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Laura S Craig[1*], Margaret A Palmer[1,2], David C Richardson[1], Solange Filoso[2], Emily S Bernhardt[3], Brian P Bledsoe[4], Martin W Doyle[5], Peter M Groffman[6], Brooke A Hassett[3], Sujay S Kaushal[2], Paul M Mayer[7], Sean M Smith[8], and Peter R Wilcock[8]

Despite decades of work on implementing best management practices to reduce the movement of excess nitrogen (N) to aquatic ecosystems, the amount of N in streams and rivers remains high in many watersheds. Stream restoration has become increasingly popular, yet efforts to quantify N-removal benefits are only just beginning. Natural resource managers are asking scientists to provide advice for reducing the downstream flux of N. Here, we propose a framework for prioritizing restoration sites that involves identifying where potential N loads are large due to sizeable sources and efficient delivery to streams, and when the majority of N is exported. Small streams (1st–3rd order) with considerable loads delivered during low to moderate flows offer the greatest opportunities for N removal. We suggest approaches that increase in-stream carbon availability, contact between the water and benthos, and connections between streams and adjacent terrestrial environments. Because of uncertainties concerning the magnitude of N reduction possible, potential approaches should be tested in various landscape contexts; until more is known, stream restoration alone is not appropriate for compensatory mitigation and should be seen as complementary to land-based best management practices.

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Nitrogen (N) is vital to the functioning of aquatic ecosystems, yet can be extremely detrimental in excess. Elevated levels of N moving down streams and rivers are of particular concern for coastal areas, due to problems associated with eutrophication (Howarth *et al.* 2002). While agricultural and urban best management practices (BMPs) contribute to reduced N loads, the amount of N reaching coastal waters is still higher than desired (Howarth *et al.* 2002). Natural resource managers are now asking how restoration of stream ecosystems might reduce the downstream movement of N.

In a nutshell:

- Reducing the amount of nitrogen (N) moving down streams and rivers remains a top priority in many watersheds
- Stream restoration can contribute to N removal if project site selection includes consideration of land-use characteristics and local hydrology
- Opportunities for achieving N reductions are greatest in streams that receive N loads during low or moderate flows
- Restoration designs should increase N processing within the stream corridor while maintaining ecological and geomorphologic integrity

Galloway *et al.* (2004) estimated that ~ 50% of the N entering streams and rivers may be removed before it reaches coastal waters; however, many streams have been so heavily impacted by human activities that they cannot appreciably reduce in-stream N (Bernot and Dodds 2005). Attention has therefore turned to ecological restoration as a tool for reducing N loading. While more than 30% of the stream restoration projects in the US are intended to improve water quality (Bernhardt *et al.* 2005), investigators are only just beginning to quantify N reductions associated with such projects.

We propose a framework for prioritizing sites and selecting approaches to maximize N-removal benefits from stream restoration projects. While well-known guidelines for stable channel design exist (Copeland *et al.* 2001), there are no current "guidelines" for improving N retention and removal. The challenge is to select the most appropriate sites and introduce design elements that enhance the potential for reduction or regulation of N, while upholding geomorphic and ecological integrity.

Our focus here is on restoration directed toward removing N that has already entered the stream channel; overviews already exist on methods to reduce N delivery to waterways via riparian planting and other land-based forms of management (eg Mayer *et al.* 2005). Throughout this paper, we use examples from the Chesapeake Bay watershed, where problems associated with excess N have been studied extensively (eg Jordan *et al.* 1997) and the implementation rate of stream restoration projects is extremely high (Hassett *et al.* 2005).

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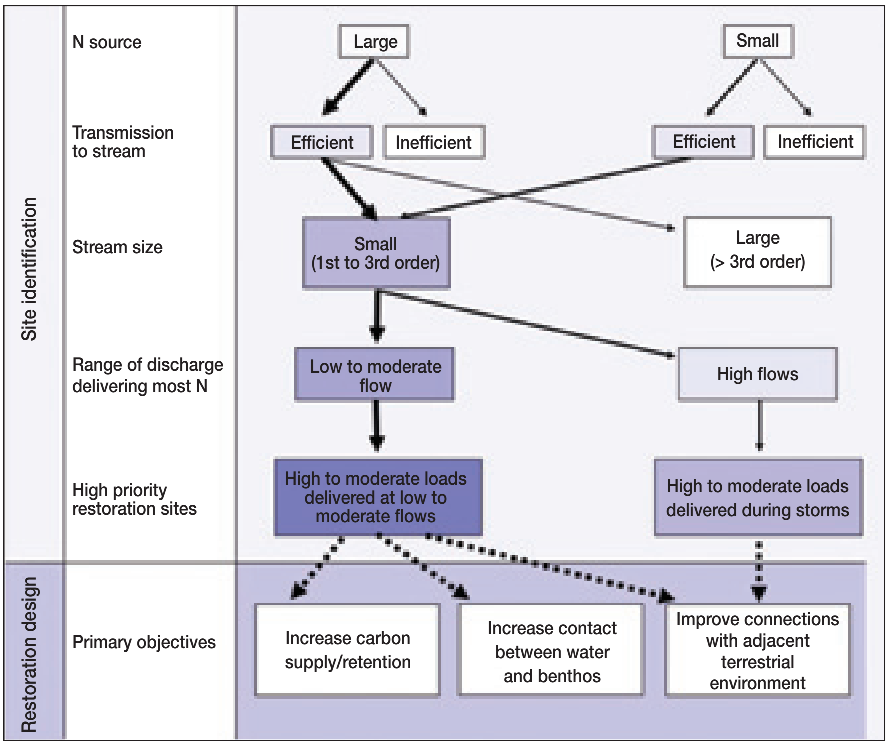


Figure 1. *Schematic showing factors to consider when prioritizing sites for restoration aimed at N removal and suggestions for restoration approaches. Priority should be given to small (1st- to 3rd-order) streams that carry sizeable N loads as a result of major N sources and efficient transmission pathways. Highest priority sites are those that receive the greatest proportion of their annual N load during low to moderate flows, where restorations aimed at increasing C availability, contact with the benthos, and connections with adjacent terrestrial environments are feasible.*

Nitrogen processing in stream ecosystems

Nitrogen enters streams from various point and non-point sources (eg runoff, groundwater, atmospheric deposition). Nitrate is the predominant form of N in many streams, because it is highly soluble and readily leached from soils. Ammonium is also common, but less prevalent in the water column, because it is readily immobilized, adsorbs to negatively charged clay particles and organic matter (OM), and is often nitrified in small streams. Dissolved or particulate organic N may also be present in substantial amounts in some streams (Kaushal and Lewis 2005). The amount of N delivered to downstream ecosystems is controlled by both the permanent removal and temporary storage of N.

Permanent removal of N occurs primarily through denitrification, the microbially mediated reduction of nitrate to gaseous forms (N_2 and N_2O) under anaerobic conditions. Denitrification typically involves the oxidation of OM, and thus debris dams and OM-rich sediments are potential "hotspots" for N removal within streams (Groffman *et al.* 2005). Riparian zones, floodplains, and streambanks are also locations of potentially high N removal, but rates vary with local conditions (eg hydrology, soils, OM availability; Vidon and Hill 2004).

Temporary storage refers to biological and physical retention of N that is subsequently returned to surface waters. Biological retention occurs when biota (eg microbes, algae, vegetation) assimilate and store N until it is released by decomposition and remineralization. Physical retention occurs in locations of reduced water movement, including hyporheic zones (areas where groundwater and surface water mix) and backwaters (Hall *et al.* 2002; Ensign and Doyle 2005). While permanent removal of N is ultimately more desirable in the context of restoration, temporary storage can increase contact time with OM and denitrifying bacteria (Kemp and Dodds 2002; Groffman *et al.* 2005).

Identifying priority sites

Stream restoration is an expensive enterprise; therefore, site selection should involve a rigorous process in which watershed location, history and characteristics of the landscape setting, and feasibility of implementation are taken into consideration (Palmer *et al.* 2005). Prioritization of restoration sites involves a step-wise process (Figure 1). First, regions of the landscape where N supplies are large and transmission of N is likely to be efficient should be identified. Within these sub-regions, small streams that receive most of their annual N load during low to moderate flows should be targeted. Finally, local and reach-scale characteristics should be considered when choosing targets where the potential for effective restoration is high.

Sources of N

The amount of N entering a stream is determined by both the size of the N supply, which is primarily influenced by land-use characteristics, and the efficiency of the hydrologic pathways connecting uplands to drainage networks. Large N sources are typically associated with agricultural activities; however, in some regions atmospheric deposition can be substantial (Boyer *et al.* 2002), as can inputs from septic systems, leaky sewers, and wastewater treatment plants (Brakebill and Preston 2004; Wollheim *et al.* 2005). Regions where N supplies are large can be identified using land-use data combined with estimates of agricultural application and atmospheric deposition. Land-based BMPs, such as repairing sewer infrastructure or minimizing the application of N in agricultural areas, should be employed prior to application of in-channel approaches.

Mode of transmission

The efficiency of N transmission to streams is related to the mode of delivery from upland sources. Nitrogen may be delivered via runoff, interflow (the lateral movement of water along shallow, subsurface flowpaths), groundwater, or artificial drainage systems, including stormwater and tiled-agricultural networks (agricultural land where subsurface infrastructure promotes rapid drainage; Figure 2). The dominant flowpath depends upon many factors, including land use, geology, aquifer geometry, hydraulic gradient, soils, and drainage infrastructure (Bachman *et al.* 1998). Runoff and interflow efficiently deliver N to channels, because flowpaths are relatively short, allowing water to move rapidly to the stream with little loss of N (Lindsey *et al.* 1998); however, deeper groundwater flowpaths may also be efficient if conditions for natural attenuation are not met (Bachman and Krantz 2000; Figure 3). Artificial drainage is also likely to rapidly deliver N to streams, yet little is known about N processing within these networks.

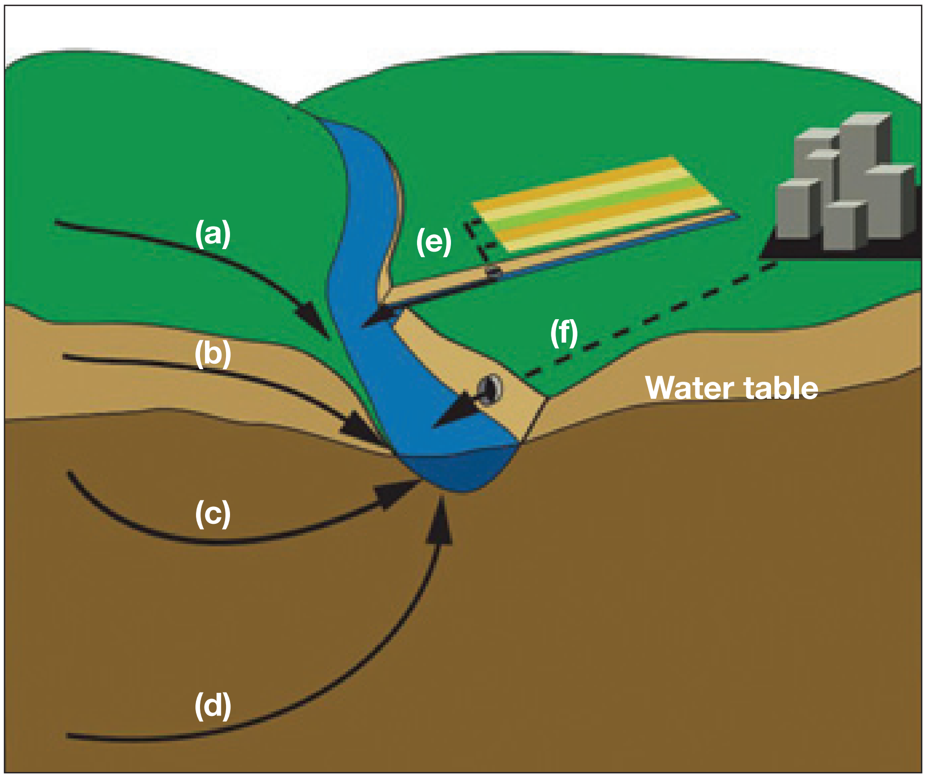


Figure 2. *Possible modes of N transmission from upland sources to streams include (a) overland flow, (b) interflow, (c) shallow groundwater, (d) deep groundwater, (e) tiled-agricultural drainage networks, and (f) stormwater drainage networks.*

Runoff is common after heavy rainfalls, especially in watersheds with a large amount of impervious cover, sparse vegetation and low-permeability soils, or saturated hillslopes. There is minimal biological removal of N when it is delivered in runoff (Wollheim *et al.* 2005). Interflow is common in areas with relatively large slopes and thin soils overlying less permeable layers of rock, silt, or clay. When N is transported with interflow, N removal may occur if water passes through OM-rich soils. However, if water moves rapidly along these flowpaths following storm events, large reductions are unlikely.

While groundwater does not move N to streams as rapidly as runoff and interflow, it still plays a major role in delivering N to streams. As N-laden water moves along groundwater flowpaths, the N load may be attenuated by biological uptake or denitrification. However, the biogeochemical properties required for N removal may be absent in many hydrogeologic settings (Bachman and Krantz 2000), or there may be insufficient time for removal to occur (Lindsey *et al.* 2003). Nitrogen removal may be substantial along shallow groundwater flowpaths if water passes through organically rich riparian soils before entering the stream, yet in many deeply incised channels, water bypasses these soils and opportunities for N removal are reduced (Groffman *et al.* 2002). Opportunities for denitrification of groundwater N arise when it comes into contact with organically rich material, either at depth or as water moves toward the surface (Bachman and Krantz 2000).

Determining the pathway of transmission can be difficult because it is influenced by aquifer geometry, permeability, and hydraulic gradients, all of which may vary across small scales (Lindsey *et al.* 2003). While pathways can be determined using field measurements, they can also be estimated at coarse geographic scales, using knowledge of physiography and lithology. The physiographic provinces delineated within North America integrate many of the factors influencing N transmission and, to some degree, land use and N supply. Province sub-units, such as geomorphic districts, provide finer detail regarding relief and lithology that influence watershed N yield characteristics. For example, areas with an underlying layer of carbonate bedrock have high subsurface N transmission capability and coincide with low-relief soils, which historically have favored agricultural activities that generate large amounts of N (Figure 3).

Stream size

Nitrogen uptake rates generally increase as stream order and discharge decrease (Alexander *et al.* 2000; Peterson *et al.* 2001). Ensign and Doyle (2006) conducted a meta-analysis of previous studies and found that N uptake per unit area peaks for ammonium in 2nd-order streams and for nitrate in 3rd-order streams. Large streams and rivers (> 3rd order) may carry large N loads, but proportional

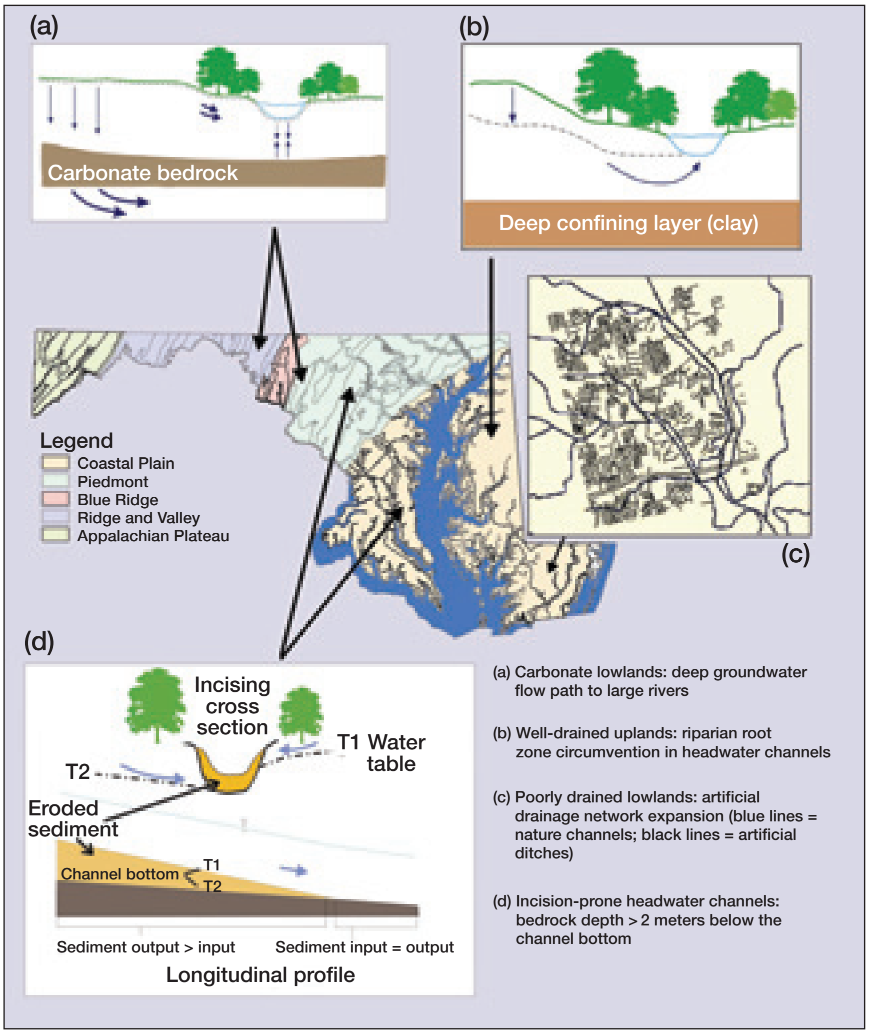


Figure 3. *Map showing the physiographic provinces in Maryland (center), with examples of landscape characteristics that may contribute to large N loads in streams. (a) Carbonate lowlands with low-relief soils have historically favored agriculture and have characteristic subsurface flowpaths that efficiently transmit water, and N, to streams. (b) In watersheds with well-drained uplands, groundwater circumvents the riparian zone, reducing opportunities for N attenuation before entering the channel. (c) Artificial drainage networks, common in agricultural settings in poorly drained lowlands, efficiently deliver surface-applied N to streams. (d) Hydrologic connections to adjacent terrestrial environments are lost in incision-prone channels in the Piedmont and Coastal Plain. Insets (a) and (b) are adapted from Lowrance* et al. *(1995); (c) redrawn from unpublished Maryland Department of Natural Resources data; (d) redrawn from Smith* et al. *(2003).*

reduction in N loading through restoration is difficult at this scale. Uptake data and engineering feasibility considerations therefore indicate that small streams (1st–3rd order) are the best targets for restoration to reduce N loads. Knowledge of stream order can be obtained using a combination of published drainage networks and ground surveys.

Discharges delivering N

In designing a restoration project with the goal of N removal, it is important to identify the range of discharges that deliver most of the annual N load to the target stream. N delivery may occur primarily during baseflows or high flows, or equally during both (Table 1). The flow at which most of the N is delivered will dictate the most suitable restoration design for enhancing N removal. Factors controlling removal, particularly hydraulic resistance and water residence time, are easier to manipulate in streams with baseflow-dominated delivery of N, but with careful design, enhancing N removal need not be limited to baseflows.

Delivery and transport of N during high-discharge events occurs in areas with efficient runoff conveyance (eg urbanized areas; Shields *et al.* in review); stormwater management focuses on reductions in hydrologic efficiency to counteract these effects. Streams that drain agricultural watersheds can also carry large N loads during storms if fields overlie tiles that limit infiltration and promote delivery of surface-applied N with interflow (Royer *et al.* 2006), or if ammonium-laden sediment or nitrate enters streams in runoff.

While high flows are known to export large amounts of N, export during baseflow can also be substantial (Shields *et al.* in review). This is often true even in urban systems, due to leaky sewer pipes, extensive septic systems, or wastewater treatment effluents (Brakebill and Preston 2004). Phillips *et al.* (1999) estimated that approximately 50% of the nitrate loading to the Chesapeake Bay occurs during baseflow, with groundwater delivering large loads from both urban and agricultural landscapes that overlie permeable, unconsolidated, or fractured substratum.

Use of the terms baseflow and high flow with respect to N delivery is not meant to suggest a dichotomy in restoration opportunities, but simply to emphasize that designing a project that effectively removes N requires knowledge of when most of the N is delivered. Streams that receive and transport the greatest proportion of N at high flows should not be completely disregarded in the selection process, especially if they are destined to be restored for other reasons (eg bank stabilization) or are in close proximity to water bodies of special concern (eg lakes, bays, or protected wetlands). Ideally, designs should be based on knowledge of discharge versus cumulative annual N load, so that design calculations ensure the desired hydraulic resistance for the range of flows that carry the largest proportion of N.

Table 1. The proportion of the total nitrate load delivered during baseflow versus high flow for a range of streams draining watersheds of differing land use in a variety of landscape settings

Stream characteristics		*% of nitrate exported during*	
Land use	*Setting*	*Baseflow*	*High flow*
Agricultural, forested buffer[1†]	Piedmont physiographic province	94	6
Urban[2]	Piedmont physiographic province	86	14
Mixed (forest/agriculture/urban)[3†]	Piedmont crystalline hydrogeomorphic region	78	22
Mixed (forest/agriculture)[3†]	Valley and Ridge siliciclastic hydrogeomorphic region	58	42
Mixed (forest/agriculture)[3†]	Appalachian Plateau siliciclastic hydrogeomorphic region	47	53
Forested/residential[4*]	Piedmont physiographic province	21	79
Urban/suburban[4*]	Piedmont physiographic province	10	90
Urban/residential/commercial[4*]	Piedmont physiographic province	7	93
Agricultural, tile-drained[5†*]	Central Lowland physiographic province	3	97

[*] Baseflow was considered as ≤ median discharge. [†] Represents data for multiple streams.
[1] Newbold *et al.* (2002); [2] calculated from Doyle *et al.* (2005); [3] Bachman *et al.* (1998); [4] Shields *et al.* (in review); [5] Royer *et al.* (2006).

Determining the range of discharges at which most of the N is delivered is complicated, because it requires knowledge of the relationship between nutrient load and discharge for a given site. However, this relationship may be predicted using information about the hydrogeologic setting and impervious cover, empirical data, or spatially explicit water-quality models that account for agricultural and urban drainage schemes (Doyle *et al.* 2005; Shields *et al.* in review).

Additional considerations

Local and reach-scale characteristics may result in greater delivery of N to downstream ecosystems than expected based on physiography, climate, and regional land-use patterns (Table 2) and should be considered during site selection. For example, large N loads may result, in part, from channel incision or low local OM availability. Proximity to downstream water bodies should also be considered, as should arrangement of sites when funding exists for multiple projects. Finally, neighboring infrastructure and other features that may limit available restoration approaches should be taken into account during prioritization.

To summarize, in restoration aimed at N reduction, priority should be given to small streams that convey sizeable N loads and receive a substantial fraction of their annual load during discharges that can be manipulated to enhance N removal (Figure 1). Reach-scale characteristics and regional water-quality goals will help to further focus site selection.

■ Selecting a restoration approach

Examples of approaches that can be applied to reduce N yields are presented below and summarized in Table 3. Throughout, we use the term "restoration" to include both those activities intended to restore a system to a natural state and activities aimed at managing for increased N removal. Before selecting an approach, it is important to decide if the project should only include elements comparable to a reference stream or if an engineered ecosystem is an acceptable endpoint. Regardless of the selected approach, reduction of N loading via land-based BMPs should be attempted prior to in-channel restoration.

Increasing carbon availability

Several authors have shown that nitrate and ammonium are removed more rapidly from the water column when there is a high biological demand for N (eg Hall and Tank 2003; Webster *et al.* 2003; Dodds *et al.* 2004). Microbial assimilation and denitrification may be limited by carbon (C) availability (Bernhardt and Likens 2002; Groffman *et al.* 2005); therefore, increasing C supply and promoting OM storage by establishing and maintaining in-stream elements that foster retention may increase in-stream N removal (Bernhardt *et al.* 2003; Hall and Tank 2003; Webster *et al.* 2003; Rosi-Marshall *et al.* 2005).

Nitrogen removal may also be enhanced by creating "hotspots" for denitrification through the installation of debris dams or similar structures (Figure 4). These structures enhance denitrification by providing energy for denitrifying bacteria, promoting anoxia via heterotrophic respiration, and slowing water velocities to increase contact time with denitrifiers. Groffman *et al.* (2005) found rates as high as 185 to 4955 μg N kg^{-1} hr^{-1} in debris dam sediments in several Maryland streams, indicating that debris dams and other structures that provide hydrologic retention and store C may contain denitrification hotspots.

While research examining the response of biological N removal to C amendments is limited, several studies have suggested that providing bioavailable C has potential for reducing N in streams (Bernhardt and Likens 2002; Ensign and Doyle 2005; Roberts *et al.* 2007). Restoration efforts should focus on fostering permanent removal of N, so that loads are reduced without transformation to bioavailable organic forms (Kaushal and Lewis 2005) or ammonium (Burgin and Hamilton 2007), which could compromise the ecological integrity of downstream

Table 2. Examples of three factors that may limit terrestrial N processing and increase loading to streams, local conditions often associated with these factors, and common settings for these conditions in the mid-Atlantic region

Factors limiting terrestrial N processing	*Local conditions*	*Common settings*
Groundwater circumvention of riparian roots	Incised channels[1]	Mountain Piedmont Upper Coastal Plain regions
	Deep aquifer transmission[2]	Carbonate valleys Coastal Plain uplands
Circumvention of hotspots or lack of conditions for denitrification	Unconsolidated subsurface materials[2]	Coastal Plain uplands
	Low abundance of organic matter[1,2]	Coastal Plain uplands Limited forest cover (all settings)
Efficient conveyance of rainfall runoff	Drainage network expansion[1]	Coastal Plain lowlands
	Stream channelization[1]	Coastal Plain lowlands Poorly drained valleys (all settings)
	Hydraulically smooth surfaces[1,2]	Unvegetated slopes and valleys (all settings)
	Close proximity to large water bodies[1,2]	Coastal Plains, valley side slopes (rural areas) Tidal and non-tidal flood zones Valley side slopes (urban settings) Piedmont–Coastal Plain transition (urban settings)
	Artificial conveyance (storm drains)[1]	Urban/suburban land uses (all settings)
	Flood control structures[1]	Coastal Plain lowlands Confined valleys Poorly drained valleys (all settings)

[1]Anthropogenic causes; [2]natural causes

coastal ecosystems. Furthermore, because flashy hydrological regimes and high flows present a challenge for maintaining stored C, restoration approaches may also require channel or floodplain modifications that increase hydraulic resistance sufficiently to improve retention of OM in the stream channel.

Increasing contact with benthos

N removal can also be enhanced by physical modifications of the channel that increase topographic complexity, surface-area-to-volume ratio, and hydraulic retention to allow for greater contact between the water and the benthos (eg introduction of large, woody debris, construction of pool-riffle or step-pool sequences; Rosi-Marshall *et al.* 2005; Kasahara and Hill 2006). Creating low-velocity environments and increasing hydraulic retention using step pools or other physical modifications (Figure 5) may be the most favorable course of action in urban headwater channels, where options are limited by adjacent infrastructure. It should be noted that while deep pools reduce water velocities, allowing for the temporary storage of N, they will not be as effective for permanent removal as maximization of surface-area-to-volume ratios.

Depending on their design, physical modifications such as channel reconfiguration and the addition of streambed topography may enhance nutrient uptake by promoting contact with the benthos via groundwater–surface water mixing (eg Triska *et al.* 1993; Valett *et al.* 1996; Seitzinger *et al.* 2002). Kasahara and Hill (2006) showed that the creation of riffles in a restored stream enhanced hyporheic exchange, which contributed to reductions in stream nitrate, but indicated that measures to reduce siltation may ensure longer lasting effects.

Increasing connectivity between streams and adjacent environments

Restoration activities that establish connections between the stream and adjacent environments have also been shown to increase N removal (Kaushal *et al.* in press). In many impacted watersheds, riparian zones and floodplains are absent or disconnected from stream channels as a result of stormwater and transportation infrastructure, incision, entrenchment, or levees. Strategies to improve N processing in riparian zones and floodplains include re-establishment of forest vegetation and earthworks to create more extensive connections between the channel and adjacent areas. This can be accomplished by regrading in the riparian corridor, raising the channel bed, breaching of levees and spoil piles, or constructing vegetated benches within the channel (Figure 6). Reconnecting streams with adjacent environments increases opportunities for N-rich streamwater to saturate C-rich soils, thereby decreasing the downstream loading of inorganic N (Fennessy and Cronk 1997). Creation of two-stage channels with defined flood berms (Ward *et al.* 2004) may be a viable option for streams in which most of the N delivery occurs during high flows. Two-stage channels can provide opportunities for longer flowpaths and

Table 3. Approaches suitable for restoration projects aimed at reducing downstream N loading and the mechanism(s) through which N removal is likely to be enhanced for each approach

	Mechanism of enhanced N removal				
Stream restoration approach	*Promotes conditions required for denitrification*	*Promotes groundwater–surface water mixing and contact with benthos*	*Increases surface area-to-volume ratio and contact with benthos*	*Increases water residence time and contact with benthos*	*Increases opportunities for removal through contact with vegetation and organic soils*
Carbon additions	●				
Installation of artificial debris dams	●			●	
Large woody debris additions		●		●	
Creation of meander bends		●		●	
Construction of geomorphic features		●		●	
Channel widening			●	●	
Creation of two-stage channel				●	●
Floodplain reconnection/bank grading				●	●
Flow path modification (eg side channels, ponds/wetlands)				●	●

increased contact with riparian vegetation and OM, while containing storm flows within the channel (Fischenich and Morrow 2000).

Other hydrologic approaches can potentially reduce downstream N loading through flowpath modification. For example, it may be feasible in some locations to convey prescribed fractions of streamflow onto organically rich floodplain sediments (Chung *et al.* 2005). Another possible, although highly interventionist, approach is to construct artificial channels or connections to off-channel management structures (ie wetlands, ponds) that provide opportunities for water movement between the main channel and the adjacent landscape over a wide range of flow conditions. Ideally, these features would contain labile sources of C required for denitrification and/or wetland plants.

■ The future of stream restoration for N reduction

We have proposed a strategic approach for the selection and restoration of streams to reduce N loading to downstream ecosystems. The potential for successful reduction of N is maximized by targeting relatively small (<3rd-order) streams that carry large N loads and receive substantial portions of their annual load during periods of low to moderate flows. While abundant data on in-stream N removal and retention have been published in the past few years (eg Peterson *et al.* 2001; Kemp and Dodds 2002; Bernhardt *et al.* 2003; Mulholland *et al.* 2004), data collection on the efficacy of stream restoration as a tool to enhance in-stream N removal has only just begun (Bukaveckas 2007; Roberts *et al.* 2007; Kaushal *et al.* in

Figure 4. *Artificial debris dam installed as part of a pilot-scale stream restoration project, sponsored by the US Department of Defense, Strategic Environmental Research and Development Program, at Fort Benning, GA. Restoration that promotes the storage of organic matter through the creation of debris dams has the potential to decrease downstream N loading.*

Courtesy of P Mulholland

Courtesy of BG Laub

***Figure 5**. Riffle-weir restoration in Anne Arundel County, MD. The creation of low-velocity environments, such as step pools, increases hydraulic retention and contact time with the benthos, potentially leading to increased N removal in the channel.*

press). At present, we can only roughly estimate the potential for N removal from stream restoration.

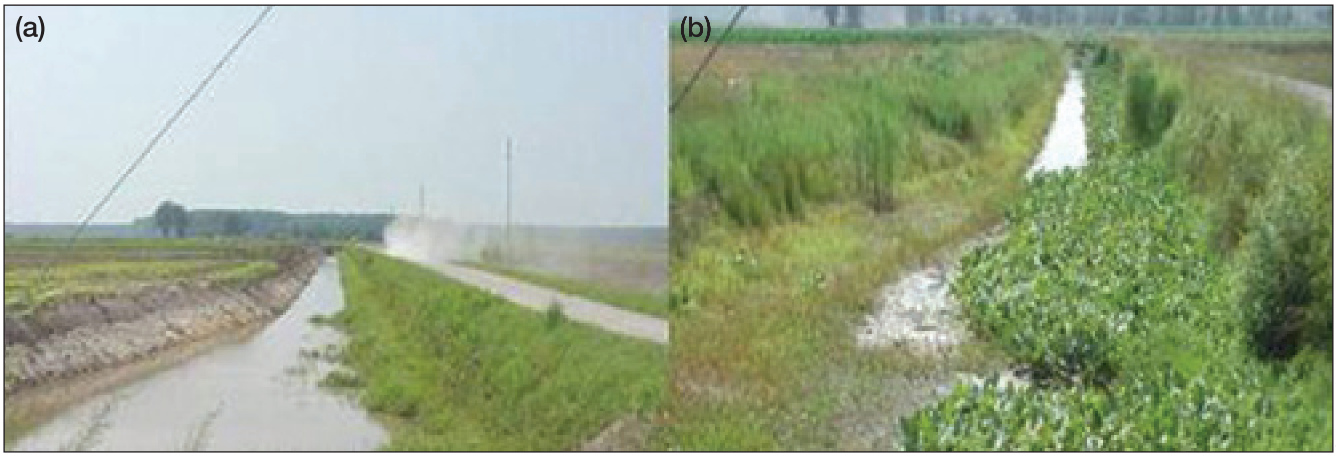
Ensign and Doyle (2006) report a range of areal N uptake rates for second-order streams across the US to be 0.97–15.3 µg NO_3–N m^{-2} min^{-1}. Assuming constant rates for a period of 24 hours, we can estimate that between 1.4 and 22 mg N are removed in a square meter of stream per day. If restoration increases NO_3–N uptake tenfold (as found by Bukaveckas 2007), these rates could increase to 14–220 mg N d^{-1}. Assuming that denitrification is the only process resulting in permanent loss of N to the atmosphere and that denitrification accounts for 16% of nitrate uptake (Mulholland *et al*. 2004), then restoration could yield losses of 2.2–35.2 mg N m^{-2} d^{-1}.

Given the important role that riparian reforestation is assumed to play in reducing nutrient loads, we compared these estimates to our own. The upper soil layers of properly functioning riparian buffers (ie established vegetation, water saturated) potentially denitrify between 3.0 and 78 mg N m^{-2} d^{-1} (Pinay *et al*. 1993; Lowrance *et al*. 1997). While our estimates must be viewed with caution because there is extremely high spatial and temporal variability in denitrification rates (PJ Mulholland pers comm; Lotic Intersite Nitrogen Experiment [LINX] unpublished), it is clear that on a per area basis, N removal is important both in stream channels and riparian buffers.

Because N removal rates are site and time specific, it is difficult to predict the effectiveness of different restoration approaches. Clarifying how stream restoration influences N removal will require an evaluation of restoration projects within different landscape contexts that employs the approaches we suggest, both alone and in concert. These approaches should therefore be implemented as adaptive management "experiments", rather than as solutions to N loading issues, until we can ascertain the actual N removal capacity of such projects. Moreover, evaluating the ability of current methods to measure the effectiveness of restoration, along with conceptualizing and implementing new methods, is critical to our understanding of how restoration affects N removal.

Moving forward with caution

Quantification of the benefits of restoration aimed at N reduction is just beginning (eg Bukaveckas 2007; Roberts *et al*. 2007; Kaushal *et al*. in press), and data are sorely needed to support the idea that stream restoration leads to substantial N reductions. We have a good understand-



Courtesy of R Evans

Courtesy of R Evans

***Figure 6**. Wetland bench restoration in Shepard's Ditch, Pasquotank County, NC, (a) shortly after construction and (b) following establishment of wetland plants. Restoration approaches that increase contact between the stream and adjacent terrestrial environments and improve the N processing functions of these areas have the potential to remove excess N from stream ecosystems.*

ing of the processes that govern N removal and retention, but the application of this knowledge to stream and river restoration is still in its infancy. As such, restoration alone should not be used or advocated as a compensatory mitigation measure, but should be viewed as a complement to source reductions and land-based BMPs. However, since the primary motivation for many restoration projects is not to reduce N but to stabilize banks or protect infrastructure (Palmer *et al.* 2005), implementation of the in-stream approaches we outline here may provide added water-quality benefits at incremental costs that are small compared to the cost of channel reconfiguration or bank stabilization (Bernhardt *et al.* 2005; Hassett *et al.* 2005).

In closing, we support a series of actions that begins with land-based strategies to reduce N loads and ends with improving conditions for N processing within the stream corridor, through the application of approaches that enhance retention and permanent removal of N in the riparian buffer, streambanks, and channel.

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