic mapping. For flowing waters, maximum discharge plotted against time between floods (recurrence interval) roughly follows a logarithmic decay relationship approximated by the following equation:

$$Q = c \times T^k, \tag{1}$$

where Q is the maximum discharge, c is a constant, T is the 1/recurrence interval, and k is the expected probability of a flood of a certain size during each year. The form of this equation describes an exponential decay in the probability of flood magnitude. A modified logarithmic decay equation (log Pearson Type III) is used by the United States Geological Survey and many hydrologists because it accounts for skew in Equation (1) (England et al., 2018), which can vary regionally. This relationship could also roughly delineate the gradient of hydrological influence on the width of flood influence if the elevational cross section of the area abutting the riparian zone is known. However, these elevational gradients near streams can vary over small distances, especially in mountainous areas, and can change substantially during a single large flood that creates extensive erosion and deposition across the river corridor.

A strong determinant of riparian width depends on site-specific factors such as valley-floor geometry and surface and subsurface hydrological regimes. Ilhardt et al. (2000) suggested broadly that the floodplain corresponding to a flood return interval of 50 years corresponds to riparian width, but given differences in geomorphology and flooding characteristics, these recommendations could vary widely. Fortunately, modern workflows with increasingly precise, high-resolution remote-sensed imagery (e.g., LiDAR [Light Detection and Ranging]) now produce high-resolution maps of flood-prone areas (Zheng et al., 2018). Such mapping could be used to delineate riparian zones when combined with hydrological flood return data (Table 3 [8]).

3.3.2 | Groundwater depth

The average depth to groundwater is crucial relative to the rooting depth of vegetation, particularly in drier habitats. Assuming an approximately constant water table elevation near a permanent stream, the water table depth is determined by the elevational cross-section. By combining this depth with the elevation above the capillary zone (the soil immediately above the water table where capillary forces operate), the maximum riparian zone width where plants can be expected to access groundwater can be estimated from well depth data and extrapolated from the well to the stream (Table 3 [9]). This width, W, in a simple generalized form, can be calculated as follows:

$$W = \frac{D}{S_{\text{land}} - S_{\text{cap}}}, \tag{2}$$

where D is the maximum depth to the capillary zone that the plants with the deepest roots can reach, S_{land} is the slope of the land surface, and S_{cap} is the slope of the capillary zone

TABLE 3 Physical and biogeochemical properties that could be used to delineate the spatial extent of the riparian zone and associated approaches to measuring riparian width. Note that the numeration of properties continues that in Table 2.

Property	Quantitative criteria that could be used as targets and metrics of success for management goals	Area or width determination	Potential methodological approaches
[8] Episodic inundation	Flood recurrence interval, geomorphological features, flood-adapted vegetation, high water line	Width of active floodplain defined by thresholds of flood recurrence	LiDAR during flooding (Zheng et al., 2018)
[9] Vegetative interaction with groundwater	Depth of the groundwater table and capillary zone, and maximum depth of the root system	Width over which capillary fringe is root-accessible for most of the year	Models incorporating remote sensing, ground-truthing with observations from wells (Rohde et al., 2021)
[10] Retention of dissolved materials	Uptake capacity of plants and soil during periods of overland flow, overbank flow, or elevated groundwater table	Distance over which a proportion of the load of a dissolved compound delivered to the riparian zone is removed or retained	Measured rates of material retention (Sweeney & Newbold, 2014); remote sensing to find areas of groundwater input and establish variable width areas for protection (Kuglerová et al., 2014); hydrological and nitrogen tracer experiments (Dodds et al., 2022)
[11] Retention of particulate materials	Retention of materials in surface flow during periods of overland flow, overbank flow	Distance within which a proportion of the load of particulate materials delivered to the riparian zone is removed or retained	Remote sensing of bare soil areas; modeling surface flowpaths (Västilä & Järvelä, 2018)
[12] Hydric soils	Presence of dark colored soils, organic matter accumulation, anaerobic metabolism, sulfide generation, negative redox potential	Area encompassing periodically or permanently saturated soils and reducing conditions	Ground-based survey of soil properties; ground-truthed remote sensing of soil properties (Mello et al., 2023).

Abbreviation: LiDAR, Light Detection and Ranging.

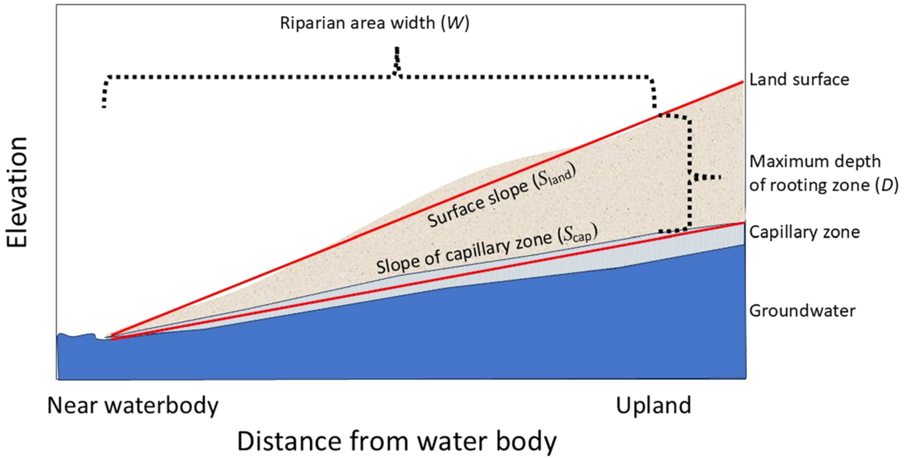

FIGURE 3 Conceptual diagram depicting how the riparian width (W) can be delineated based on the depth of the capillary zone as defined by maximum rooting depth (D) and its slope (S_{cap}) in relation to the land surface slope (S_{land}) as described by Equation (2). This approach can be used at each transect where an upland well gives known depth to water table and soil is relatively homogeneous. Multiple transects can inform local models.

(Figure 3). The value for S_{cap} could be more difficult to determine than the depth to the water table because it can change depending on the porosity of the soil matrix, but the slope of the capillary zone and the water table should be similar within homogeneous substrata.

D depends on the species of vegetation present and the average depth at which they still can sustain growth if they mostly depend upon groundwater for their survival. While roots can be up to 70-m deep, maximum rooting depths for riparian woody plants are generally around 10 m (Fan et al., 2017) with substantial variation among species. Equation (2) also assumes that depth to water table and capillary rise is approximately linear. Accordingly, S_{cap} is negative for a losing stream and positive in a gaining stream. Thus, for a similar land surface slope and depth of the root system, the riparian width W influencing the groundwater table will be shorter in losing streams.

Variations in surface slopes and water table depths necessitate estimation of average or median depths using multiple measurements from streamside and upslope wells to establish hydrological gradients. Remote sensing, including gravitational and altimetry data, can facilitate mapping of groundwater depth over broader scales than empirical observations alone (Bastow et al., 2002). Such multi-parameter spatial models have been applied to generate a global map of groundwater-dependent ecosystems (Rohde, Albano, et al. [2024]). Maps of groundwater depth based on wells and regional groundwater-dependent ecosystems paired with remotely sensed greenness (normalized difference vegetation index) observations have also been applied to delineate riparian vegetation and the influence of streamflow modification on vegetation across the state of California (Rohde et al., 2021; Rohde, Stella, et al., 2024). Machine-learning methods such as random forest models can also be used to infer riparian groundwater levels. For instance, Cummings et al. (2023) applied this type of approach to detailed geomorphologic, hydrologic, and snowpack data from 11,000 wetlands and meadows to predict approximately three times as many potential additional occurrences. Coupling such approaches with estimates of maximum rooting depths and seasonal variations in groundwater tables, which can be considerable in intermittent streams, could distinguish riparian zones of hydrologically gaining and losing reaches.

3.3.3 | Material transport and retention

The retention of materials in riparian zones depends on the interaction between their physical movement as determined by hydrology and biological activity. Aboveground and belowground transport can be important, and the movement of materials associated with flow of water toward streams can be divided into two categories: (1) movement of dissolved materials in groundwater and (2) movement of dissolved and particulate matter very near the soil surface and by sheet flow across the surface. The materials being moved can be categorized as biologically refractory (e.g., salts and dissolved organic materials that plants or microbes cannot assimilate or bioconcentrate) or biologically active (e.g., materials that plants or soil microbes can take up, transform, or transport).

We link formal, unidirectional equations used to characterize biologically active and refractory solute movement in streams (Stream Solute Workshop, 1990) with retention in riparian zones after adapting some of the parameters to riparian features. This follows the framework of Sweeney and Newbold (2014) for nitrate removal by riparian zones as a function of riparian width. While the approach has mostly been used for biotic uptake in stream channels (e.g., Mulholland et al., 2009), it has also been used to characterize movement of inert materials, such as plastic, in flowing waters (Hoellein et al., 2017, 2019) and could be applied in riparian zones as well.

Material retention depends on the time water spends in the riparian zone, physical processes retaining the material, and the bioreactivity of the matrix that the water travels through (whether groundwater is in contact with shallow organic layers, for instance). The first parameter of interest is the uptake (retention) length of a given material (S_w), which can be thought of as the average distance a molecule or particle travels through the riparian zone before uptake or processing by biota or retention by abiotic processes. This distance is related to the specific uptake rate coefficient of each compound (k_c, the average amount of time it spends in the water) and the water velocity (u):

$$S_w = u/k_c. \tag{3}$$

This equation can be related to the average uptake velocity, v_f, of the material into a given uptake compartment (e.g., soil microbes or riparian vegetation) after considering the hydrological depth (h):

$$v_f = h \times k_c. \tag{4}$$

In riparian zones, h could be the vertical depth of groundwater flowing toward the stream that intersects the roots and the rhizosphere or, in the case of lateral overland flow (sheet flow and flow through shallow soils), the depth of water moving across the surface. Then v_f is a “velocity” of retention out of the groundwater (uptake, adsorption, or deposition) or the velocity of materials moving out of the surface flow toward the land surface. From v_f, we can then calculate U; this is the flux of material taken up per unit area per unit time:

$$U = v_f \times C, \tag{5}$$

where C is the average concentration of the material retained as it flows through the riparian zone.

Note that these interrelated parameters can be calculated from each other depending upon which parameters can be measured directly. The S_w is the most appropriate parameter to calculate since we are interested in defining the width of the riparian zone as a function of the retention distance. There are several ways to estimate S_w from direct and indirect measurements. Average velocity of water within the riparian zone, u, can be estimated from tracer releases or by estimating mean water residence time from changes in groundwater level and average hydraulic conductivity. In its turn, U for biologically active materials can be estimated from biomass accumulation in riparian plants and microbes and elemental analysis of plant tissues and soil. Concentration values, C, can be measured directly in shallow and deep groundwater.

Determining the width of the riparian zone could then be linked to S_w for the solute of interest. For example, Sweeney and Newbold (2014) estimated S_w as an average of 46 m for the riparian zone in the Chesapeake Bay watershed. This value resulted in a predicted nitrate removal of 35% for a 20 m wide buffer, 48% for 30 m wide buffers, and 90% for 100 m wide buffers. Lindt et al. (2019) found that, on average, a smaller width (<30 m) is sufficient for retaining more than 75% of nutrients and sediments entering the riparian zone. Together, these studies provide general ranges of expected values of riparian width that can be used as a reference for delineating an effective width of the riparian zone for material retention (Table 3 [10]). Note that the application of these equations in specific locations needs to be combined with local data and published nitrate removal experiments or measurements to successfully infer S_w.

The application of this approach requires additional considerations. First, the values of solute uptake by biota are influenced by microbial kinetics with saturation of nutrient uptake with increasing concentration (Dodds et al., 2002; Payn et al., 2005; Stream Solute Workshop, 1990). Second, for inorganic solutes such as nutrients, the export toward the stream will be ultimately determined by the balance between biological uptake and remineralization (Dodds, 2003; von Schiller et al., 2011). Moreover, there might be additional losses to the atmosphere (e.g., CO_2 from respiration and other carbon oxidations, N_2 from denitrification). Perhaps most importantly, solute uptake will be influenced by the heterogeneity of hydrological flow paths within the riparian zones, and thus, the partitioning between surface, shallow soil water, and groundwater flow can be important, especially during storms or in riparian zones with perched water tables. While these hydrological pathways and S_w might be difficult to characterize and generalize across spatially and temporally variable conditions, the approach allows specific measurement of material retention and net effects of biogeochemical activity in the riparian zone.

The mechanical retention distance of fine and coarse particles (e.g., sediments, organic materials such as leaves, or recalcitrant organic matter) with overland flow also could delineate the functional width of the riparian zone (Table 3 [11]). For example, the relationship of vegetation cover to sediment transport can be modeled (Västilä & Järvelä, 2018). The retention length for sediments has also been the subject of several reviews and has been placed in a similar framework to ours by Sweeney and Newbold (2014). While the parameter S_w and the associated proportion of material removal per unit width of the riparian zone can be related to total width of the riparian zone, longer term storage is more difficult to determine and not amenable to the relationships previously discussed. For example, the riparian zone could transitorily retain sediments, but large floods could either mobilize the sediment back into the channel via bank erosion or deposit sediments from upstream zones into the riparian zone. Such processes then would link to whether the floodplain is depositional or erosional.

Field measurements of material retention could be linked to larger scale patterns in the effectiveness of riparian areas as buffers. For example, Kuglerová et al. (2014) used digital elevation models to identify areas most likely to be groundwater pathways through the riparian zone and to the stream and to identify potential hotspots of nutrient inputs where riparian protection or restoration could be most effective. This approach could be useful to scale up empirical estimates of riparian nutrient retention to larger areas.

3.3.4 | Bank stability

Stream and riverbank failure and erosion depend upon sediment characteristics, soil moisture, and cohesion provided by roots of riparian vegetation (Zhao et al., 2022). Here we focus on the influence of riparian vegetation on bank stability. Consequently, stream channels tend to be wider in forested areas compared to nearby deforested areas (particularly agricultural land) because deforested areas are more susceptible to sediment accumulation resulting from slope failure and erosion during floods (Micheli et al., 2004; Sweeney et al., 2004). However, different dynamics can occur in drylands where flow stabilization can lead to narrowing of stream channels by vegetation (W. C. Johnson et al., 1995; Kui et al., 2017; Ligon et al., 1995), or following floods upon riparian vegetation re-establishment (Räpple et al., 2017).

In addition, vegetation intercepts water that infiltrates banks and their evapotranspiration further reduces moisture. This is important because moisture in stream banks can increase the probability of slope failure. Slope failure and erosion at the base of the slope can influence both terrestrial stability of land as well as inputs of sediment into water. Different species of vegetation stabilize banks to various degrees based on properties of their roots (Polvi et al., 2014). Grasses have more roots, but those roots are shallower and finer relative to trees. Trees have different depth distributions and tensile root strengths (Simon & Collison, 2002). Thus, the width of the riparian zone that most efficiently stabilizes banks and shorelines is based on specific vegetation types. In general, living vegetation stabilizes riparian soils over relatively small distances from the aquatic habitat and may be one of the ecosystem functions that is most effective along narrow channels.

The effects of inputs of dead riparian wood on hydrogeomorphology and habitat heterogeneity are large and can extend across the entire floodplain (Collins et al., 2012). Large wood can shape river morphology, and the accumulation of dead wood can have contrasting roles depending on whether rivers are small, single thread, larger, braided and wandering, or steep, and boulder-rich (Faustini & Jones, 2003; Piegay & Gurnell, 1997). Wood may have only modest influences on rivers in highly modified ecosystems because of its removal and the hydraulic effects of infrastructure and channel modification (Blauch & Jefferson, 2019; Czarnecka, 2016). Overall, average riparian tree height can be used as a gauge to infer the riparian width that is most effective at providing large logs to aquatic ecosystems via individual or mass tree mortality on site. The approach to using regionally dominant tree height to infer riparian width has been employed previously (Ilhardt et al., 2000; Jayasuriya et al., 2022).

3.4 | Soil properties and associated biogeochemical activity

Riparian soils differ from upland soils because water and imported materials strongly influence soil formation (Naiman et al., 2005). Wetland soil attributes have long been used to define the spatial extent of wetlands (Faulkner & Richardson, 2020), and this approach could be extended to define stream riparian zones. Due to low landscape position, allochthonous organic matter inputs from uplands or streams are often retained within riparian zones, increasing their organic carbon content (Barros et al., 2022). However, alluvial materials deposited by flooding close to the river margin could lead to areas that are lower in organic carbon content relative to older soils further from the water body. Allochthonous inputs of nutrients and access to shallow groundwater can support greater and more stable primary production than adjacent upland or aquatic ecosystems, increasing stocks of soil organic matter. However, local hydrological variation, such as contrasts in water table depth along hydrologically gaining compared to losing reaches, can modify patterns of organic matter inputs and nutrient processing (Harms et al., 2009). Therefore, when soil organic matter content is used to define riparian width, multiple criteria might be required, even within the same basin.

The parent material in riparian zones often originates in part as alluvium (i.e., stream-deposited materials), creating stratified vertical bands and greater vertical and horizontal heterogeneity than upland soils. This spatial heterogeneity intersects with temporal variation in soil moisture conditions to establish fluctuating redox conditions. Resulting redoximorphic features are more common in riparian than upland soils (Naiman et al., 2005). Extended anoxia due to inundation by shallow groundwater or overbank floods results in patches or strata of gleying, defined by gray soils containing the reduced form of iron (Fe^{2+}) that visually distinguish hydric soils. Such soils may contain relatively higher content of reduced forms of organic carbon that decompose more readily. However, fluctuating redox conditions can promote complexing of dissolved organic carbon by iron, contributing to accumulation of carbon in riparian soils (Bhattacharyya et al., 2018; Duchaufour, 1982; Rossatto et al., 2014; Silva et al., 2013).

The hydrological and chemical attributes of riparian soils have implications for biogeochemical processes. Fluctuating soil redox regimes in riparian zones can facilitate the co-occurrence of microbial communities that are responsible for carbon and nutrient transformations with significantly different sensitivities to soil O_2 availability. Enhanced microbial activity in wet, organic-rich soils and associated low redox conditions can result in significant emissions of trace and greenhouse gases (e.g., CO_2, N_2O, NO, and CH_4). For example, inundation of soil organic layers by groundwater or rewetting of soils by overbank floodwaters drives production of greenhouse gases (e.g., Harms & Grimm, 2012; Pinay et al., 2000), and indicates that microbial communities are adapted to temporally variable hydrology. Land management, including forest harvest, can reshape the dynamics of microbial processes and trace gas emissions from riparian soils (e.g., Silverthorn & Richardson, 2021; Vidon et al., 2015). For example, removing woody vegetation encroaching on grassland riparian zones led to increased rates of denitrification relative to intact forested areas or areas with native grasses (Reisinger et al., 2013).

Thus, management of riparian zones for biogeochemical functions such as nitrogen removal could consider riparian width defined by soil hydrology and organic matter, which support these functions (Table 3 [12]). The hydric state of riparian soils is difficult to characterize without direct measurements of soil chemistry, but remote sensing methods to detect methane sources (which indicate saturated anoxic soils) could help to identify saturated riparian zones, particularly surrounding large rivers (Melack et al., 2004). Mello et al. (2023) also used remote sensing of agricultural areas to detect hydric soils, which could aid in detecting former margins of riparian areas.

4 | SPATIAL AND TEMPORAL SCALES AND RIPARIAN DELINEATION

Spatial and temporal heterogeneity characteristics of riparian zones dictate that their boundaries will shift in time and space. Accounting for such heterogeneity could assist in creation of flexible definitions of riparian width that accommodate multiple functions by considering multi-dimensional gradients and changing delineation over time. We therefore briefly summarize spatial variation (Section 4.1) and temporal trends (Section 4.2) that could influence our definitions.

4.1 | Spatial patterns

Riparian zones can vary spatially over small scales as a function of geology, position in catchment, stream size, groundwater depth, and slope. Indeed, the entire evaluation of riparian zone width is an exercise in environmental classification at these site scales. However, management and cross-system comparisons commonly occur over larger scales, such as among positions within catchments or across regional to continental scales (e.g., Dodds et al., 2021; Heffernan et al., 2014). In practical terms, the scale of comparisons can be important to consider when determining the characteristic width and the variance in the widths of riparian zones along the length of the interface between a stream and terrestrial habitat. The objective of this section is to provide examples to illustrate broader patterns influencing delineation of riparian zones, rather than a comprehensive assessment of all possible factors contributing to variation in the width of the riparian zone.

Topography affects the width of riparian zones across watersheds. Shallow topography suggests that distance to the water table increases slowly with distance from the stream, while steeper topography suggests a sharper decline in depth to the water table with distance from the stream. Therefore, the width of the riparian zone tends to correlate with stream size because smaller streams often form in areas with steeper topography, while wider streams are usually found in lower elevation areas.

While wider streams may be flanked by wider riparian zones, the proportional influence of riparian zones on aquatic ecosystems may lessen as the aquatic body gets larger. Wide rivers will have the most open water that is far from riparian zones, receive more light, and have less influence from shoreline vegetation (e.g., particulate carbon inputs). However, riparian-aquatic interactions can extend far from the river in floodplains and low-gradient networks. For example, the Amazon floodplain width can be over 60 km (Trigg et al., 2012). River meandering leads to complex patterns in riparian zones consisting of wetlands, swales, oxbows, or ridges that can change with large floods and support riparian ecosystems that are disconnected from the main channel (Cooper et al., 2003; Stella et al., 2011). The meandering of very large rivers forms wide floodplains, and because meander shape is roughly scale invariant (Leopold, 1994), larger rivers will have larger meanders, leading to broader zones of influence of riparian zones on the rivers. Channel avulsion and formation of an anastomosing planform (Makaske, 2001) can also create broader zones of influence, as can the development of a braided planform (Stecca et al., 2019).

The spatial arrangement of riparian zones at the watershed level can also influence riparian functions. Longitudinal continuity of undisturbed riparian corridors protects animals adapted to the wetter conditions and associated vegetation found near streams and facilitates movement along streams and rivers (Hobbs, 1992; Knopf et al., 1988). Because riparian habitats are small relative to upland habitats, long stretches may need to be protected to ensure the survival of dependent species. In addition, riparian corridors can provide important connectivity to larger patches of suitable habitat, allowing stabilization of populations found in the larger connected habitats (Beier & Noss, 1998). Therefore, the most appropriate width when restoring a riparian zone will vary depending on the shape of catchment, connectivity within that catchment, and the location of the well-preserved and restored reaches within the river network (Rutherford et al., 2023).

Finally, we note that riparian zones of small intermittent streams can be important for nutrient retention and as habitat and refuge for animals even during times when the bordering streams do not flow. For example, natural riparian cover along small upstream intermittent reaches had a positive influence on the water quality of downstream perennial reaches (Dodds & Oakes, 2006). This finding presents a challenge for management in regions with many intermittent headwater streams or where intermittency is increasing (Zipper et al., 2021) because it is more difficult to justify the conservation of riparian zones adjacent to non-flowing waters. Messager et al. (2021) documented that over half the global stream reaches are intermittent, and Brinkerhoff et al. (2024) found that 61% of stream discharge originates from intermittent streams. This is particularly problematic in the United States following the Rapanos and Sackett decisions by the US Supreme Court, which ruled that intermittent streams are not considered connected to streams they feed into (Greenhill et al., 2024) and leaves many waterbodies of the United States unprotected based on “wetness” (Gold, 2024).

4.2 | Temporal patterns

Temporal scales relevant to defining riparian width vary with the process of interest. Geological features that shape riparian zones develop over millennia, some geomorphic processes and biological speciation that might define riparian zones occur at decadal time scales, and erosion and deposition processes occur on the timescale of individual floods. Accordingly, riparian delineation should focus on the timing of the maximum potential influence of the phenomenon in question. For example, if the dominant pollutant transfer to aquatic systems is governed by intense rainstorms, then managers may want to protect riparian vegetation buffers up to a width that intercepts a large portion of the pollutant during intense events.

Seasonal changes in the availability of water, stream discharge, and plant phenology could result in variable definition of the extent of riparian zones. For example, the activity of riparian vegetation decreases during dormancy, especially in cold habitats or during non-leaf periods for caducifolious species. In temperate, subtropical, and seasonal tropical forest regions, riparian detrital inputs concentrate following senescence, and this strongly influences soil processes and stream functioning (Acuña et al., 2007; Naiman et al., 2005). In dry regions, riparian functions such as material retention and processing in soils may be most important during wet seasons. Seasonal flooding will also influence storage of organic matter and the timing of transport of materials between the riparian zone and stream (e.g., Acuña et al., 2007; S. L. Johnson et al., 2000).

Global change will have multi-decadal influences on riparian zone functions (Larsen et al., 2016; Stella & Bendix, 2019), affecting many of the features that define riparian width. For example, climate change is expected to alter flood frequency and drying in many areas of the world, with some areas increasing (Southeast Asia, the Indian Peninsula, eastern Africa, and the northern Andes) and others decreasing (Hirabayashi et al., 2013). Areas with increased flooding frequency could experience larger events for a given recurrence interval, increasing the extent of inundated areas. In contrast, increasing frequency and intensity of drought in arid lands can result in mortality of groundwater-dependent riparian vegetation (Kibler et al., 2021), effectively narrowing the riparian zone as defined by vegetation cover and species composition. Restorations of rivers will require consideration of global change and local anthropogenic effects on riparian river interactions (Palmer & Ruhi, 2019).

Anthropogenic activities and climate change threaten groundwater resources (Condon & Maxwell, 2019; Jasechko & Perrone, 2021) as well as surface waters. We are facing increasing threats from pollutants including nutrients, road salt, and per- and polyfluoroalkyl substances. In groundwater-dependent ecosystems, such as riparian zones, changes in climate could therefore lead to tipping points that drive ecosystems into alternative trajectories (Condon et al., 2020; Gleeson et al., 2019). Changes in the delivery of groundwater to streams may shift them from perennial to intermittent or even ephemeral under severe declines in the groundwater table (Carlson et al., 2024). For example, study of streams across the United States showed that no-flow periods have increased in intermittent streams since 1980 (Zipper et al., 2021), potentially indicating transition to an alternative stable state (Zipper et al., 2022). This alternative state could strongly influence the functioning of the riparian zone as declines in the water table could lead to shifts in primary productivity, community composition of riparian vegetation, and soil moisture patterns that influence fluxes of greenhouse gases (Hefting et al., 2004).

Species invasions are also altering riparian functions worldwide, and this process often occurs over decades or more. Thus, there is a directional temporal component to riparian function that can be altered by species invasions. These invasions increase as humans transport species more rapidly. Such invasions include *Acacia mearnsii* or *Eucalyptus* drying rivers in South Africa and monospecific *Tamarix* stands in the Southwest United States that dry streams, salinize soils, and homogenize riparian habitat (Richardson et al., 2007; Stromberg et al., 2007). Similarly, reduced flooding related to river damming in the Southwest United States led to narrowing of stream channels, particularly related to establishment and expansion of non-native tamarisk (Kui et al., 2017). Meta-analysis of riparian invasive species revealed that these species altered temporal patterns of input of allochthonous organic matter inputs, decomposition rates of coarse organic matter in bordering streams, nutrient cycling, and shifts in nearby aquatic communities (Robertson & Coll, 2019). Species invasions could therefore change the assigned width of riparian zones over time.

5 | IMPLICATIONS

Implementing a dynamic definition of riparian zones requires determining the distance from the stream that provides sufficient area to allow for ecosystem properties that support the preservation, modification, conservation, or restoration of the functions of interest. Similarly, specific criteria differentiating the riparian zone from the uplands will vary depending on functions of interest. For functions dependent on multiple properties, the function that requires the greatest buffer width could take greatest precedence, as it would potentially maintain other ecosystem functions that regulate additional ecosystem properties. For example, if preservation of an animal species requires maintaining a riparian zone with appropriate vegetation structure, the vegetation could also intercept nutrients, provide large wood to the stream, and stabilize the banks abutting the water.

Spatial and temporal considerations will be important at larger scales amenable to management and relevant to watershed-scale properties. Additionally, many of the properties and functions that define riparian zones are changing along temporal climate trajectories that can be rapid relative to past human experience and may not be easily reversible (Dodds et al., 2023; Williams & Jackson, 2007). These changes could lead to shifts in climate, hydrology, biomes, and other properties. Spatial and temporal variation therefore demand a flexible definition of riparian zones. Temporal variation could require revisiting riparian functions over time and necessitate a non-static, multidimensional definition of riparian zones.

A refined and unified view of riparian zones defined by function could inform existing regulatory approaches to management. The European Union Water Framework Directive does not explicitly mention riparian protection. However, definitions based on specific functions that allow for variable riparian widths have been used in the European Union (EU) for a variety of purposes (Clerici et al., 2011, 2013; Piedelobo et al., 2019; Weissteiner et al., 2016), but there is no consistent overarching EU policy that coordinates protection (Urbanič et al., 2022). Notwithstanding, methods have been devised to map riparian zones across the entire EU as a first step of coordination protections (Weissteiner et al., 2016).

A method based on defining riparian functions spatially over longitudinal, lateral, and vertical dimensions as proposed by the Region 9 United States Forest Service (Ilhardt et al., 2000) was compared to methods adopted by 17 states (Jayasuriya et al., 2022). Most of the state methods were based on fixed widths, and they were generally narrower than the variable width method based on functional attributes. This lack of alignment could be in part because states must respond to many different types of land ownership and agency control. For example, Section 404 of the Clean Water Act, administered by the US Environmental Protection Agency and the US Army Corps of Engineers, provides a framework for wetland delineation (an important component of many riparian areas) that has been adopted in many areas. This framework relies upon the US Army Corps of Engineers Wetland Delineation Manual (US Army Corps of Engineers, 1987), which uses soils, hydrology, and vegetation as indicators of the presence of wetlands (Gage et al., 2020). Given the spatial and temporal variation of riparian zones and multiple ecosystem services they provide, a more nuanced functional view is probably warranted.

Remote sensing and advanced analytical tools have helped in delineation of variable width riparian zones over wide spatial areas that are typically the scales at which management and regulation are applied. Achieving characterization and protection of riparian zones, as well as their ongoing management, will require bringing together diverse disciplines, developing consistent and well-designed regulatory frameworks (Hering et al., 2010), and acknowledgement of socioecological and environmental settings (Rodríguez-González et al., 2022).

Given the multiple functions and potential benefits of riparian zones, creating a regulatory framework for protection and restoration is complex. Each desired function of riparian zones could be scored with a relative benefit or value (e.g., Brander et al., 2013) as the start of the process of determining actions to take, and the total benefit balanced against the costs of taking those actions. One scheme of assigning benefit and harm to freshwater systems has been based on economic valuation (Dodds et al., 2013), but economic benefit is not the only consideration in many cases such as those where cultural and ecological benefits are important. While this approach may add complexity to the process and would be contingent upon the region of interest and the goals of regulation, it could also help buttress efforts for conservation or restoration as protecting riparian areas could accrue multiple benefits in addition to those with the highest priority. Thus, the idea of multiple beneficial functions of riparian zones could help strengthen arguments for legislation to protect specific riparian functions. At the same time, a flexible-width approach could avoid perceptions of overreach to avoid cases that include areas that are clearly irrelevant to specific riparian functions. Such an approach could be tailored to specific regions. For example, protection of salmonid habitat may be a priority in one region, and abatement of agricultural pollution the top priority in another region. This approach also suggests that more site-specific analyses of riparian functions are warranted.

6 | CONCLUSIONS

We review various avenues for objectively delineating riparian zones based on properties of interest to researchers and managers (Tables 2 and 3). We define riparian zones as occurring across ecotonal gradients at the terrestrial-aquatic interface with the upland boundary varying depending upon the ecosystem properties of interest, while recognizing generality may not cover all local contingencies. When delineating riparian zones, we encourage approaches that consider multiple riparian ecosystem functions that include (1) increasing biodiversity, (2) supplying carbon to aquatic food webs, (3) influencing water quality and quantity, and (4) modifying greenhouse gas flux to and from the atmosphere and supporting carbon sequestration. The width of riparian zones can then be defined multidimensionally (across multiple physical and biological gradients as well as at different temporal scales) by properties that influence these functions. The width is not necessarily fixed (as flood zones are delineated) to account for the highly heterogeneous nature of riparian systems. In general, those responsible for delineation of riparian zones would include ranking of ecological and biogeochemical functions that are critical for that biome and regionally important. This would need to include the recognition that some approaches that protect one function may not equally protect all others before identifying boundaries that protect the greatest proportion of key functions.

AUTHOR CONTRIBUTIONS

Walter K. Dodds: Conceptualization; writing—original draft; writing—review and editing. **Leon A. Barmuta**:

Conceptualization; writing—original draft; writing—review and editing. **Susana Bernal**: Conceptualization; writing—original draft; writing—review and editing. **Jessica Corman**: Conceptualization; writing—original draft; writing—review and editing. **Tamara K. Harms**: Conceptualization; writing—original draft; writing—review and editing. **Sherri L. Johnson**: Conceptualization; writing—original draft; writing—review and editing. **Li Li**: Conceptualization; writing—original draft; writing—review and editing. **Davi Gasparini Fernandes Cunha**: Conceptualization; writing—original draft; writing—review and editing. **Julian D. Olden**: Conceptualization; writing—review and editing. **Tenna Riis**: Conceptualization; writing—original draft; writing—review and editing. **Lucas C. R. Silva**: Conceptualization; writing—original draft. **John C. Stella**: Conceptualization; writing—review and editing. **Pamela Sullivan**: Conceptualization; writing—original draft; writing—review and editing. **Ellen Wohl**: Conceptualization; writing—original draft; writing—review and editing.

ACKNOWLEDGMENTS

We thank the Konza NSF Long Term Ecological Research Program DEB-2025849 for funding support for this work. The work by Susana Bernal was supported by the projects EVASIONA (PID2021-122817-NB-100) and RIPAMED (CNS2023-144737) funded by MICIU/AEI/FEDER-UE and Next Generation funding. The work by Leon A. Barmuta was supported by a Kansas State University Fulbright Scholar Award and the Future Drought Fund of the TAS FARM Innovation Hub, DAFF, Australian Government. This is contribution #26-028-J from the Kansas Agricultural Experiment Station.

CONFLICT OF INTEREST STATEMENT

All authors declare no conflicts of interest.

ORCID

Walter K. Dodds https://orcid.org/0000-0002-6666-8930
Leon A. Barmuta https://orcid.org/0000-0002-8946-3727
Susana Bernal https://orcid.org/0000-0002-6726-8840
Jessica Corman https://orcid.org/0000-0002-2633-8080
Tamara K. Harms https://orcid.org/0000-0001-7845-1109
Sherri L. Johnson https://orcid.org/0000-0002-4223-3465
Li Li https://orcid.org/0000-0002-1641-3710
Davi Gasparini Fernandes Cunha https://orcid.org/0000-0003-1876-3623
Julian D. Olden https://orcid.org/0000-0003-2143-1187
Tenna Riis https://orcid.org/0000-0003-2501-4444
Lucas C. R. Silva https://orcid.org/0000-0002-4838-327X
John C. Stella https://orcid.org/0000-0001-6095-7726
Pamela Sullivan https://orcid.org/0000-0001-8780-8501
Ellen Wohl https://orcid.org/0000-0001-7435-5013

REFERENCES

Acuña, V., Giorgi, A., Muñoz, I., Sabater, F., & Sabater, S. (2007). Meteorological and riparian influences on organic matter dynamics in a forested Mediterranean stream. *Journal of the North American Benthological Society*, *26*(1), 54–69.

Ardón, M., Zeglin, L. H., Utz, R. M., Cooper, S. D., Dodds, W. K., Bixby, R. J., Burdett, A. S., Follstad Shah, J., Griffiths, N. A., Harms, T. K., Johnson, S. L., Jones, J. B., Kominoski, J. S., McDowell, W. H., Rosemond, A. D., Trentman, M. T., Van Horn, D., & Ward, A. (2021). Experimental nitrogen and phosphorus enrichment stimulates multiple trophic levels of algal and detrital-based food webs: A global meta-analysis from streams and rivers. *Biological Reviews*, *96*(2), 692–715. https://doi.org/10.1111/brv.12673

Baker, S., Richardson, A., & Barmuta, L. (2007). Site effects outweigh riparian influences on ground-dwelling beetles adjacent to first order streams in wet eucalypt forest. *Biodiversity and Conservation*, *16*(7), 1999–2014. https://doi.org/10.1007/s10531-006-9056-3

Barros, T. L., Bracewell, S. A., Mayer-Pinto, M., Dafforn, K. A., Simpson, S. L., Farrell, M., & Johnston, E. L. (2022). Wildfires cause rapid changes to estuarine benthic habitat. *Environmental Pollution*, *308*, 119571. https://doi.org/10.1016/j.envpol.2022.119571

Bartels, P., Cucherousset, J., Steger, K., Eklöv, P., Tranvik, L. J., & Hillebrand, H. (2012). Reciprocal subsidies between freshwater and terrestrial ecosystems structure consumer resource dynamics. *Ecology*, *93*(5), 1173–1182. http://www.jstor.org/stable/23213511

Bastow, J. L., Sabo, J. L., Finlay, J. C., & Power, M. E. (2002). A basal aquatic-terrestrial trophic link in rivers: Algal subsidies via shore-dwelling grasshoppers. *Oecologia*, *131*, 261–268. https://doi.org/10.1007/s00442-002-0879-7

Beier, P., & Noss, R. F. (1998). Do habitat corridors provide connectivity? *Conservation Biology*, *12*(6), 1241–1252. https://doi.org/10.1111/j.1523-1739.1998.98036.x

Benda, L., Poff, N. L., Miller, D., Dunne, T., Reeves, G., Pess, G., & Pollock, M. (2004). The network dynamics hypothesis: How channel networks structure riverine habitats. *Bioscience*, *54*(5), 413–427. https://doi.org/10.1641/0006-3568(2004)054%5b0413:TNDHHC%5d2.0.CO;2

Bendix, J., & Hupp, C. R. (2000). Hydrological and geomorphological impacts on riparian plant communities. *Hydrological Processes*, *14*(16–17), 2977–2990. https://doi.org/10.1002/1099-1085(200011/12)14:16/17%3c2977::AID-HYP130%3e3.0.CO;2-4

Bernhardt, E. S., Blaszczak, J. R., Ficken, C. D., Fork, M. L., Kaiser, K. E., & Seybold, E. C. (2017). Control points in ecosystems: Moving beyond the hot spot hot moment concept. *Ecosystems*, *20*(4), 665–682. https://doi.org/10.1007/s10021-016-0103-y

Bertoldi, W., Gurnell, A., & Drake, N. (2011). The topographic signature of vegetation development along a braided river: Results of a combined analysis of airborne LiDAR, color air photographs, and ground measurements. *Water Resources Research*, *47*(6), W06525. https://doi.org/10.1029/2010WR010319

Bhattacharyya, A., Campbell, A. N., Tfaily, M. M., Lin, Y., Kukkadapu, R. K., Silver, W. L., Nico, P. S., & Pett-Ridge, J. (2018). Redox fluctuations control the coupled cycling of iron and carbon in tropical forest soils. *Environmental Science & Technology*, *52*(24), 14129–14139. https://doi.org/10.1021/acs.est.8b03408

Blauch, G. A., & Jefferson, A. J. (2019). If a tree falls in an urban stream, does it stick around? Mobility, characteristics, and geomorphic influence of large wood in urban streams in northeastern

Ohio, USA. *Geomorphology*, *337*, 1–14. https://doi.org/10.1016/j.geomorph.2019.03.033

Boisjolie, B. A., Flitcroft, R. L., & Santelmann, M. V. (2019). Patterns of riparian policy standards in riverscapes of the Oregon Coast Range. *Ecology & Society*, *24*(1), 22. https://doi.org/10.5751/ES-10676-240122

Brander, L., Brouwer, R., & Wagtendonk, A. (2013). Economic valuation of regulating services provided by wetlands in agricultural landscapes: A meta-analysis. *Ecological Engineering*, *56*, 89–96. https://doi.org/10.1016/j.ecoleng.2012.12.104

Brinkerhoff, C. B., Gleason, C. J., Kotchen, M. J., Kysar, D. A., & Raymond, P. A. (2024). Ephemeral stream water contributions to United States drainage networks. *Science*, *384*(6703), 1476–1482. https://doi.org/10.1126/science.adg9430

Brown, G. W., & Krygier, J. T. (1970). Effects of clear-cutting on stream temperature. *Water Resources Research*, *6*(4), 1133–1139. https://doi.org/10.1029/WR006i004p01133

Burton, J. I., Olson, D. H., & Puettmann, K. J. (2016). Effects of riparian buffer width on wood loading in headwater streams after repeated forest thinning. *Forest Ecology and Management*, *372*, 247–257. https://doi.org/10.1016/j.foreco.2016.03.053

Burton, T. M., & Likens, G. E. (1973). The effect of strip-cutting on stream temperatures in the Hubbard Brook Experimental Forest, New Hampshire. *BioScience*, *23*(7), 433–435.

Caissie, D. (2006). The thermal regime of rivers: A review. *Freshwater Biology*, *51*(8), 1389–1406. https://doi.org/10.1111/j.1365-2427.2006.01597.x

Carlson, S. M., Ruhí, A., Bogan, M. T., Hazard, C. W., Ayers, J., Grantham, T. E., Batalla, R. J., & Garcia, C. (2024). Losing flow in free-flowing Mediterranean-climate streams. *Frontiers in Ecology and the Environment*, *22*(5), e2737. https://doi.org/10.1002/fee.2737

Catford, J. A., & Jansson, R. (2014). Drowned, buried and carried away: Effects of plant traits on the distribution of native and alien species in riparian ecosystems. *New Phytologist*, *204*(1), 19–36.

Clerici, N., Weissteiner, C., Paracchini, M., & Strobl, P. (2011). *Riparian zones: Where green and blue networks meet*. Publications Office of the European Union.

Clerici, N., Weissteiner, C. J., Paracchini, M. L., Boschetti, L., Baraldi, A., & Strobl, P. (2013). Pan-European distribution modelling of stream riparian zones based on multi-source Earth Observation data. *Ecological Indicators*, *24*, 211–223. https://doi.org/10.1016/j.ecolind.2012.06.002

Clinton, B. D., Vose, J. M., Knoepp, J. D., Elliott, K. J., Reynolds, B. C., & Zarnoch, S. J. (2010). Can structural and functional characteristics be used to identify riparian zone width in southern Appalachian headwater catchments? *Canadian Journal of Forest Research*, *40*(2), 235–253.

Collins, B. D., Montgomery, D. R., Fetherston, K. L., & Abbe, T. B. (2012). The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. *Geomorphology*, *139*, 460–470. https://doi.org/10.1016/j.geomorph.2011.11.011

Condon, L. E., Atchley, A. L., & Maxwell, R. M. (2020). Evapotranspiration depletes groundwater under warming over the contiguous United States. *Nature Communications*, *11*(1), Article 873. https://doi.org/10.1038/s41467-020-14688-0

Condon, L. E., & Maxwell, R. M. (2019). Simulating the sensitivity of evapotranspiration and streamflow to large-scale groundwater depletion. *Science Advances*, *5*(6), eaav4574. https://doi.org/10.1126/sciadv.aav4574

Cooper, D. J., Andersen, D. C., & Chimner, R. A. (2003). Multiple pathways for woody plant establishment on floodplains at local to regional scales. *Journal of Ecology*, *91*(2), 182–196. https://doi.org/10.1046/j.1365-2745.2003.00766.x

Corenblit, D., Steiger, J., Gurnell, A. M., & Naiman, R. J. (2009). Plants intertwine fluvial landform dynamics with ecological succession and natural selection: A niche construction perspective for riparian systems. *Global Ecology and Biogeography*, *18*(4), 507–520.

Cronk, J. K., & Fennessy, M. S. (2016). *Wetland plants: Biology and ecology*. CRC Press. https://doi.org/10.1201/9781420032925

Cummings, A. K., Pope, K. L., & Mak, G. (2023). Resetting the baseline: Using machine learning to find lost meadows. *Landscape Ecology*, *38*(10), 2639–2653. https://doi.org/10.1007/s10980-023-01726-7

Czarnecka, M. (2016). Coarse woody debris in temperate littoral zones: Implications for biodiversity, food webs and lake management. *Hydrobiologia*, *767*, 13–25. https://doi.org/10.1007/s10750-015-2502-z

da Silva, N. M., Angeoletto, F., Santos, j. W. M. C., Paranhos Filho, A. C., Vacchiano, M. C., Bohrer, J. F. C., & Candido, A. K. A. A. (2017). The negative influences of the new Brazilian forest code on the conservation of riparian forests. *European Journal of Ecology*, *3*(2), 116–122. https://doi.org/10.1515/eje-2017-0019

Davies-Colley, R. J., & Payne, G. W. (2023). Cooling streams with riparian trees: Thermal regime depends on total solar radiation penetrating the canopy. *Austral Ecology*, *48*, 1064–1073. https://doi.org/10.1111/aec.13345

Dieterich, M., & Anderson, N. H. (1998). Dynamics of abiotic parameters, solute removal and sediment retention in summer-dry headwater streams of western Oregon. *Hydrobiologia*, *379*, 1–15. https://doi.org/10.1023/A:1003423016125

Dodds, W. K., & Oakes, R. M. (2006). Controls on nutrients across a prairie stream watershed: Land use and riparian cover effects. *Environmental Management*, *37*(5), 634–646. https://doi.org/10.1007/s00267-004-0072-3

Dodds, W. K. (2003). Misuse of inorganic N and soluble reactive P concentrations to indicate nutrient status of surface waters. *Journal of the North American Benthological Society*, *22*, 171–181.

Dodds, W. K., Lopez, A. J., Bowden, W. B., Gregory, S., Grimm, N. B., Hamilton, S. K., Hershey, A. E., Marti, E., McDowell, W. H., Meyer, J. L., Morrall, D., Mulholland, P. J., Peterson, B. J., Tank, J. L., Valett, H. M., Webster, J. R., & Wollheim, W. (2002). N uptake as a function of concentration in streams. *Journal of the North American Benthological Society*, *21*(2), 206–220. https://doi.org/10.2307/1468410

Dodds, W. K., Perkin, J. S., & Gerken, J. E. (2013). Human impact on freshwater ecosystem services: A global perspective. *Environmental Science & Technology*, *47*(16), 9061–9068.

Dodds, W. K., Ratajczak, Z., Keen, R. M., Nippert, J. B., Grudzinski, B., Veach, A., Taylor, J. H., & Kuhl, A. (2023). Trajectories and state changes of a grassland stream and riparian zone after a decade of woody vegetation removal. *Ecological Applications*, *33*(4), e2830. https://doi.org/10.1002/eap.2830

Dodds, W. K., Rose, K. C., Fei, S., & Chandra, S. (2021). Macrosystems revisited: Challenges and successes in a new subdiscipline of ecology. *Frontiers in Ecology and the Environment*, *19*(1), 4–10. https://doi.org/10.1002/fee.2286

Dodds, W. K., Tromboni, F., Aparecido Saltarelli, W., & Fernandes Cunha, D. G. (2017). The root of the problem: Direct influence of riparian vegetation on estimation of stream ecosystem metabolic rates. *Limnology and Oceanography Letters*, *2*(1), 9–17. https://doi.org/10.1002/lol2.10032

Dodds, W. K., Wichman, G., Guinnip, J. P., Corman, J. R., & Blair, J. M. (2022). Assessing transport and retention of nitrate and other materials through the riparian zone and stream channel with simulated precipitation. *Methods in Ecology and Evolution*, *13*(3), 757–766. https://doi.org/10.1111/2041-210X.13791

Duchaufour, P. (1982). Hydromorphic soils. In P. Duchaufour (Ed.), *Pedology: Pedogenesis and classification* (pp. 335–372). Springer. https://doi.org/10.1007/978-94-011-6003-2_12

Dugdale, S. J., Hannah, D. M., & Malcolm, I. A. (2020). An evaluation of different forest cover geospatial data for riparian shading and river temperature modelling. *River Research and Applications*, *36*(5), 709–723. https://doi.org/10.1002/rra.3598

Dybala, K. E., Steger, K., Walsh, R. G., Smart, D. R., Gardali, T., & Seavy, N. E. (2019). Optimizing carbon storage and biodiversity co-benefits in reforested riparian zones. *Journal of Applied Ecology*, *56*(2), 343–353. https://doi.org/10.1111/1365-2664.13272

England, J. F., Jr., Cohn, T. A., Faber, B. A., Stedinger, J. R., Thomas, W. O., Jr., Veilleux, A. G., Kiang, J. E., & Mason, R. R., Jr. (2018). *Guidelines for determining flood flow frequency—Bulletin 17C* (1411342232). USGS.

Fan, Y., Miguez-Macho, G., Jobbágy, E. G., Jackson, R. B., & Otero-Casal, C. (2017). Hydrologic regulation of plant rooting depth. *Proceedings of the National Academy of Sciences*, *114*(40), 10572–10577. https://doi.org/10.1073/pnas.1712381114

Faulkner, S. P., & Richardson, C. J. (2020). Physical and chemical characteristics of freshwater wetland soils. In D. A. Hammer (Ed.), *Constructed wetlands for wastewater treatment* (pp. 41–72). CRC Press. https://doi.org/10.1201/9781003069850

Faustini, J. M., & Jones, J. A. (2003). Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. *Geomorphology*, *51*(1–3), 187–205. https://doi.org/10.1016/S0169-555X(02)00336-7

Fisher, S. G., & Likens, G. E. (1973). Energy flow in Bear Brook, New Hampshire: An integrative approach to stream ecosystem metabolism. *Ecological Monographs*, *43*(4), 421–439. https://doi.org/10.2307/1942301

Fritz, K. M., & Feminella, J. W. (2011). Invertebrate colonization of leaves and roots within sediments of intermittent Coastal Plain streams across hydrologic phases. *Aquatic Sciences*, *73*(4), 459–469. https://doi.org/10.1007/s00027-011-0192-9

Gage, E., Cooper, D. J., & Lichvar, R. (2020). Comparison of USACE three-factor wetland delineations to national wetland inventory maps. *Wetlands*, *40*(5), 1097–1105. https://doi.org/10.1007/s13157-019-01234-y

Gillies, C. S., & St. Clair, C. C. (2008). Riparian corridors enhance movement of a forest specialist bird in fragmented tropical forest. *Proceedings of the National Academy of Sciences*, *105*(50), 19774–19779. https://doi.org/10.1073/pnas.0803530105

Gleeson, T., Villholth, K., Taylor, R., Perrone, D., & Hyndman, D. (2019). Groundwater: A call to action. *Nature*, *576*(7786), 213–214. https://doi.org/10.1038/d41586-019-03711-0

Gold, A. C. (2024). How wet must a wetland be to have federal protections in post-*Sackett* US? *Science*, *385*(6716), 1450–1453. https://doi.org/10.1126/science.adp3222

González, E., Sher, A. A., Tabacchi, E., Masip, A., & Poulin, M. (2015). Restoration of riparian vegetation: A global review of implementation and evaluation approaches in the international, peer-reviewed literature. *Journal of Environmental Management*, *158*, 85–94. https://doi.org/10.1016/j.jenvman.2015.04.033

Gray, L. J. (1993). Response of insectivorous birds to emerging aquatic insects in riparian habitats of a tallgrass prairie stream. *American Midland Naturalist*, *129*, 288–300.

Greenhill, S., Druckenmiller, H., Wang, S., Keiser, D. A., Girotto, M., Moore, J. K., Yamaguchi, N., Todeschini, A., & Shapiro, J. S. (2024). Machine learning predicts which rivers, streams, and wetlands the Clean Water Act regulates. *Science*, *383*(6681), 406–412. https://doi.org/10.1126/science.adi3794

Gregory, S. V., Swanson, F. J., McKee, W. A., & Cummins, K. W. (1991). An ecosystem perspective of riparian zones. *BioScience*, *41*(8), 540–551. https://doi.org/10.2307/1311607

Guidotti, V., Ferraz, S. F. D. B., Pinto, L. F. G., Sparovek, G., Taniwaki, R. H., Garcia, L. G., & Brancalion, P. H. S. (2020). Changes in Brazil's Forest Code can erode the potential of riparian buffers to supply watershed services. *Land Use Policy*, *94*, 104511. https://doi.org/10.1016/j.landusepol.2020.104511

Gurnell, A., Corenblit, D., García de Jalón, D., González del Tánago, M., Grabowski, R., O'hare, M., & Szewczyk, M. (2016). A conceptual model of vegetation–hydrogeomorphology interactions within river corridors. *River Research and Applications*, *32*(2), 142–163.

Hagan, J. M., Pealer, S., & Whitman, A. A. (2006). Do small headwater streams have a riparian zone defined by plant communities? *Canadian Journal of Forest Research*, *36*(9), 2131–2140. https://doi.org/10.1139/x06-114

Hagar, J. C., Li, J., Sobota, J., & Jenkins, S. (2012). Arthropod prey for riparian associated birds in headwater forests of the Oregon Coast Range. *Forest Ecology and Management*, *285*, 213–226. https://doi.org/10.1016/j.foreco.2012.08.026

Harms, T. K., & Grimm, N. B. (2012). Responses of trace gases to hydrologic pulses in desert floodplains. *Journal of Geophysical Research: Biogeosciences*, *117*(G1), G01035. https://doi.org/10.1029/2011JG001775

Harms, T. K., Wentz, E. A., & Grimm, N. B. (2009). Spatial heterogeneity of denitrification in semi-arid floodplains. *Ecosystems*, *12*(1), 129–143. https://doi.org/10.1007/s10021-008-9212-6

Hawley, R. J., & MacMannis, K. R. (2019). Tree roots as a dominant agent of streambed habitat, profile pattern, and grade control. *Geomorphology*, *343*, 81–91. https://doi.org/10.1016/j.geomorph.2019.06.021

Heffernan, J. B., Soranno, P. A., Angilletta, M. J., Jr., Buckley, L. B., Gruner, D. S., Keitt, T. H., Kellner, J. R., Kominoski, J. S., Rocha, A. V., & Xiao, J. (2014). Macrosystems ecology: Understanding ecological patterns and processes at continental scales. *Frontiers in Ecology and the Environment*, *12*(1), 5–14. https://doi.org/10.1890/130017

Hefting, M., Clement, J.-C., Dowrick, D., Cosandey, A.-C., Bernal, S., Cimpian, C., Tatur, A., Burt, T., & Pinay, G. (2004). Water table elevation controls on soil nitrogen cycling in riparian wetlands along a European climatic gradient. *Biogeochemistry*, *67*(1), 113–134. https://doi.org/10.1023/B:BIOG.0000015320.69868.33

Helfield, J. M., & Naiman, R. J. (2001). Effects of salmon-derived nitrogen on riparian forest growth and implications for stream productivity. *Ecology*, *82*(9), 2403–2409. https://doi.org/10.1890/0012-9658(2001)082%5b2403:EOSDNO%5d2.0.CO;2

Hering, D., Borja, A., Carstensen, J., Carvalho, L., Elliott, M., Feld, C. K., Heiskanen, A.-S., Johnson, R. K., Moe, J., & Pont, D. (2010). The European Water Framework Directive at the age of 10: A critical review of the achievements with recommendations for the future. *Science of the Total Environment*, *408*(19), 4007–4019. https://doi.org/10.1016/j.scitotenv.2010.05.031

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., & Kanae, S. (2013). Global flood risk under climate change. *Nature Climate Change*, *3*(9), 816–821. https://doi.org/10.1038/nclimate1911

Hobbs, R. J. (1992). The role of corridors in conservation: Solution or bandwagon? *Trends in Ecology & Evolution*, *7*(11), 389–392.

Hoellein, T. J., McCormick, A. R., Hittie, J., London, M. G., Scott, J. W., & Kelly, J. J. (2017). Longitudinal patterns of microplastic concentration and bacterial assemblages in surface and benthic habitats of an urban river. *Freshwater Science*, *36*(3), 491–507. https://doi.org/10.1086/693012

Hoellein, T. J., Shogren, A. J., Tank, J. L., Risteca, P., & Kelly, J. J. (2019). Microplastic deposition velocity in streams follows patterns for naturally occurring allochthonous particles. *Scientific Reports*, *9*(1), Article 3740. https://doi.org/10.1038/s41598-019-40126-3

Hoffmann, W. A., Franco, A., Moreira, M. Z., & Haridasan, M. (2005). Specific leaf area explains differences in leaf traits between congeneric savanna and forest trees. *Functional Ecology*, *19*(6), 932–940. https://doi.org/10.1111/j.1365-2435.2005.01045.x

Hoffmann, W. A., Geiger, E. L., Gotsch, S. G., Rossatto, D. R., Silva, L. C., Lau, O. L., Haridasan, M., & Franco, A. C. (2012). Ecological thresholds at the savanna-forest boundary: How plant traits, resources and fire govern the distribution of tropical biomes. *Ecology Letters*, *15*(7), 759–768. https://doi.org/10.1111/j.1461-0248.2012.01789.x

Holland, M. M., & Risser, P. G. (1991). The role of landscape boundaries in the management and restoration of changing environments: Introduction. In M. M. Holland, P. G. Risser, & R. J. Naiman (Eds.), *Ecotones: The role of landscape boundaries in the management and restoration of changing environments* (pp. 1–7). Springer. https://doi.org/10.1007/978-1-4615-9686-8_1

Hynes, H. B. N. (1975). The stream and its valley. *SIL Proceedings, 1922–2010*, *19*(1), 1–15. https://doi.org/10.1080/03680770.1974.11896033

Ilhardt, B., Verry, E., & Palik, B. (2000). Defining riparian areas. In E. Verry, J. Hornbeck, & D. Dolloff (Eds.), *Riparian management in forests of the continental eastern United States* (pp. 23–42). Lewis Publishers.

Jasechko, S., & Perrone, D. (2021). Global groundwater wells at risk of running dry. *Science*, *372*(6540), 418–421. https://doi.org/10.1126/science.abc2755

Jayasuriya, M. T., Germain, R. H., & Stella, J. C. (2022). Applying the "Goldilocks rule" to riparian buffer widths for forested headwater streams across the contiguous U.S.—How much is "just right"? *Forests*, *13*(9), 1509. https://www.mdpi.com/1999-4907/13/9/1509

Jayasuriya, M. T., Stella, J. C., & Germain, R. H. (2021). Can understory plant composition and richness help designate riparian management zones in mesic headwater forests of the northeastern United States? *Journal of Forestry*, *119*(6), 574–588.

Johnson, S. L., Swanson, F. J., Grant, G. E., & Wondzell, S. M. (2000). Riparian forest disturbances by a mountain flood—The influence of floated wood. *Hydrological Processes*, *14*(16–17), 3031–3050. https://doi.org/10.1002/1099-1085(200011/12)14:16/17%3c3031::AID-HYP133%3e3.0.CO;2-6

Johnson, W. C., Dixon, M. D., Simons, R., Jenson, S., & Larson, K. (1995). Mapping the response of riparian vegetation to possible flow reductions in the Snake River, Idaho. *Geomorphology*, *13*(1–4), 159–173. https://doi.org/10.1016/0169-555X(95)00048-A

Kałuża, T., Sojka, M., Wróżyński, R., Jaskuła, J., Zaborowski, S., & Hämmerling, M. (2020). Modeling of river channel shading as a factor for changes in hydromorphological conditions of small lowland rivers. *Water*, *12*(2), 527.

Kark, S. (2013). Effects of ecotones on biodiversity. *Encyclopedia of Biodiversity*, *3*, 142–148.

Kibler, C. L., Schmidt, E. C., Roberts, D. A., Stella, J. C., Kui, L., Lambert, A. M., & Singer, M. B. (2021). A brown wave of riparian woodland mortality following groundwater declines during the 2012–2019 California drought. *Environmental Research Letters*, *16*(8), 084030. https://doi.org/10.1088/1748-9326/ac1377

Kiffney, P. M., Richardson, J. S., & Bull, J. P. (2004). Establishing light as a causal mechanism structuring stream communities in response to experimental manipulation of riparian buffer width. *Journal of the North American Benthological Society*, *23*(3), 542–555. https://doi.org/10.1899/0887-3593(2004)023%3c0542:ELAACM%3e2.0.CO;2

Knopf, F. L., Johnson, R. R., Rich, T., Samson, F. B., & Szaro, R. C. (1988). Conservation of riparian ecosystems in the United States. *The Wilson Bulletin*, *100*(2), 272–284.

Kramer, N., & Wohl, E. (2015). Driftcretions: The legacy impacts of driftwood on shoreline morphology. *Geophysical Research Letters*, *42*(14), 5855–5864. https://doi.org/10.1002/2015GL064441

Kuglerová, L., Ågren, A., Jansson, R., & Laudon, H. (2014). Towards optimizing riparian buffer zones: Ecological and biogeochemical implications for forest management. *Forest Ecology and Management*, *334*, 74–84. https://doi.org/10.1016/j.foreco.2014.08.033

Kuglerová, L., Muotka, T., Chellaiah, D., Jyväsjärvi, J., & Richardson, J. S. (2024). Protecting our streams by defining measurable targets for riparian management in a forestry context. *Journal of Applied Ecology*, *61*(2), 206–214. https://doi.org/10.1111/1365-2664.14549

Kui, L., Stella, J. C., Shafroth, P. B., House, P. K., & Wilcox, A. C. (2017). The long-term legacy of geomorphic and riparian vegetation feedbacks on the dammed Bill Williams River, Arizona, USA. *Ecohydrology*, *10*(4), e1839. https://doi.org/10.1002/eco.1839

Ladd, B., Laffan, S. W., Amelung, W., Peri, P. L., Silva, L. C., Gervassi, P., Bonser, S. P., Navall, M., & Sheil, D. (2013). Estimates of soil carbon concentration in tropical and temperate forest and woodland from available GIS data on three continents. *Global Ecology and Biogeography*, *22*(4), 461–469. https://doi.org/10.1111/j.1466-8238.2012.00799.x

Ladd, B., Peri, P. L., Pepper, D. A., Silva, L. C., Sheil, D., Bonser, S. P., Laffan, S. W., Amelung, W., Ekblad, A., & Eliasson, P. (2014). Carbon isotopic signatures of soil organic matter correlate with leaf area index across woody biomes. *Journal of Ecology*, *102*(6), 1606–1611. https://doi.org/10.1111/1365-2745.12309

Larsen, S., Muehlbauer, J. D., & Marti, E. (2016). Resource subsidies between stream and terrestrial ecosystems under global change. *Global Change Biology*, *22*(7), 2489–2504. https://doi.org/10.1111/gcb.13182

Leopold, L. B. (1994). *A view of the river*. Harvard University Press.

Ligon, F. K., Dietrich, W. E., & Trush, W. J. (1995). Downstream ecological effects of dams. *BioScience*, *45*(3), 183–192.

Lind, L., Hasselquist, E. M., & Laudon, H. (2019). Towards ecologically functional riparian zones: A meta-analysis to develop guidelines for protecting ecosystem functions and biodiversity in agricultural landscapes. *Journal of Environmental Management*, *249*, 109391. https://doi.org/10.1016/j.jenvman.2019.109391

Lopez, J. W., Hartnett, R. N., Parr, T. B., & Vaughn, C. C. (2023). Ecosystem bioelement variability is associated with freshwater animal aggregations at the aquatic-terrestrial interface. *Oecologia*, *202*(4), 795–806. https://doi.org/10.1007/s00442-023-05437-3

Lowrance, R., Todd, R., Fail, J., Jr., Hendrickson, O. Jr., Leonard, R., & Asmussen, L. (1984). Riparian forests as nutrient filters in agricultural watersheds. *BioScience*, *34*(6), 374–377. https://doi.org/10.2307/1309729

MacNally, R., Parkinson, A., Horrocks, G., & Young, M. (2002). Current loads of coarse woody debris on southeastern Australian floodplains: Evaluation of change and implications for restoration. *Restoration Ecology*, *10*(4), 627–635. https://doi.org/10.1046/j.1526-100X.2002.01043.x

Makaske, B. (2001). Anastomosing rivers: A review of their classification, origin and sedimentary products. *Earth-Science Reviews*, *53*(3–4), 149–196. https://doi.org/10.1016/S0012-8252(00)00038-6

Marczak, L. B., Sakamaki, T., Turvey, S. L., Deguise, I., Wood, S. L. R., & Richardson, J. S. (2010). Are forested buffers an effective conservation strategy for riparian fauna? An assessment using meta-analysis. *Ecological Applications*, *20*(1), 126–134. https://doi.org/10.1890/08-2064.1

Matzek, V., Stella, J., & Ropion, P. (2018). Development of a carbon calculator tool for riparian forest restoration. *Applied Vegetation Science*, *21*(4), 584–594. https://doi.org/10.1111/avsc.12400

Mayer, P. M., Reynolds, S. K., Jr., McCutchen, M. D., & Canfield, T. J. (2007). Meta-analysis of nitrogen removal in riparian buffers. *Journal of Environmental Quality*, *36*(4), 1172–1180. https://doi.org/10.2134/jeq2006.0462

McMahon, C. A., Roberts, D. A., Stella, J. C., Trugman, A. T., Singer, M. B., & Caylor, K. K. (2024). A river runs through it: Robust automated mapping of riparian woodlands and land surface phenology across dryland regions. *Remote Sensing of Environment*, *305*, 114056. https://doi.org/10.1016/j.rse.2024.114056

McMahon, J. M., Olley, J. M., Brooks, A. P., Smart, J. C., Stewart-Koster, B., Venables, W. N., Curwen, G., Kemp, J., Stewart, M., & Saxton, N. (2020). Vegetation and longitudinal coarse sediment connectivity affect the ability of ecosystem restoration to reduce riverbank erosion and turbidity in drinking water. *Science of the Total Environment*, *707*, 135904. https://doi.org/10.1016/j.scitotenv.2019.135904

Melack, J. M., Hess, L. L., Gastil, M., Forsberg, B. R., Hamilton, S. K., Lima, I. B., & Novo, E. M. (2004). Regionalization of methane emissions in the Amazon Basin with microwave remote sensing. *Global Change Biology*, *10*(5), 530–544. https://doi.org/10.1111/j.1365-2486.2004.00763.x

Meleason, M. A., Gregory, S. V., & Bolte, J. P. (2003). Implications of riparian management strategies on wood in streams of the Pacific Northwest. *Ecological Applications*, *13*(5), 1212–1221. https://doi.org/10.1890/02-5004

Mello, F. A., Demattê, J. A., Bellinaso, H., Poppiel, R. R., Rizzo, R., de Mello, D. C., Rosin, N. A., Rosas, J. T., Silvero, N. E., & Rodríguez-Albarracín, H. S. (2023). Remote sensing imagery detects hydromorphic soils hidden under agriculture system. *Scientific Reports*, *13*(1), Article 10897.

Messager, M. L., Lehner, B., Cockburn, C., Lamouroux, N., Pella, H., Snelder, T., Tockner, K., Trautmann, T., Watt, C., & Datry, T. (2021). Global prevalence of non-perennial rivers and streams. *Nature*, *594*(7863), 391–397. https://doi.org/10.1038/s41586-021-03565-5

Micheli, E., Kirchner, J., & Larsen, E. (2004). Quantifying the effect of riparian forest versus agricultural vegetation on river meander migration rates, Central Sacramento River, California, USA. *River Research and Applications*, *20*(5), 537–548. https://doi.org/10.1002/rra.756

Mikryukov, V., Dulya, O., Zizka, A., Bahram, M., Hagh-Doust, N., Anslan, S., Prylutskyi, O., Delgado-Baquerizo, M., Maestre, F. T., Nilsson, H., Pärn, J., Öpik, M., Moora, M., Zobel, M., Espenberg, M., Mander, Ü., Khalid, A. N., Corrales, A., Agan, A., … Tedersoo, L. (2023). Connecting the multiple dimensions of global soil fungal diversity. *Science Advances*, *9*(48), eadj8016. https://doi.org/10.1126/sciadv.adj8016

Muehlbauer, J. D., Collins, S. F., Doyle, M. W., & Tockner, K. (2014). How wide is a stream? Spatial extent of the potential "stream signature" in terrestrial food webs using meta-analysis. *Ecology*, *95*(1), 44–55. https://doi.org/10.1890/12-1628.1

Mulholland, P. J., Hall, R. O., Sobota, D. J., Dodds, W. K., Findlay, S. E. G., Grimm, N. B., Hamilton, S. K., McDowell, W. H., Obrien, J. M., Tank, J. L., Ashkenas, L. R., Cooper, L. W., Dahm, C. N., Gregory, S. V., Johnson, S. L., Meyer, J. L., Peterson, B. J., Poole, G. C., Valett, H. M., … Thomas, S. M. (2009). Nitrate removal in stream ecosystems measured by 15N addition experiments: Denitrification. *Limnology and Oceanography*, *54*, 666–680.

Naiman, R. J., Bilby, R. E., & Bisson, P. A. (2000). Riparian ecology and management in the pacific coastal rain forest. *Bioscience*, *50*(11), 996–1011.

Naiman, R., & Décamps, H. (1997). The ecology of interfaces: Riparian zones. *Annual Review of Ecology and Systematics*, *28*(1), 621–658. https://doi.org/10.1146/annurev.ecolsys.28.1.621

Naiman, R., Decamps, H., & McClain, M. E. (2005). *Riparia: Ecology, conservation, and management of streamside communities*. Elsevier.

Naiman, R., Decamps, H., & Pollock, M. (1993). The role of riparian corridors in maintaining regional biodiversity. *Ecological Applications*, *3*(2), 209–212. https://doi.org/10.2307/1941822

National Research Council. (2002). *Riparian areas: Functions and strategies for management*. The National Academies Press. https://doi.org/10.17226/10327

Nelson, A. D., Collins, V. D., Payne, J. S., & Abbe, T. B. (2024). Proactive river corridor definition: Recommendations for a process-based width optimization approach illustrated in the context of the coastal Pacific Northwest. *Wiley Interdisciplinary Reviews: Water*, *11*(3), e1711. https://doi.org/10.1002/wat2.1711

Olson, D. H., Anderson, P. D., Frissell, C. A., Welsh, H. H., & Bradford, D. F. (2007). Biodiversity management approaches for stream–riparian areas: Perspectives for Pacific Northwest headwater forests, microclimates, and amphibians. *Forest Ecology and Management*, *246*(1), 81–107. https://doi.org/10.1016/j.foreco.2007.03.053

Paiva, A. O., Silva, L. C. R., & Haridasan, M. (2015). Productivity-efficiency tradeoffs in tropical gallery forest-savanna transitions: Linking plant and soil processes through litter input and composition. *Plant Ecology*, *216*, 775–787.

Palmer, M., & Ruhi, A. (2019). Linkages between flow regime, biota, and ecosystem processes: Implications for river restoration. *Science*, *365*(6459), eaaw2087. https://doi.org/10.1126/science.aaw2087

Payn, R. A., Webster, J. R., Mulholland, P. J., Valett, H. M., & Dodds, W. K. (2005). Estimation of stream nutrient uptake from nutrient addition experiments. *Limnology and Oceanography: Methods*, *3*, 174–182. https://doi.org/10.4319/lom.2005.3.174

Peterjohn, W. T., & Correll, D. L. (1984). Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest. *Ecology*, *65*(5), 1466–1475. https://doi.org/10.2307/1939127

Piedelobo, L., Taramelli, A., Schiavon, E., Valentini, E., Molina, J.-L., Nguyen Xuan, A., & González-Aguilera, D. (2019). Assessment of green infrastructure in riparian zones using Copernicus programme. *Remote Sensing*, *11*(24), 2967. https://www.mdpi.com/2072-4292/11/24/2967

Piegay, H., & Gurnell, A. (1997). Large woody debris and river geomorphological pattern: Examples from S.E. France and S. England. *Geomorphology*, *19*(1–2), 99–116.

Pinay, G., Black, V. J., Planty-Tabacchi, A. M., Gumiero, B., & Décamps, H. (2000). Geomorphic control of denitrification in large river floodplain soils. *Biogeochemistry*, *50*, 163–182. https://doi.org/10.1023/A:1006317004639

Polvi, L. (2009). *Characterization of riparian zones in mountain valleys of the Colorado Front Range* [Master's thesis]. Colorado State University.

Polvi, L., Wohl, E., & Merritt, D. (2011). Geomorphic and process domain controls on riparian zones in the Colorado Front Range. *Geomorphology*, *125*(4), 504–516. https://doi.org/10.1016/j.geomorph.2010.10.012

Polvi, L., Wohl, E., & Merritt, D. M. (2014). Modeling the functional influence of vegetation type on streambank cohesion. *Earth Surface Processes and Landforms*, *39*(9), 1245–1258. https://doi.org/10.1002/esp.3577

Pusey, B. J., & Arthington, A. H. (2003). Importance of the riparian zone to the conservation and management of freshwater fish: A review. *Marine and Freshwater Research*, *54*(1), 1–16.

Räpple, B., Piégay, H., Stella, J. C., & Mercier, D. (2017). What drives riparian vegetation encroachment in braided river channels at patch to reach scales? Insights from annual airborne surveys (Drôme River, SE France, 2005–2011). *Ecohydrology*, *10*(8), e1886. https://doi.org/10.1002/eco.1886

Reisinger, A. J., Blair, J. M., Rice, C. W., & Dodds, W. K. (2013). Woody vegetation removal stimulates riparian and benthic denitrification in tallgrass prairie. *Ecosystems*, *16*, 547–560. https://doi.org/10.1007/s10021-012-9630-3

Richardson, J. S., Holmes, P. M., Esler, K. J., Galatowitsch, S. M., Stromberg, J. C., Kirkman, S. P., Pyšek, P., & Hobbs, R. J. (2007). Riparian vegetation: Degradation, alien plant invasions, and restoration prospects. *Diversity and Distributions*, *13*(1), 126–139. https://doi.org/10.1111/j.1366-9516.2006.00314.x

Richardson, J. S., Naiman, R. J., & Bisson, P. A. (2012). How did fixed-width buffers become standard practice for protecting freshwaters and their riparian areas from forest harvest practices? *Freshwater Science*, *31*(1), 232–238. https://doi.org/10.1899/11-031.1

Riis, T., Kelly-Quinn, M., Aguiar, F. C., Manolaki, P., Bruno, D., Bejarano, M. D., Clerici, N., Fernandes, M. R., Franco, J. C., & Pettit, N. (2020). Global overview of ecosystem services provided by riparian vegetation. *BioScience*, *70*(6), 501–514. https://doi.org/10.1093/biosci/biaa041

Robertson, D. J., & Coll, M. (2019). Effects of Riparian invasive nonindigenous plants on freshwater quantity and ecological functioning in mesic temperate landscapes. *Natural Areas Journal*, *39*(1), 22–32. https://doi.org/10.3375/043.039.0102

Rodríguez-González, P. M., Abraham, E., Aguiar, F., Andreoli, A., Baležentienė, L., Berisha, N., Bernez, I., Bruen, M., Bruno, D., & Camporeale, C. (2022). Bringing the margin to the focus: 10 Challenges for riparian vegetation science and management. *Wiley Interdisciplinary Reviews: Water*, *9*(5), e1604. https://doi.org/10.1002/wat2.1604

Rohde, M. M., Albano, C. M., Huggins, X., Klausmeyer, K. R., Morton, C., Sharman, A., Zaveri, E., Saito, L., Freed, Z., Howard, J. K., Job, N., Richter, H., Toderich, K., Rodella, A.-S., Gleeson, T., Huntington, J., Chandanpurkar, H. A., Purdy, A. J., Famiglietti, J. S., … Stella, J. C. (2024). Groundwater-dependent ecosystem map exposes global dryland protection needs. *Nature*, *632*(8023), 101–107. https://doi.org/10.1038/s41586-024-07702-8

Rohde, M. M., Stella, J. C., Roberts, D. A., & Singer, M. B. (2021). Groundwater dependence of riparian woodlands and the disrupting effect of anthropogenically altered streamflow. *Proceedings of the National Academy of Sciences*, *118*(25), e2026453118. https://doi.org/10.1073/pnas.2026453118

Rohde, M. M., Stella, J. C., Singer, M. B., Roberts, D. A., Caylor, K. K., & Albano, C. M. (2024). Establishing ecological thresholds and targets for groundwater management. *Nature Water*, *2*(4), 312–323. https://doi.org/10.1038/s44221-024-00221-w

Rossatto, D., Silva, L., Sternberg, L., & Franco, A. (2014). Do woody and herbaceous species compete for soil water across topographic gradients? Evidence for niche partitioning in a Neotropical savanna. *South African Journal of Botany*, *91*, 14–18. https://doi.org/10.1016/j.sajb.2013.11.011

Rusnák, M., Goga, T., Michaleje, L., Šulc Michalková, M., Máčka, Z., Bertalan, L., & Kidová, A. (2022). Remote sensing of riparian ecosystems. *Remote Sensing*, *14*(11), 2645. https://doi.org/10.3390/rs14112645

Rutherford, J. C., Haidekker, S., Matheson, F. E., & Hicks, A. (2023). Modelled effects of channel orientation and tree canopy shape on average shade in streams. *New Zealand Journal of Marine and Freshwater Research*, *57*(1), 22–46. https://doi.org/10.1080/00288330.2021.1950193

Sabo, J. L., & Hagen, E. M. (2012). A network theory for resource exchange between rivers and their watersheds. *Water Resources Research*, *48*(4), W04515. https://doi.org/10.1029/2011WR010703

Sabo, J. L., McCluney, K. E., Marusenko, Y., Keller, A., & Soykan, C. U. (2008). Greenfall links groundwater to aboveground food webs in desert river floodplains. *Ecological Monographs*, *78*(4), 615–631. https://doi.org/10.1890/07-1382.1

Sabo, J. L., & Power, M. E. (2002). River–watershed exchange: Effects of riverine subsidies on riparian lizards and their terrestrial prey. *Ecology*, *83*(7), 1860–1869. https://doi.org/10.1890/0012-9658(2002)083[1860:RWEEOR]2.0.CO;2

Sabo, J. L., Sponseller, R., Dixon, M., Gade, K., Harms, T., Heffernan, J., Jani, A., Katz, G., Soykan, C., Watts, J., & Welter, J. (2005). Riparian zones increase regional species richness by harboring different, not more, species. *Ecology*, *86*(1), 56–62. https://doi.org/10.1890/04-0668

Sanzone, D. M., Meyer, J. L., Marti, E., Gardiner, E. P., Tank, J. L., & Grimm, N. B. (2003). Carbon and nitrogen transfer from a desert stream to riparian predators. *Oecologia*, *134*, 238–250. https://doi.org/10.1007/s00442-002-1113-3

Schindler, D. E., & Smits, A. P. (2017). Subsidies of aquatic resources in terrestrial ecosystems. *Ecosystems*, *20*(1), 78–93. https://doi.org/10.1007/s10021-016-0050-7

Schwarz, M., Lehmann, P., & Or, D. (2010). Quantifying lateral root reinforcement in steep slopes—From a bundle of roots to tree stands. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *35*(3), 354–367. https://doi.org/10.1002/esp.1927

Semlitsch, R. D., & Bodie, J. R. (2003). Biological criteria for buffer zones around wetlands and riparian habitats for amphibians and reptiles. *Conservation Biology*, *17*(5), 1219–1228. https://doi.org/10.1046/j.1523-1739.2003.02177.x

Silva, L., Hoffmann, W., Rossatto, D. R., Haridasan, M., Franco, A. C., & Horwath, W. R. (2013). Can savannas become forests? A coupled analysis of nutrient stocks and fire thresholds in central Brazil. *Plant and Soil*, *373*, 829–842. https://doi.org/10.1007/s11104-013-⟨?PMU?⟩1822-x

Silva, L., & Lambers, H. (2021). Soil-plant-atmosphere interactions: Structure, function, and predictive scaling for climate change mitigation. *Plant and Soil*, *461*(1), 5–27. https://doi.org/10.1007/s11104-020-04427-1

Silverthorn, T. K., & Richardson, J. S. (2021). Forest management impacts on greenhouse gas fluxes from riparian soils along headwater streams. *Ecosystems*, *24*(7), 1810–1822. https://doi.org/10.1007/s10021-021-00621-z

Simon, A., & Collison, A. J. (2002). Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. *Earth Surface Processes and Landforms*, *27*(5), 527–546. https://doi.org/10.1002/esp.325

Soykan, C. U., & Sabo, J. L. (2009). Spatiotemporal food web dynamics along a desert riparian–upland transition. *Ecography*, *32*(2), 354–368. https://doi.org/10.1111/j.1600-0587.2008.05615.x

Stecca, G., Zolezzi, G., Hicks, D. M., & Surian, N. (2019). Reduced braiding of rivers in human-modified landscapes: Converging trajectories and diversity of causes. *Earth-Science Reviews*, *188*, 291–311. https://doi.org/10.1016/j.earscirev.2018.10.016

Stella, J. C., & Bendix, J. (2019). Multiple stressors in riparian ecosystems. In S. Sabater, A. Elosegi, & R. Ludwig (Eds.), *Multiple stressors in river ecosystems* (pp. 81–110). Elsevier. https://doi.org/10.1016/B978-0-12-811713-2.00005-4

Stella, J. C., Hayden, M. K., Battles, J. J., Piégay, H., Dufour, S., & Fremier, A. K. (2011). The role of abandoned channels as refugia for sustaining pioneer riparian forest ecosystems. *Ecosystems*, *14*(5), 776–790. https://doi.org/10.1007/s10021-011-9446-6

Stella, J. C., Kui, L., Golet, G. H., & Poulsen, F. (2021). A dynamic riparian forest structure model for predicting large wood inputs to meandering rivers. *Earth Surface Processes and Landforms*, *46*(15), 3175–3193. https://doi.org/10.1002/esp.5229

Stream Solute Workshop. (1990). Concepts and methods for assessing solute dynamics in stream ecosystems. *Journal of the North American Benthological Society*, *9*(2), 95–119.

Stromberg, J. C., Lite, S. J., Marler, R., Paradzick, C., Shafroth, P. B., Shorrock, D., White, J. M., & White, M. S. (2007). Altered streamflow regimes and invasive plant species: The *Tamarix* case. *Global Ecology and Biogeography*, *16*(3), 381–393. https://doi.org/10.1111/j.1466-8238.2007.00297.x

Stromberg, J. C., Setaro, D. L., Gallo, E. L., Lohse, K. A., & Meixner, T. (2017). Riparian vegetation of ephemeral streams. *Journal of Arid Environments*, *138*, 27–37. https://doi.org/10.1016/j.jaridenv.2016.12.004

Sweeney, B. W., Bott, T. L., Jackson, J. K., Kaplan, L. A., Newbold, J. D., Standley, L. J., Hession, W. C., & Horwitz, R. J. (2004). Riparian deforestation, stream narrowing, and loss of stream ecosystem services. *Proceedings of the National Academy of Sciences*, *101*(39), 14132–14137. https://doi.org/10.1073/pnas.0405895101

Sweeney, B. W., & Newbold, J. D. (2014). Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: A literature review. *JAWRA Journal of the American Water Resources Association*, *50*(3), 560–584. https://doi.org/10.1111/jawr.12203

Treadwell, S. A., Koehn, J., & Bunn, S. (1999). Large woody debris and other aquatic habitat. In S. Lovett, & P. Price (Eds.), *Riparian land management technical guidelines* (pp. 79–96). LWRRDC.

Trigg, M. A., Bates, P. D., Wilson, M. D., Schumann, G., & Baugh, C. (2012). Floodplain channel morphology and networks of the middle Amazon River. *Water Resources Research*, *48*(10), W10504.

Urbanič, G., Politti, E., Rodríguez-González, P. M., Payne, R., Schook, D., Alves, M. H., Anđelković, A., Bruno, D., Chilikova-Lubomirova, M., Di Lonardo, S., Egozi, R., Garófano-Gómez, V., Gomes Marques, I., González del Tánago, M., Gültekin, Y. S., Gumiero, B., Hellsten, S., Hinkov, G., Jakubínský, J., … Dufour, S. (2022). Riparian zones—From policy neglected to policy integrated. *Frontiers in Environmental Science*, *10*, Article 868527. https://doi.org/10.3389/fenvs.2022.868527

US Army Corps of Engineers. (1987). *Corps of engineers wetlands delineation manual* (Y-87-1).

US Bureau of Land Management. (2017). *Riparian area management: Process for assessing proper functioning condition*. https://www.blm.gov/documents/national-office/blm-library/technical-reference/riparian-area-management-process-assessing

US Department of Agriculture. (2010). *GM_190_411—Part 411—Riparian zone recognition and management*. USDA. https://directives.sc.egov.usda.gov/viewerFS.aspx?id=2640

US Environmental Protection Agency. (2005). *National management measures to protect and restore wetlands and riparian areas for the abatement of nonpoint source pollution* (EPA 841-B-05-003). US EPA. https://www.epa.gov/sites/default/files/2015-10/documents/wetmeasures_guidance.pdf

US Fish and Wildlife Service. (2023). *Riparian*. https://www.fws.gov/glossary/riparian

Västilä, K., & Järvelä, J. (2018). Characterizing natural riparian vegetation for modeling of flow and suspended sediment transport. *Journal of Soils and Sediments*, *18*, 3114–3130. https://doi.org/10.1007/s11368-017-1776-3

Veach, A. M., Stegen, J. C., Brown, S. P., Dodds, W. K., & Jumpponen, A. (2016). Spatial and successional dynamics of microbial biofilm communities in a grassland stream ecosystem. *Molecular Ecology*, *25*(18), 4674–4688. https://doi.org/10.1111/mec.13784

Verry, E. S., Dolloff, C. A., & Manning, M. E. (2004). Riparian ecotone: A functional definition and delineation for resource assessment. *Water, Air, & Soil Pollution: Focus*, *4*, 67–94. https://doi.org/10.1023/B:WAFO.0000012825.77300.08

Vidon, P., Marchese, S., Welsh, M., & McMillan, S. (2015). Short-term spatial and temporal variability in greenhouse gas fluxes in riparian zones. *Environmental Monitoring and Assessment*, *187*, Article 503. https://doi.org/10.1007/s10661-015-4717-x

von Schiller, D., Bernal, S., & Martí, E. (2011). Technical note: A comparison of two empirical approaches to estimate in-stream net nutrient uptake. *Biogeosciences*, *8*(4), 875–882. https://doi.org/10.5194/bg-8-875-2011

Weissteiner, C. J., Ickerott, M., Ott, H., Probeck, M., Ramminger, G., Clerici, N., Dufourmont, H., & De Sousa, A. M. R. (2016). Europe's green arteries—A continental dataset of riparian zones. *Remote Sensing*, *8*(11), 925. https://www.mdpi.com/2072-4292/8/11/925

Williams, J. W., & Jackson, S. T. (2007). Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment*, *5*(9), 475–482.

Wohl, E. (2017). Bridging the gaps: An overview of wood across time and space in diverse rivers. *Geomorphology*, *279*, 3–26. https://doi.org/10.1016/j.geomorph.2016.04.014

Zhao, K., Coco, G., Gong, Z., Darby, S. E., Lanzoni, S., Xu, F., Zhang, K., & Townend, I. (2022). A review on bank retreat: Mechanisms, observations, and modeling. *Reviews of Geophysics*, *60*(2), e2021RG000761. https://doi.org/10.1029/2021RG000761

Zheng, X., Maidment, D. R., Tarboton, D. G., Liu, Y. Y., & Passalacqua, P. (2018). GeoFlood: Large-scale flood inundation mapping based on high-resolution terrain analysis. *Water Resources Research*, *54*(12), 10013–10033.

Zhou, S., Butenschoen, O., Barantal, S., Handa, I. T., Makkonen, M., Vos, V., Aerts, R., Berg, M. P., McKie, B., Van Ruijven, J., Hättenschwiler, S., & Scheu, S. (2020). Decomposition of leaf litter mixtures across biomes: The role of litter identity, diversity and soil fauna. *Journal of Ecology*, *108*(6), 2283–2297. https://doi.org/10.1111/1365-2745.13452

Zipper, S. C., Hammond, J. C., Shanafield, M., Zimmer, M., Datry, T., Jones, C. N., Kaiser, K. E., Godsey, S. E., Burrows, R. M., & Blaszczak, J. R. (2021). Pervasive changes in stream intermittency across the United States. *Environmental Research Letters*, *16*(8), 084033.

Zipper, S., Popescu, I., Compare, K., Zhang, C., & Seybold, E. C. (2022). Alternative stable states and hydrological regime shifts in a large intermittent river. *Environmental Research Letters*, *17*(7), 074005. https://doi.org/10.1088/1748-9326/ac7539

How to cite this article: Dodds, W. K., Barmuta, L. A., Bernal, S., Corman, J., Harms, T. K., Johnson, S. L., Li, L., Fernandes Cunha, D. G., Olden, J. D., Riis, T., Silva, L. C. R., Stella, J. C., Sullivan, P., & Wohl, E. (2025). Defining stream riparian zones across multidimensional environmental gradients. *Journal of Environmental Quality*, 1–24. https://doi.org/10.1002/jeq2.70080