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THE ROLE OF RIPARIAN VEGETATION IN PROTECTING AND IMPROVING CHEMICAL WATER QUALITY IN STREAMS[1]

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ABSTRACT: We review the research literature and summarize the major processes by which riparian vegetation influences chemical water quality in streams, as well as how these processes vary among vegetation types, and discuss how these processes respond to removal and restoration of riparian vegetation and thereby determine the timing and level of response in stream water quality. Our emphasis is on the role that riparian vegetation plays in protecting streams from nonpoint source pollutants and in improving the quality of degraded stream water. Riparian vegetation influences stream water chemistry through diverse processes including direct chemical uptake and indirect influences such as by supply of organic matter to soils and channels, modification of water movement, and stabilization of soil. Some processes are more strongly expressed under certain site conditions, such as denitrification where groundwater is shallow, and by certain kinds of vegetation, such as channel stabilization by large wood and nutrient uptake by faster-growing species. Whether stream chemistry can be managed effectively through deliberate selection and management of vegetation type, however, remains uncertain because few studies have been conducted on broad suites of processes that may include compensating or reinforcing interactions. Scant research has focused directly on the response of stream water chemistry to the loss of riparian vegetation or its restoration. Our analysis suggests that the level and time frame of a response to restoration depends strongly on the degree and time frame of vegetation loss. Legacy effects of past vegetation can continue to influence water quality for many years or decades and control the potential level and timing of water quality improvement after vegetation is restored. Through the collective action of many processes, vegetation exerts substantial influence over the well-documented effect that riparian zones have on stream water quality. However, the degree to which stream water quality can be managed through the management of riparian vegetation remains to be clarified. An understanding of the underlying processes is important for effectively using vegetation condition as an indicator of water quality protection and for accurately gauging prospects for water quality improvement through restoration of permanent vegetation.

(KEY TERMS: assessment; biogeochemistry; buffers; legacy effects; nonpoint source pollution; resilience; restoration; rivers/streams; soils; watershed management.)

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INTRODUCTION

Waterways throughout the United States (U.S.) contain excessive sediments and chemical pollutants (USEPA, 2000). Protecting supplies of clean water and improving the chemical quality of degraded waters for both human consumption and ecosystem health have become important policy goals in the U.S. and worldwide (NRC, 2002; Arthurton *et al.*, 2007). One strategy commonly advanced to achieve these goals is management of riparian vegetation. It is well documented that vegetated riparian zones can strongly influence the chemical contents of adjacent streams, particularly through the removal of nutrients in runoff from agricultural uplands (Dosskey, 2001; Hefting *et al.*, 2005; Baker *et al.*, 2006). Vegetation restoration and management in riparian zones is therefore widely recommended and promoted in agricultural areas to, in part, improve chemical water quality in streams (NRC, 2002).

However, the effective use of vegetation for water quality protection and improvement requires a broad understanding among land and water resource managers of the varied ways that riparian vegetation can affect water chemistry. A process-based knowledge of how riparian vegetation affects chemical water quality should help gauge the effectiveness of strategies that involve managing riparian vegetation, and we expect that perspective would be useful for water resource managers that need to address specific water quality targets, such as Maximum Contaminant Level and Total Maximum Daily Load, and administer water quality trading mechanisms that involve nonpoint source pollutants (USEPA, 2007). Diverse processes by which riparian vegetation influences water chemistry range from direct chemical uptake and cycling by plants to indirect influences such as by supply of chemically active detritus to soils and channels, modification of water movement, and stabilization of soil. The strength of each process varies with pollutant type (e.g., Dosskey, 2001), site condition (e.g., Vidon and Hill, 2004a), and vegetation type (e.g., Lyons *et al.*, 2000), and each process has a different time lag in its response to removal and restoration of permanent vegetation (e.g., Beschta and Kauffman, 2000; Gregory *et al.*, 2007). Consequently, the extent to which riparian vegetation influences water chemistry varies among situations, and the effect of vegetation restoration on water chemistry is similarly variable.

In this paper, we review the research literature and summarize the major processes by which riparian vegetation can influence chemical water quality in streams, as well as how these processes vary among vegetation types. Finally, we discuss how these processes respond to removal and restoration of riparian vegetation and thereby determine the timing and level of response in stream water quality.

LOCATION OF RIPARIAN VEGETATION-WATER INTERACTION

Landscape Position and Water Flow Paths

Riparian zones are lands adjacent to streams and shorelines, and through which overland and subsurface flow paths connect waterways with runoff from uplands. They typically occupy a small fraction of the landscape, but they often play a disproportionately important role in controlling water and chemical exchange between surrounding lands and stream systems (NRC, 2002; Burt and Pinay, 2005).

Water can converge on riparian zones from many directions. Precipitation falls on riparian zones. Some precipitation is intercepted by plant foliage and evaporated back to the atmosphere, but most of it reaches the soil. Overland and subsurface runoff from uplands flows laterally across riparian zones to streams. Overland runoff is generated when infiltration is limited by low soil permeability or its saturation. Subsurface flow occurs where infiltrated water accumulates in and saturates the subsoil and then flows laterally toward streams in response to water table gradients. Subsurface flow is more rapid through layers of relatively coarse, permeable strata, but subsurface flow is still much slower than overland flow. After reaching the channel, stream water may continue to interact with riparian zones. Channel water commonly flows into and out of bed sediments (i.e., hyporheic zone) and can pass laterally to varying distances under riparian zones (Winter *et al.*, 1998). Floods also transport channel water into riparian zones, both over the ground surface and through streambanks into the subsurface. The relative magnitudes of these water flow paths can exhibit wide variations that depend on specific local conditions (Burt, 1997; Winter *et al.*, 1998; Vidon and Hill, 2004b; Naiman *et al.*, 2005).

Vegetation Components

The spatial distribution of plant shoots, roots, and plant litter within a riparian zone and adjacent stream channel define the spatial dimensions of interaction between riparian vegetation and water (Figure 1). Aboveground vegetation and surface litter interact directly with precipitation, surface runoff,

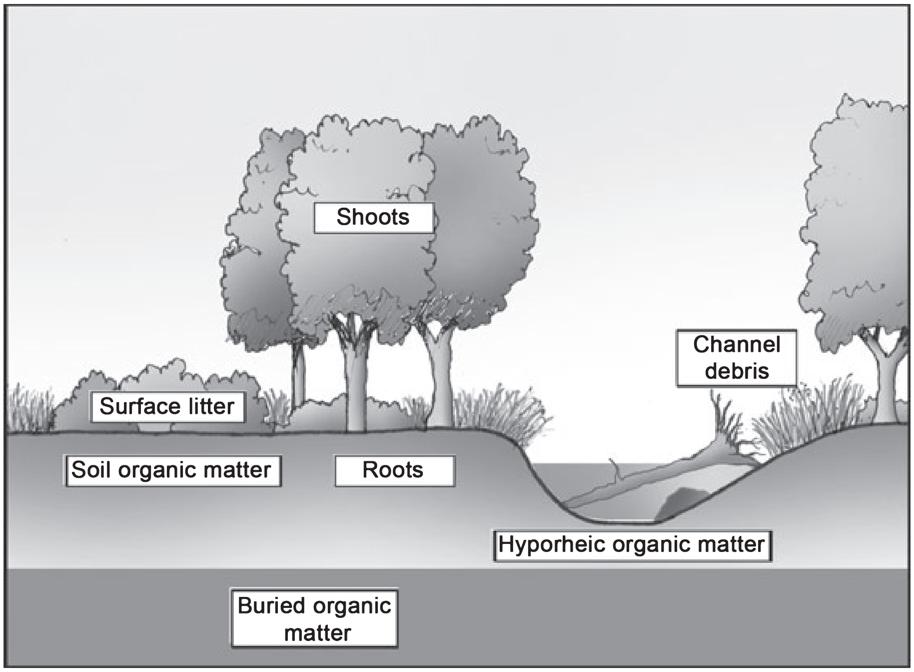

FIGURE 1. Major Components of Riparian Vegetation That Influence Stream Water Chemistry.

and flood waters in riparian zones. Root systems interact with soil water and with groundwater that is shallow enough for roots to reach. Roots of many plants have the potential to reach several meters deep into the soil (Sprackling and Read, 1979; Canadell *et al.*, 1996), but most roots occur in the upper 1 m of soil (Jackson *et al.*, 1996; Tufekcioglu *et al.*, 1999). Roots generally do not grow far below a water table due to lack of oxygen supply to their living tissues (Farrish, 1991; Baker *et al.*, 2001), so significant root interaction with groundwater probably is limited to the upper groundwater layer. Where large seasonal variation in water table depth occurs, roots may be found far below the water table during high water periods (Crawford, 1996).

Organic matter that drives many biogeochemical processes in riparian zones has a broad spatial distribution and can vary widely in age. Decaying aboveground vegetation and roots produce relatively young soil organic matter that can have a profound effect on chemical quality of soil water and groundwater. Vegetation generally decays *in situ* generating organic matter-rich surface soils. The depth of the root zone has traditionally been assumed to determine the depth limit of significant organic matter interaction with subsurface waters (Rotkin-Ellman *et al.*, 2004). However, buried organic matter can profoundly affect groundwater quality below the root zone (Devito *et al.*, 2000; Gurwick *et al.*, 2008a,b). Substantial amounts of organic matter can occur deep in the ground by accumulating over millennia or longer, such as in the evolution of peatlands, by burial of riparian vegetation and litter as channels migrate and develop floodplains, and by slow accumulation from deep-growing roots and illuvial soil organic matter (Blazejewski *et al.*, 2005). Once deposited, buried organic matter can remain chemically active for very long periods (Gurwick *et al.*, 2008b). At the extreme, Parkin and Simpkins (1995) found that present microbial decomposition of organic matter buried during the Pleistocene epoch sustains high methane concentrations in groundwater in Iowa.

Plant debris from riparian vegetation is a major source of organic matter to stream channels, particularly to headwater streams (Figure 1). For example, Dosskey and Bertsch (1994) estimated that a riparian forest contributed 93% of the total organic matter load exported annually in streamflow from a 12.6 km^2 watershed in South Carolina and that this export represented 10% of annual detritus production by the riparian forest. Large tree debris influences stream chemistry mainly through its affect on erosion and deposition of sediments, organic matter, and associated chemicals within channels. Tree stems, root wads, and large branches lodge in channels and provide roughness to the channel bed and bank toe-slopes that slows stream velocity and promotes stability and deposition (Harmon *et al.*, 1986). Finer debris, such as herbaceous litter, tree leaves, and twigs, can deposit in packs in channels or incorporate into bed sediments where they decompose and fuel chemical transformations within channels (Vannote *et al.*, 1980). Riparian vegetation supplies a declining proportion of stream organic matter as streams get larger and aquatic vegetation and other autochthonous sources increase (Cummins, 1975; Vannote *et al.*, 1980).

PROCESSES INVOLVING RIPARIAN VEGETATION

Chemical Uptake by Plants

Uptake of nutrients from the root zone by vegetation directly influences the supply of nutrients in water flowing through riparian zones (Figure 2). Vegetation demand is relatively large for nitrogen (N). Demand is smaller for phosphorus (P), potassium, calcium, magnesium, and sulfur, and minor for several other mineral elements (Mengel and Kirkby, 1982). From a water quality perspective, N and P have motivated widespread concerns because excesses of these nutrients in streams, lakes, and estuaries are common and create serious ecological stresses and public health risks. Reported estimates of uptake rates by forest and herbaceous vegetation in N-enriched riparian zones have ranged as high as 170 kg N/ha/year and accounted for major portions of the total input load to these riparian zones (e.g., Peterjohn and Correll, 1984; Tufekcioglu *et al.*, 2003; Hefting *et al.*, 2005). For P, estimates have ranged up to 49 kg P/ha/year (e.g., Peterjohn and Correll, 1984; Kelly *et al.*, 2007; Kiedrzyńska *et al.*, 2008).

Assimilated nutrients are stored in live tissues until death and decay. Periodic leaf drop, litterfall, and fine root turnover of perennial plants release only part of the N and P they contain during their physiologically active stage because these nutrients are re-mobilized to some extent into branches, stems, and large roots prior to senescence (Ericsson, 1994; Barnes *et al.*, 1998).

The magnitude of the nutrient uptake process varies as vegetation ages. The rate of nutrient uptake from soil is greatest when vegetation is growing vigorously, with leaf, stem, and root tissues rapidly adding biomass (Ericsson, 1994). Leaves and fine roots contain relatively greater concentrations of N and P than other plant parts. As vegetation matures and leaf cover fully occupies aerial space, leaf and fine root biomass growth slows and the uptake demand for nutrients declines (Vitousek and Reiners, 1975; Boggs and Weaver, 1994). During this stage of vegetation development, there is a decline in the rate at which vegetation absorbs and sequesters additional N and P (Kelly *et al.*, 2007). As stands of vegetation age beyond maturity, net nutrient assimilation into live vegetation may reach zero and even decline (Boggs and Weaver, 1994).

Nonnutrient chemicals are also absorbed from soil by plant roots. Heavy metals (e.g., Cd, Cr, Hg, Ni, Pb), metalloids (e.g., As, Se), and other elements (e.g., B, Cs, Sr) can also be taken up in small amounts and

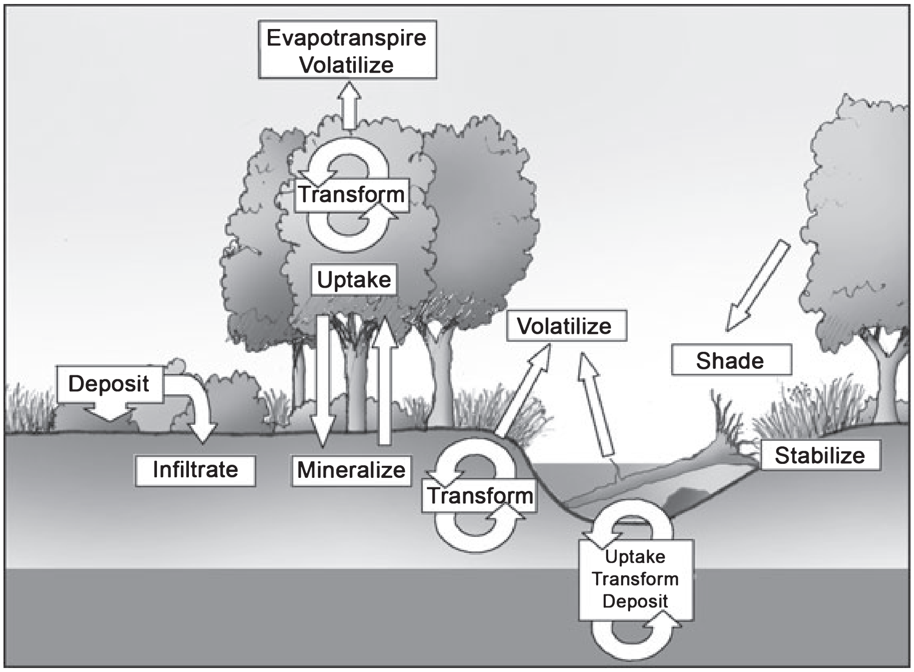

FIGURE 2. Processes Through Which the Major Components of Vegetation in Riparian and Channel Systems Influence Stream Water Chemistry.

sequestered in plant tissues (Adriano, 1986; Roca and Vallejo, 1995). Many of these elements are toxic to plants, but sublethal concentrations in plant tissues are common where they are present in soil in trace amounts. Like nutrient elements, they are released upon the death and decay of the plant tissues.

Other chemicals are taken up by plants but not returned to the soil through litterfall and decay. Plant uptake is an important process in the fate of many organic pesticides (Paterson and Schnoor, 1992) which are subsequently transformed and degraded within plant tissues (Lin *et al.*, 2004, 2008; Juraske *et al.*, 2008). Volatile organic compounds such as benzene, trichloroethylene, and toluene can be taken up by roots, translocated, and largely volatilized from leaves into the atmosphere (Burken and Schnoor, 1999). Similarly, selenium and organo-mercury compounds can be taken up by roots and then volatilized from leaves (Terry and Zayed, 1994; Hussein *et al.*, 2007).

Biogeochemical Processes in Soil

The decay of plant detritus produces soil organic matter that has enormous influence on chemical transport and transformations in soils (Figure 2). Decomposition of dead vegetation by heterotrophic microbes produces an array of humic substances that are resistant to further degradation, accumulate in soils, and are chemically active (McFee and Kelly, 1995). The assemblage of heterotrophic bacteria, fungi, and actinomycetes that perform decomposition also take part in chemical transformations in soil (Alexander, 1977).

Soil organic matter can retain dissolved substances from percolating water by ionic attraction, hydrogen and ligand bonding, and steric processes. Soil organic matter often contributes the majority of ion exchange capacity in soil even when it occurs in amounts as small as a few percent of soil mass (Brady and Weil, 2008). For mineral elements, these retention processes are more or less reversible and often represent temporary storage until they are absorbed and assimilated by plant roots and soil microbes, are re-dissolved by a change in soil conditions (e.g., pH, eH), or are displaced by mass input of other dissolved minerals and organic compounds. Many synthetic organic chemicals, such as agricultural pesticides and endocrine disruptors, bind strongly to and are immobilized by soil organic matter (Yamamoto *et al.*, 2003) and are subject to degradation by heterotrophic microbes that decompose plant litter (Smith *et al.*, 2008). For example, Benoit *et al.* (1999) found that soil organic matter content was one of the primary variables regulating the immobilization and degradation rate of the pesticide isoproturon in a vegetated buffer strip. Lin *et al.* (2008) found that more than 85% of applied atrazine was immobilized from leaching through soil, and up to 80% of the soil-retained atrazine was degraded to less toxic metabolites within 25 days.

The decay of plant litter also produces myriad small molecular weight compounds that affect the mobility of minerals in soil (Qualls and Haines, 1991). Acidic organic compounds, along with chelates exuded by plant roots, percolate through the soil and dissolve and desorb minerals from particle surfaces and mineral-humic complexes. Dissolved organic matter also contains nutrients and organo-mineral complexes and facilitates the transport of nutrients (e.g., N and P) and metals (e.g., Fe, Al, Cu, Zn, Pb) through soils and aquatic systems (Qualls *et al.*, 1991; Herbert and Bertsch, 1995; Huang *et al.*, 2008).

In wet and saturated soil, which commonly occurs in riparian zones, decomposition of plant detritus consumes the limited supply of oxygen, and as a result, microbes must switch to alternative electron acceptors such as nitrate, sulfate, and oxidized iron and manganese compounds to support further decomposition (Hill, 2000). As these compounds transform into chemically reduced forms, the solubility and mobility of these and other chemicals in soil change. For example, reduction of iron in iron-phosphate complexes causes phosphate to desorb into the soil solution; nitrate is reduced to ammonium or to nitrous oxide and nitrogen gas; sulfate reduction produces sulfides of iron and hydrogen; decomposition produces methane, and methyl-mercury if mercury contamination is present in the soil (Duff and Triska, 2000; Hill, 2000). Decomposition proceeds more slowly under anaerobic conditions. Incomplete decomposition (common under anaerobic conditions) and the absence of oxidized iron and aluminum to bind and immobilize organic matter leads to a buildup of dissolved organic compounds. Many of these compounds have appreciable contents of nitrogen, phosphorus, and other minerals. Together, these anaerobic processes produce soil solutions that are relatively enriched with ammonium forms of nitrogen, dissolved phosphate, reduced sulfur compounds, and dissolved organic matter (including organic N and P) compared to aerobic soil solutions and pass from riparian soils to streams (Hill, 2000).

Denitrification can be a major pathway of N removal from N-enriched groundwater in riparian zones. For example, Lowrance *et al.* (1984) estimated a denitrification rate of 31.5 kg N/ha/year in a riparian forested wetland compared to a plant uptake rate of 51.8 kg N/ha/year. In a recent study of multiple riparian sites across Europe, denitrification commonly accounted for greater N removal than plant uptake on wetter sites (Hefting *et al.*, 2005).

Denitrification was the primary mechanism for nitrate removal rates of 12 to 291 kg N/ha/year that were measured during high water-table periods at several riparian sites in Ontario, Canada (Vidon and Hill, 2004a,b). In riparian soil containing sufficient labile organic matter, denitrification rate can increase greatly in response to increased inorganic N inputs (Jordan *et al.*, 1998; Ettema *et al.*, 1999). High nitrate removal rates, primarily by denitrification, have also been observed in deeper groundwater where buried organic matter occurs below the root zones of existing vegetation (Devito *et al.*, 2000; Hill *et al.*, 2004; Gurwick *et al.*, 2008a).

Chemical Transport Into Root Zones

Vegetation also affects the transport of chemicals by mediating water flow and distribution in riparian zones. Infiltration of precipitation and overland runoff transports dissolved and colloid-associated chemicals into the root zone where they can interact with soil minerals, living roots, soil organic matter, and microbes. Infiltration is improved by the presence of vegetation (Bharati *et al.*, 2002; Wilcox *et al.*, 2003; Bartens *et al.*, 2008). Plant stems and litter at the ground surface create roughness that retards overland flow and increases concentration time for water to infiltrate the soil. The action of root growth and decay and of burrowing by macroinvertebrates grazing on roots and litter increase the permeability of the soil by creating large pores through which water can easily flow. Stems and plant litter at the soil surface also promote infiltration by providing roughness that slows overland flow and disperses it more widely across the riparian soil surface. A prominent view is that vegetation, particularly grass, disperses convergent, or concentrated, overland flows (Lowrance *et al.*, 1995). Even though spreading patterns may not occur (Dosskey *et al.*, 2002), vegetation may nevertheless impede the tendency of overland flow to converge (Dillaha *et al.*, 1989; Dabney *et al.*, 2004).

Infiltration of overland flow strongly promotes the deposition of sediments and sediment-bound chemicals carried in overland runoff. Infiltration reduces runoff volume and its physical capacity to carry sediment, so excess sediment deposits on the ground surface (Hayes *et al.*, 1984; Lee *et al.*, 1989). The deposited sediments eventually become overgrown by vegetation and the associated chemicals become part of the root zone pool and subject to soil biogeochemical processes (Sharpley and Rekolainen, 1997).

Rainfall interception and transpiration by live vegetation enhances infiltration capacity of soil by enabling the soil to absorb greater amounts of water before becoming saturation-limited. Foliage and stems can intercept and evaporate significant amounts of rainfall and prevent it from reaching the soil (Lull, 1964; Tabacchi *et al.*, 2000). Water uptake from the root zone dries the soil further. It is well established that vegetation increases evapotranspiration from watersheds (Borman and Likens, 1979; Trimble *et al.*, 1987) and riparian zones (Cleverly *et al.*, 2006; Kellogg *et al.*, 2008). Drier riparian soils are capable of infiltrating and temporarily storing a greater volume of overland flow than wet soils.

Evapotranspiration by riparian plants can lower water tables and reduce contact between groundwater and the root zone. In some cases, water table recession may substantially reduce groundwater flow into the receiving stream channel (Kellogg *et al.*, 2008). Vegetation may also draw stream water out of the channel through the hyporheic zone and into the riparian zone (Rood and Mahoney, 1995). Groundwater movement to roots draws nutrients and other chemical solutes into the root zone where they become subject to plant uptake and soil transformations (Kellogg *et al.*, 2008).

Periodically, floods transport chemical-laden stream water back into riparian zones and under the influence of vegetation-mediated process described above. Vegetation in riparian zones slows overbank streamflow and promotes deposition of sediment and the infiltration of chemicals entrained in flood water. For example, Brunet *et al.* (1994) estimated that the floodplain and riparian zone of a 25 km reach of a seventh-order river retained 10 to 20% of the suspended sediment and particulate N load carried into that reach during two floods. Even though the riparian zone occupied only 6 to 7% of the floodplain, the riparian zone was responsible for the majority of retention. Dissolved nutrients and other chemicals associated with riparian soils and litter can be mobilized into flood waters (Baldwin and Mitchell, 2000; Roulet *et al.*, 2001). During longer-duration floods, anaerobic processes can be temporarily boosted in the riparian soil. As the flood recedes, floodplain soil water and its dissolved contents slowly drain back into the channel.

Channel Stability and Instream Biogeochemical Processes

When streambanks erode, the pool of nutrients and other chemicals stored in the bank soil washes into channels and contributes to the chemical load in streams. In some locations, streambank erosion is the main source of sediment and phosphorus to stream water (Svendsen *et al.*, 1995; Sekely *et al.*, 2002; Laubel *et al.*, 2003). However, few studies have quantified the relative contributions of bank erosion to total stream load of chemicals and this prevents an estimation of the extent of this problem in agricultural regions.

Riparian vegetation helps to stabilize and protect streambanks from the erosive force of flowing stream water and wave action (Thorne, 1990; Beeson and Doyle, 1995). Roots of riparian vegetation increase cohesion in sloping banks while shoots and surface litter protect the soil surface (Thorne, 1990). Large woody debris, created by the toppling of riparian trees into channels, provides additional channel stability in several ways (Thorne, 1990). Stable logs and root wads protect toeslopes and channel beds from erosion. The roughness they create slows water velocity around them and promotes deposition of sediment. Channel aggradation that results from sediment deposition reduces bank height and diminishes the force of weight that can cause block erosion. Deposition also removes sediment-bound chemicals from the water column, and soil organic matter associated with sediments originating from upstream banks and hillslopes contribute to biogeochemical processes (described below) in the stream channel. Conversely, the upturning of tree root wads and stream turbulence around logs create localized channel and bank erosion in the short term (Thorne, 1990; Trimble, 1997b; Lyons *et al.*, 2000).

The degree to which vegetation can stabilize streambanks is determined by fluvial forces and landscape geomorphic trends. Channels that are actively incising and widening are often too unstable for riparian vegetation to stabilize. Incision and widening below the depth of the root zone can undermine a bank to the point where gravitational force overwhelms the tensile reinforcement provided by plant roots resulting in block erosion into the channel (Thorne, 1990). High storm flows periodically scour surface vegetation, litter, and soil from banks. Some streams experience naturally high rates of channel and bank erosion, such as is common in the arid southwestern U.S. High rates of channel and bank erosion are also a response to increased runoff and storm flows resulting from extensive land development and channel modifications for urban and agriculture purposes (Simon, 1989; Trimble, 1997a; Walter and Merritts, 2008). Even along relatively stable streams, vegetation does not halt channel and bank erosion entirely. Bank erosion rates between 28 and 56 metric tons/year/km of bank are considered typical background rates for banks of relatively stable natural streams (FISRWG, 1998).

Organic matter in channel sediments fuels the same biogeochemical processes that occur in soil (e.g., immobilization, denitrification, organic degradation) and these processes often proceed fast enough to significantly affect stream water quality (Hill, 1979; Mulholland, 1992, 2004; Jansson *et al.*, 1994; Peterson *et al.*, 2001; Bernhardt *et al.*, 2003). For example, Mulholland (2004) found that about 20% of the nitrate and 30% of the soluble reactive P that annually entered a first-order forest stream were removed from streamflow largely through uptake and assimilation by microbes colonizing leaf detritus. The continual supply of oxygenated channel water can sustain rapid litter decomposition rates in stream channels (Dobson *et al.*, 2004). Anaerobic processes such as denitrification can also develop within organic-rich bed sediments and debris packs that have limited permeability to oxygenated stream water (Fisher and Likens, 1972). Where the supply of organic matter is abundant, the retention rate of inorganic nutrients in streams can increase in response to an increase in terrestrial nutrient inputs (Bernhardt *et al.*, 2003), thereby compensating for increased input loads and dampening the downstream response (Bernhardt *et al.*, 2003; Mulholland, 2004).

Channel aggradation and accumulations of plant debris in small channels can also alter chemical processing in adjacent riparian zones (Bilby and Likens, 1980; Trotter, 1990; Warren and Kraft, 2008). Aggrading channels and debris dams raise the water table in adjacent riparian zones and can potentially increase the connection between nutrient-enriched groundwater and biogeochemically active root zones.

INFLUENCE OF VEGETATION TYPE

Direct and indirect influences of vegetation such as nutrient uptake, organic matter supply, and soil stabilization are strongly related to structural and physiological characteristics of vegetation. As plants vary widely in size, form, growth rate, longevity, and litter quality, their influences on stream water chemistry may range widely as well. This has practical significance because vegetation can be manipulated easily through selection and management. Despite its significance, there have been few direct comparisons of how much stream water chemistry can be managed through the deliberate selection and management of vegetation types.

A major distinction is commonly drawn between herbaceous and woody types of vegetation (e.g., Lyons *et al.*, 2000). Woody plants generally are much larger, taller, longer-lived, and their stems grow more widely spaced than herbaceous plants, and, woody litter generally decomposes more slowly than herbaceous litter. A similarly distinct difference in their effect on riparian groundwater and stream chemistry, however, is much less clear. To date, there has been no comparative study of vegetation types on the combined effect of all vegetation influences on stream water chemistry. The body of comparative research typically divides between a focus on processes that occur within riparian zones (e.g., Lowrance *et al.*, 1984; Hefting *et al.*, 2005) and on processes that occur within stream channels (e.g., Mulholland, 2004; Sweeney *et al.*, 2004).

Nutrient Uptake by Vegetation

Nutrient uptake and sequestration is correlated strongly with biomass production and there is substantial variation among species and cultivars (Broadmeadow and Nisbet, 2004; Missaoui *et al.*, 2005; Kelly *et al.*, 2007). For example, a riparian stand of fast-growing cottonwood trees accumulated 194 kg P/ha over four years compared to 43 kg P/ha for alfalfa and two kinds of grasses (Kelly *et al.*, 2007). Tufekcioglu *et al.* (2003) measured nitrogen immobilization rates of 37 kg N/ha/year for hybrid poplar in a riparian zone compared to 16 kg N/ha/year for switchgrass. Missaoui *et al.* (2005) found tissue P concentrations ranging from 2.8 to 9.8 g P/kg among 30 cultivars of switchgrass, suggesting that stand-level nutrient accumulation rates may also vary substantially between cultivars of the same species.

Nutrient accumulation rate levels off at a younger stand age for herbaceous vegetation than for trees (Broadmeadow and Nisbet, 2004; Kelly *et al.*, 2007; Bush, 2008). For example, Kelly *et al.* (2007) found that biomass and P accumulation by switchgrass and alfalfa stands stabilized four years after planting while P accumulation in a cottonwood stand continued to accelerate. Periodic harvest of vegetation sustains high rates of nutrient uptake (Hefting *et al.*, 2005; Kelly *et al.*, 2007; Kiedrzyńska *et al.*, 2008). For example, Hefting *et al.* (2005) found that periodic mowing exported 85 to 93% of N taken up each year by grasses. Kelly *et al.* (2007) estimated that harvest of riparian vegetation every four years would remove 62 kg P/ha from an herbaceous riparian zone and 104 kg P/ha from a zone that also included cottonwood trees.

Organic Matter Supply in Soil

Soil organic matter supply is correlated with biomass production. Stands of faster-growing woody plants such as hybrid poplar produce biomass (above and below ground) at faster annual rates than grasses such as switchgrass (Tufekcioglu *et al.*, 2003). The distribution of roots in riparian soils influences the spatial distribution (e.g., depth) of organic matter in soil, as well as chemical uptake by plants. While roots of woody plants are, on average, capable of penetrating deeper into soil profiles than herbaceous plants (Weaver, 1968; Canadell *et al.*, 1996), there is extremely high variability among species within these general vegetation types (Weaver, 1968; Sprackling and Read, 1979; Canadell *et al.*, 1996; Simon and Collison, 2002). In riparian zones, site conditions like shallow water table (i.e., low oxygen) or shallow bedrock, rather than genetic capability, often determine the depth limit to which roots will grow (Canadell *et al.*, 1996; Lyons *et al.*, 2000; Wynn *et al.*, 2004). Tree roots can also extend laterally up to many meters from trunks (Sprackling and Read, 1979) and affect chemical cycling in adjacent herbaceous-covered areas (Addy *et al.*, 1999).

Decomposition rate affects the production of labile and chemically active soil organic matter and the release of nutrients stored in plant biomass. Decomposition of woody detritus, especially from coniferous species, is slower than for herbaceous detritus due in part to its larger size and to higher C:N, lignin, and tannin contents (Collen *et al.*, 2004; Beets *et al.*, 2008).

Chemical Transport Into Root Zones

Vegetation types may differ in how they affect hydrologic processes related to infiltration of chemicals into soil. Some evidence indicates that soil porosity is greater under trees than under grass (Trimble and Mendel, 1995; Tabacchi *et al.*, 2000; Udawatta *et al.*, 2006), but this may be related more to the length of time since vegetation establishment than to vegetation type, as others have reported no differences between similar-aged stands of forest and grasses (Kumar *et al.*, 2008) and it can take years for improved porosity to develop (Schultz *et al.*, 2004; Dosskey *et al.*, 2007). Roughness of the ground surface that slows overland flow and increases infiltration time varies with vegetation type due to differences in height, stem density, and stiffness (Engman, 1986; Jin *et al.*, 2000) and in amount and size of plant litter (France, 1997). Forest vegetation may produce greater roughness (i.e., higher Manning's n) than grasses (SCS, 1986; Welle and Woodward, 1986), but variability can be high depending on the density of woody vegetation and the amount of forest litter (Welle and Woodward, 1986; France, 1997). Taller vegetation will maintain its frictional influence on deeper runoff or flood flows because submergence of vegetation and litter greatly reduces its ability to retard overland flow velocity (Jin *et al.*, 2000). Forest vegetation, particularly evergreen coniferous forest, intercepts and transpires more water than herbaceous vegetation enabling the soil beneath to absorb greater amounts of water before becoming saturated (Swank and Douglass, 1974; Simon and Collison, 2002; Huxman *et al.*, 2005). Evapotranspiration by trees is further enhanced by exposure to wind when located adjacent to shorter herbaceous and shrubby vegetation (Allen *et al.*, 1998). Water infiltration differences have also been observed among grass species and tied to differences in water use (Self-Davis *et al.*, 2003). Based on individual hydrologic components (i.e., porosity, roughness, and soil dryness) infiltration of overland flow should be generally greater under forest vegetation than under herbaceous vegetation. In one comparative study, however, no significant difference was observed (Dosskey *et al.*, 2007).

Retention of Chemicals in Riparian Zones

In general, there appears to be no strong difference between woody and herbaceous vegetation as controls on nutrient movement across vegetated riparian zones (Mayer *et al.*, 2007). For overland flow, woody litter and herbaceous vegetation on the riparian soil surface yield similar reductions in sediment and chemical transport and in soil erosion (Uusi-Kämppä and Yläranta, 1996; Uusi-Kämppä *et al.*, 2000; Udawatta *et al.*, 2002; McKergow *et al.*, 2004, 2006; Dosskey *et al.*, 2007), and yield similar sediment deposition on floodplains (Jeffries *et al.*, 2003; Sweeney *et al.*, 2004). Dense tree cover can suppress herbaceous growth and, if not replaced by sufficient woody litter, can reduce infiltration and sediment deposition and expose riparian soil to greater erosion (Abrahams *et al.*, 1995; Parsons *et al.*, 1996; Lyons *et al.*, 2000; McKergow *et al.*, 2004, 2006). For retaining chemicals from groundwater, several reviews of the literature have reported no consistent difference between woody and herbaceous vegetation types among studies (Correll, 1997; Lyons *et al.*, 2000; Dosskey, 2001). More recently, a comparative study at several sites across Europe indicated that nitrogen removal from shallow groundwater flow was greater in forested than in herbaceous riparian zones (Hefting *et al.*, 2005). These authors attributed the difference to faster plant assimilation and slower mineralization from litter in forest, as a companion study found no difference in soil denitrification rates (Sabater *et al.*, 2003). Inconsistent results across many study conditions suggest that groundwater chemistry is less sensitive to vegetation type than to variation in other site characteristics (Lyons *et al.*, 2000; Clément *et al.*, 2002; Dukes *et al.*, 2002; Young and Briggs, 2005). Many of these site variables, including topography, soil type, water table depth, and aquifer characteristics, are discussed in detail in Vidon and Hill (2004a,b).

Channel Stability and Instream Biogeochemical Processes

While herbaceous vegetation can effectively protect and stabilize surface soils from scouring erosion by overland flow and floods, woody plants may be better for stabilizing high, steep banks from mass failure (Lyons *et al.*, 2000). Woody plants generally have larger, stronger, and deeper roots that increase bank shear strength to greater depth than herbaceous plants (Waldron and Dakessian, 1982; Waldron *et al.*, 1983; Docker and Hubble, 2008), but grasses increase shear strength near the soil surface to a greater degree and more quickly after establishment (Simon and Collison, 2002). Along unstable streams, woody plants have been observed to be more effective than herbaceous vegetation at reducing high bank erosion rates (Harmel *et al.*, 1999; Geyer *et al.*, 2000; Zaimes *et al.*, 2004, 2006). However, a mix of woody and herbaceous vegetation has been suggested to provide the best overall capability for bank stabilization (Simon and Collison, 2002).

Differences between vegetation types that affect channel erosion and sediment deposition are reflected in patterns of channel morphology. Herbaceous riparian vegetation tends to produce narrower and deeper stream channels while forested riparian zones tend to produce wider and shallower channels (Trimble, 1997b; Lyons *et al.*, 2000; Hession *et al.*, 2003; Sweeney *et al.*, 2004). An implication is that conversion of grass vegetation in a riparian area to forest will increase bank erosion as the channel adjusts to a wider condition, and conversely, that conversion of forest to grasses will promote sediment deposition (Trimble, 1997b; Lyons *et al.*, 2000). On larger streams and rivers, however, this vegetation effect diminishes or even reverses (Davies-Colley, 1997; Anderson *et al.*, 2004).

Riparian trees contribute more debris, especially coarse debris, to stream channels than herbaceous vegetation (Vannote *et al.*, 1980; Lyons *et al.*, 2000; Sweeney *et al.*, 2004). Woody debris creates roughness that reduces stream erosive power (Bennett *et al.*, 2008) and creates debris dams that increase sediment deposition in channels and increase flooding frequency that promotes sediment deposition on floodplains (Wallerstein *et al.*, 1997; Jeffries *et al.*, 2003). Woody debris can be carried downstream to affect nonforested reaches (Trimble, 1997b). Trees and taller woody shrubs on floodplains create greater roughness and flow resistance against deeper floods than herbaceous vegetation (Chow, 1959; Chow *et al.*, 1988; Dudley *et al.*, 1998).

Trees have been associated with both lesser and greater chemical processing activity in stream channels than herbaceous vegetation. Forest shade can suppress algal growth and its uptake of inorganic nutrients and reduce photolysis of organic chemicals in small streams (Sabater *et al.*, 2000; Sweeney *et al.*, 2004). However, riparian forest may compensate for shading effects by promoting a greater reactive channel surface area (wider channel) and greater organic matter contributions that fuel microbial and chemical processing in streams. For example, Sweeney *et al.* (2004) found that the net effect of vegetation type on channel processes produced similar phosphate and pesticide disappearance and greater ammonium assimilation in forested reaches than in grassed reaches of streams in Maryland and eastern Pennsylvania.

WATER QUALITY RESPONSE TO RESTORATION OF RIPARIAN VEGETATION

A matter of great practical importance is the question of how degraded water quality will respond to restoration of permanent vegetation in riparian zones. Major conservation programs in the U.S., such as the Conservation Reserve Program and the Environmental Quality Incentives Program, have promoted the conversion of cleared riparian farmland to permanent vegetation to, in part, reduce the load of chemicals and sediments in streams. An understanding of the full range of influences by which vegetation affects water chemistry is important for properly assessing prospects for water quality improvement.

The response to restoration of vegetation is determined to a large extent by how much degradation of the original vegetation-related processes has occurred following clearing of the riparian zone. Restoration, then, builds upon whatever components and processes remain (Figure 3). Despite the large number of studies that have measured chemical retention in vegetated riparian zones, very few have directly examined water quality responses to the removal of riparian vegetation or to its restoration – a critical research need that was identified almost a decade ago (Dosskey, 2001). However, enough is known now about the individual processes involved that we can speculate on some general patterns of response.

Patterns of Degradation and Restoration

The overall response of stream water chemistry to removal of riparian vegetation accrues as a cumulative response by many individual processes (Figure 3). When vegetation is removed, some individual processes are immediately disrupted while others continue to function normally for a time. For example, removal of the live vegetation (i.e., shoots) from a riparian zone will immediately halt plant uptake and evapotranspiration, but infiltration and soil chemical processes that stem from soil pore development and from litter and soil organic matter accumulations will

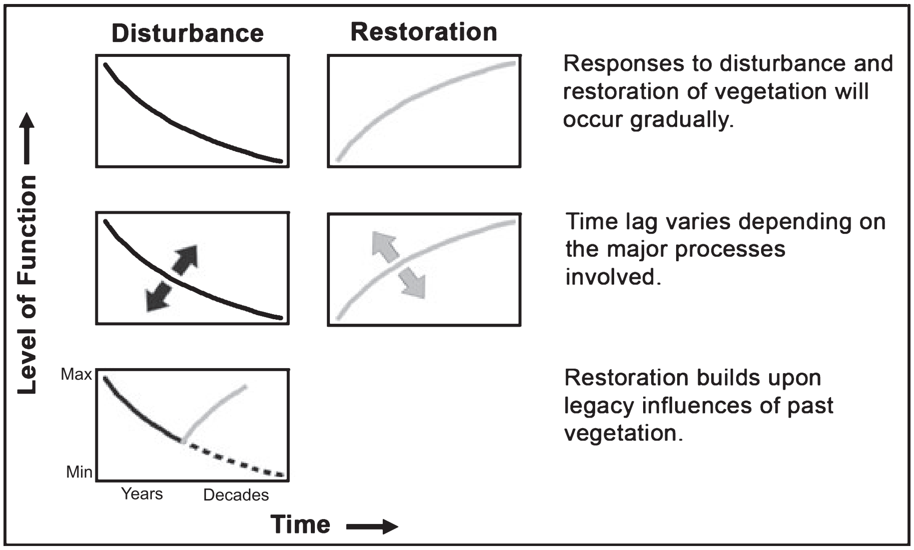

FIGURE 3. A Simple Hypothetical Example of How a Diversity of Individual Processes and Corresponding Time-Lag Responses Can Determine the Level and Timing of Stream Water Chemistry Response to Disturbance and Restoration of Riparian Vegetation. This example describes a biogeochemically resilient system in which processes recover to preexisting levels. In less resilient cases, restoration will not mirror the trajectory of disturbance and full recovery of function will not occur (Scheffer *et al.*, 2001; Suding *et al.*, 2004).

not decline as quickly. Instream processes likewise will proceed for a time despite an interruption to litter supply. Elimination of riparian vegetation for a few years may be necessary to substantially degrade soil cohesion through decay of roots (Watson *et al.*, 1999), for many years or decades to significantly reduce soil organic matter stocks (Matson *et al.*, 1997), and for centuries to decay and eliminate large woody debris (Harmon *et al.*, 1986; Stone *et al.*, 1998). Time lags, such as these, will dampen the immediate impact of vegetation removal on stream chemistry and substantially delay its ultimate level of degradation (Gregory *et al.*, 2007). Very long time frames may be necessary for the effects of vegetation removal to become fully manifested.

Time frame and level of degradation of water quality will vary from situation to situation depending on the major processes involved in each case. For example, the removal of live vegetation would have a greater and more immediate effect in a situation where immobilization and transformation are influenced more by plant uptake than by soil organic matter. For nitrate, plant uptake may be relatively more important on dry sites than on wet sites where soil organic matter helps to create anaerobic soil conditions and denitrification becomes important. Conversely for phosphate, plant uptake may be more important on wet sites where reducing conditions dissolve phosphate from iron complexes than on dry sites where mineral fixation remains strong. Site conditions and chemical type are major determinants of which vegetative components and processes are more important.

For restoration, the time frame and potential level of water quality response will depend on how much degradation occurred following clearing of the riparian zone as well as on how quickly restoration of live vegetation can restore the effective components and processes (Figure 3). For example, removal of the current stand of live vegetation by a single harvest will halt uptake and evapotranspiration processes, but they can be quickly restored by regrowth. Nodvin *et al.* (1988) reported that nutrient and water retention took about six years to fully recover after forest clearcutting and herbicide application. Prolonged removal of riparian vegetation, such as what occurs after conversion to row cropping, reduces surface litter, soil organic matter stocks, and channel organic matter which may require many years to centuries to fully recover after the restoration of permanent vegetation (Matson *et al.*, 1997; Hooker and Compton, 2003). Soil porosity and organic matter content can take many years or decades to redevelop (Seguin *et al.*, 2006). Regrowth of mature forest and production of large woody debris can take decades or centuries (Beschta and Kauffman, 2000; Gregory *et al.*, 2007). In some situations, disturbance may cause irreversible changes and effective components and processes never fully recover (Scheffer *et al.*, 2001; Dupouey *et al.*, 2002; Suding *et al.*, 2004). For example, removal of riparian vegetation that coincides with runoff-enhancing climate change and agricultural and urban development in uplands may initiate channel incision that permanently lowers the riparian water table to below the root zone. Restoration of riparian vegetation, in this case, may not include the original vegetation types and may not reconnect groundwater with the root zone and root zone processes to the original degree. Furthermore, accelerated bank erosion may remove the restoration zone before slowly accruing vegetative components, such as soil organic matter and large wood, are restored to their original status. In these examples, stream chemistry will not be resilient and return to its original condition.

Long lag times for the degradation of some vegetative components and related processes means that vegetation continues to influence water chemistry long after live vegetation has been cleared from a riparian zone, and, that restoration will build upon the residual. For situations where the degradation is relatively mild, such as the removal of live vegetation for only a few years, overall water quality response to vegetation restoration will likely be relatively small and quick (Figure 3). For example, a one-time tree removal in a riparian forest followed immediately by tree planting and herbaceous regrowth showed little effect on the flow of water and sediment (Sheridan *et al.*, 1999), pesticides (Lowrance *et al.*, 1997), and nitrate and ammonium (Hubbard and Lowrance, 1997) in overland and groundwater flow originating from an agricultural field (Lowrance *et al.*, 2000). Yeakley *et al.* (2003) found that no changes occurred in riparian groundwater nitrate concentration over three years following removal of riparian shrubs, despite a fourfold increase in nitrate concentration in groundwater on adjacent hillslopes. In contrast, stream sediment loads may respond substantially and quickly to riparian restoration. For example, McKergow *et al.* (2003) found that vegetation restoration of denuded and livestock-trampled riparian zones reduced catchment export of sediment from over 100 kg/ha/year to less than 10 within one year mainly by reducing bank erosion and stabilizing the stream channel. For more extreme circumstances, such as longer periods of absent vegetation and loss of surface litter and channel debris, there will be relatively greater potential for improvement, but it may take much longer to achieve. For example, long-term clearing and cultivation of annual crops in a riparian zone followed by restoration to grass vegetation yielded a 35% reduction in nitrate concentration in groundwater and 83, 73, and 92% reductions in nitrate, total P, and sediment concentrations, respectively, in overland flow through the riparian zone in the three years following restoration (Clausen *et al.*, 2000). In this latter study, however, it is not clear how much of the nitrate response might have been due simply to halting annual fertilizer amendments within the riparian zone, and, there is no indication of how much more improvement is possible beyond the initial three year period.

The potential for complex and dynamic water quality response to riparian restoration was demonstrated in a long-term study of a pasture having a trampled and overgrazed riparian zone that was subsequently fenced off from livestock. Howard-Williams and Pickmere (1994) observed that rapid herbaceous regrowth, including aquatic macrophytes, during the initial five years stabilized the bank and channel bed and stream nutrient levels declined. Between 5 and 12 years, woody vegetation became established, stream blockages by debris became common, and nutrient levels declined further. From 13 to 17 years, debris blockages became less common, aquatic macrophytes became shaded out, and nutrient levels increased. The authors speculated that there would be a further 10 years of change until stable forest vegetation conditions prevailed. In this study, a long time frame was required to encompass most of the water quality response to the restoration of riparian vegetation. The water quality response was uneven over that time frame, characterized by rapid initial improvement, which slowed, and then reversed as various vegetation-mediated processes manifested themselves at different times. For water managers, this suggests that a high and stable water quality function of restored vegetation may take many years to achieve. For monitoring and research, long time frames may be required to properly assess water quality response to the loss and re-establishment of riparian vegetation.

CONCLUSIONS

Riparian vegetation influences stream water quality in many ways, from direct chemical uptake and cycling by live plants to indirect influences of plant detritus on soil and channel chemistry, water movement, and erosion. These influences are exerted both within the riparian zone and in adjacent stream channels. Some of them improve water quality (e.g., uptake and denitrification of excess N) and some do not (e.g., anaerobic mobilization of methyl-mercury and dissolved P into stream water). Through a broad range of processes, vegetation exerts substantial influence over the well-documented effect that riparian zones have on water chemistry.

While vegetation, in general, plays an important role, it remains uncertain how much the chemical quality of stream water can be managed through selection of the type of riparian vegetation. Some specific processes are more strongly expressed by certain vegetation types, such as channel stabilization by large wood and nutrient uptake by faster-growing species. However, the overall effects on stream water chemistry are uncertain due to the lack of comparative research into broader suites of processes that could involve compensating or reinforcing interactions. For reducing nitrate in shallow groundwater, lack of a consistent difference among many studies between forest and herbaceous vegetation suggests that other factors, including site conditions and perhaps species variability, are more important than gross vegetation type. More research is clearly needed to clarify the relative merits of different vegetation options on stream water chemistry.

Despite a large body of research into water quality functions of riparian zones and the existence of large programs that promote restoration of permanent riparian vegetation in developed landscapes, there have been few direct studies of the responses of stream water chemistry to the loss of riparian vegetation and to its restoration. Our analysis suggests that the level and time frame of water quality improvement depends on the type of pollutant and the processes that act on it, site conditions that determine how important each process is, and the amount of degradation in these processes that occurred prior to restoration. Legacy effects of past vegetation can continue to influence water quality for many years or decades and control the potential level and timing of water quality improvement. An understanding of these underlying processes is important for effectively using vegetation condition as an indicator of water quality protection and for accurately gauging prospects for water quality improvement through restoration of permanent vegetation.

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