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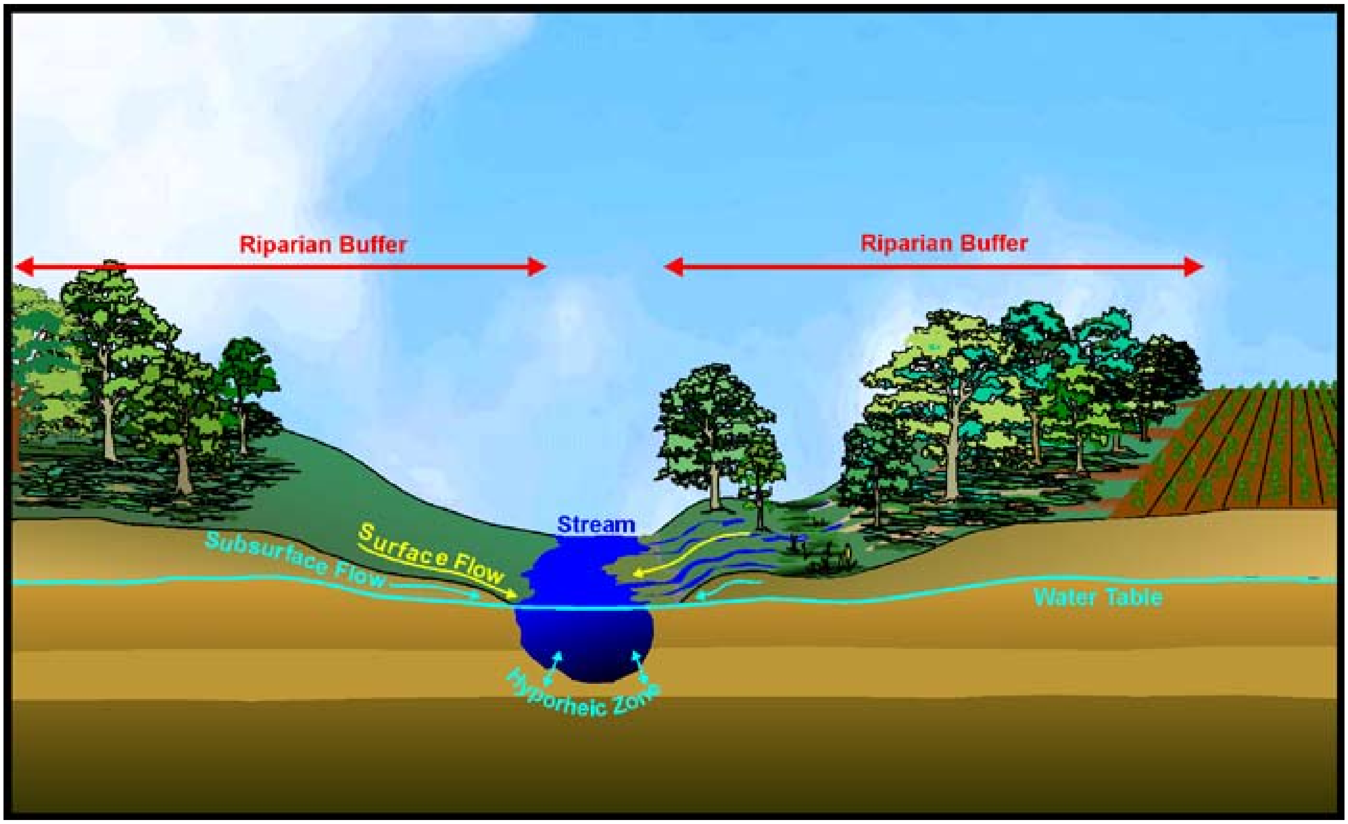
Riparian Buffer Width, Vegetative Cover, and Nitrogen Removal Effectiveness:

A Review of Current Science and Regulations



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Riparian Buffer Width, Vegetative Cover, and Nitrogen Removal Effectiveness:
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Foreword

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The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

The goal of this report is to synthesize the existing scientific literature on the effectiveness of riparian buffers to improve water quality through their inherent ability to process and remove excess anthropogenic nitrogen from surface and ground waters. Due to this ability, riparian buffers often are employed as an environmental management tool by resource management agencies. Despite significant research effort toward understanding the ecological functions of riparian buffers, there remains no consensus for what constitutes optimal riparian buffer design or proper buffer width to achieve maximum nitrogen removal effectiveness. This report does not provide a one-size-fits-all recommendation for such a design or width but rather attempts to identify generalizations and trends extracted from published literature that will aid managers in making decisions about establishing, maintaining, or restoring riparian buffers in watersheds of concern. Although, buffer width stands out as one factor influencing the capacity for buffers to remove nitrogen, numerous other factors described herein play significant roles that must be understood before employing riparian buffers as part of a comprehensive watershed management plan.

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Synopsis and Abstract

Synopsis

1) Riparian buffers are vegetated zones adjacent to streams and wetlands that represent a best management practice (BMP) for controlling nitrogen entering water bodies.
2) Current research indicates that riparian buffers of various vegetation types are effective at reducing nitrogen levels in groundwater and streams.
3) Buffer width is only one factor controlling nitrogen removal effectiveness.
4) Subsurface removal of nitrogen in riparian buffers is often high, especially where conditions promote microbial denitrification.
5) Riparian buffers are a single component of comprehensive watershed management plans, which must also include point source and non-point source control of nitrogen.

Abstract

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Riparian zones, the vegetated region adjacent to streams and wetlands, are thought to be effective at intercepting and controlling nitrogen loads entering water bodies. Buffer width may be positively related to nitrogen removal effectiveness by influencing nitrogen retention through plant sequestration or removal through microbial denitrification. We surveyed peer-reviewed scientific literature containing data on riparian buffers and nitrogen concentration in streams and groundwater of riparian zones to identify causation and trends in the relationship between buffer width and nitrogen removal capacity. We also examined Federal and State regulations regarding riparian buffer widths to determine if such legislation reflects the current scientific understanding of buffer effectiveness.

Nitrogen removal effectiveness varied widely among riparian zones studied. Subsurface removal of nitrogen was efficient but did not appear to be related to buffer width. Surface removal of nitrogen was partly related to buffer width and was generally inefficient, removing only a small fraction of the total nitrogen flowing through soil surface layers. While some narrow buffers (1-15 m) removed significant proportions of nitrogen, narrow buffers actually contributed to nitrogen loads in riparian zones in some cases. Wider buffers (>50 m) more consistently removed significant portions of nitrogen entering a riparian zone. Buffers of various vegetation types were equally effective at removing nitrogen in the subsurface but not in surface flow. The general lack of vegetation type or buffer width effects on nitrogen removal, especially in the subsurface, suggests that soil type, watershed hydrology (e.g., soil saturation, groundwater flow paths, etc.), and subsurface biogeochemistry (organic carbon supply, high nitrate inputs) may be more important factors dictating nitrogen concentrations due to their influence on denitrification.

State and Federal guidelines for buffer width also varied widely but were generally consistent with the peer-reviewed literature on effective buffer width, recommending or mandating buffers ~7-100 m wide. Proper design, placement, and protection of buffers are critical to buffer effectiveness. To maintain maximum effectiveness, buffer integrity should be protected against soil compaction, loss of vegetation, and stream incision. Maintaining buffers around stream headwaters will likely be most effective at maintaining overall watershed water quality while restoring degraded riparian zones, and stream channels may improve nitrogen removal capacity. Riparian buffers are a “best management practice” (BMP) that should be used in conjunction with a comprehensive watershed management plan that includes control and reduction of point and non-point sources of nitrogen from atmospheric, terrestrial, and aquatic inputs.

Keywords: attenuation, buffer strip, denitrification, groundwater, nitrate, nitrogen, stream, riparian buffer, surface water, watershed, vegetated filter strip

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Introduction

The U.S. Environmental Protection Agency (U.S. EPA) considers nitrogen one of the top stressors in aquatic ecosystems (U.S. EPA 2002a). Though nitrogen is an important nutrient for all organisms, excess nitrogen is a pollutant that causes eutrophication in surface water and contaminates groundwater (Carpenter et al. 1998). Streams receive chronic nitrogen inputs from upland sources such as fertilizers, animal wastes, leaking sewer lines, atmospheric deposition, and runoff from highways (Carpenter et al. 1998, Swackhamer et al. 2004). Subsequent eutrophication leads to environmental impacts such as toxic algal blooms, oxygen depletion, fish kills, and loss of biodiversity (Vitousek et al. 1997). Nitrate nitrogen (NO_3^-) also is a drinking water pollutant, especially dangerous to infants <6 months old who are at risk of methanoglobin-induced anemia or blue baby syndrome in which nitrate (converted to nitrite in the body) inhibits oxygen uptake, potentially leading to brain damage, or death (Welch 1991). The allowable level of nitrogen in drinking water for children ≤6 months old is 10 ppm (mg/1) as nitrate nitrogen (U.S. EPA 2002b).

Nitrogen enters aquatic ecosystems in one in of several forms including nitrate nitrogen (e.g. fertilizers), particulate nitrogen (e.g. litter fall from trees), ammonium (e.g. sewage and animal waste), and nitrous oxides from fossil fuel combustion (Schlesinger 1997). The means of entry into a system may differ for each type of nitrogen. For example, nitrous oxides enter by atmospheric deposition, nitrate often enters through groundwater, and particulate nitrogen follows terrestrial routes. Nitrogen is transformed by biological processes including uptake by plants and microbial denitrification, a process where anaerobic bacteria transform nitrate nitrogen to N_2, a gas phase of nitrogen (Schlesinger 1997). Only denitrification removes nitrogen from a system, whereas, nitrogen uptake by plants eventually returns nitrogen to the system through senescence and microbial decay. Nitrate nitrogen is of concern as an environmental stressor because it is biologically reactive, poses a human health risk, and often is found in groundwater.

Riparian buffers are thought to be an effective, sustainable means of buffering aquatic ecosystems against nutrient stressors such as nitrogen (Phillips 1989a) and thus are considered a best management practice (BMP) by State and Federal resource agencies (i.e., USDA-NRCS Environmental Quality Incentive Program, Conservation Programs Manual Part 515.91). Riparian buffers attenuate nitrogen through plant uptake, microbial immobilization and denitrification, soil storage, and groundwater mixing (Lowrance et al. 1997). The effectiveness of a buffer will depend upon its ability to intercept nitrogen in its various forms traveling along surface or subsurface pathways.

Often buffers are defined operationally as the zone of vegetation adjacent to streams, rivers, creeks, or wetlands (i.e., Lee et al. 2004). For this paper, riparian buffer, riparian zone, buffer strip, filter strip, and vegetated filter strip are terms used synonymously. However, these terms may be defined differently depending on the application and agency in question. Regardless of terminology, the extent to which riparian buffers attenuate nitrogen and improve stream water quality is thought to be at least partly a function of buffer width (Vidon and Hill 2004), by some estimates, accounting for 81% of a buffer's nitrogen removal effectiveness (Phillips 1989a). Intuitively, larger and wider riparian buffers should transform and remove more nitrogen from the watershed. Therefore, numerous State and Federal resource agencies have guidelines recommending buffers of minimum width to protect stream ecosystems from nutrient inputs (Belt et al. 1992, Christensen 2000, Lee et al. 2004.). Despite this trend toward regulation of riparian buffer widths, the specific mechanisms responsible for removing nitrogen within buffers are not thoroughly understood. Furthermore, what is known is not widely distributed to those who might be able to utilize the information to manage and restore riparian buffers to maintain water quality (Hickey and Doran 2004). An urgent need exists for guidance on proper and effective use of buffers to maintain water quality.

The purpose of this document is to identify causation and trends in the relationship between buffer width and nitrogen removal capacity extracted from peer-reviewed studies with empirical data on buffer effectiveness. Our secondary objective was to survey the State and Federal regulations and guidelines regarding riparian buffers to determine if buffer widths required under current law are consistent with effective buffer widths identified from the peer-reviewed literature.

Literature Survey Methods

We employed database search engines (e.g., Cambridge Abstracts, Google Scholar, etc.) and existing bibliographies (e.g., Correll 2003) to locate riparian buffer zone literature. We used search terms singly or combination including: riparian, buffer, width, filter strip, vegetated filters, nitrogen, etc. We summarized the conclusions from comprehensive and regional literature syntheses and the results from peer-reviewed research papers that contained original data quantifying the effects of riparian buffer width on nitrogen attenuation. We also surveyed Federal agency documents and previously published reviews of buffer width literature for opinions and recommendations on minimum effective buffer width. Papers that did not relate nitrogen removal to buffer width were not included in the results. Data presented in proceedings and other non-peer-reviewed sources were generally not included here except as part of generalizations presented in other literature reviews because methods therein could not be verified. We placed greater emphasis on studies that quantified a rate of nitrogen removal calculated per unit distance or per unit area. Such data may provide a quantifiable estimate of buffer effectiveness and aid in establishing minimum buffer widths based on removal effectiveness.

We also surveyed relevant Federal and State regulation codes, peer-reviewed literature reviews of government guidelines, and recommendations by government agencies that were not part of regulatory legislation. We attempted to locate Federal regulations and laws concerning riparian buffers by searching the web versions of the United States Code, Public and Private Laws, and the Code of Federal Regulations. Various agency websites were searched, including the websites of the United States Department of Agriculture (USDA), the United States Forest Service (USFS), the United States Army Corps of Engineers (USACE), the Bureau of Land Management (BLM), and the Government Accountability Office (GAO). We spoke directly with agency officials to clarify findings and to aid in the search for other regulations. Federal and State regulations and recommendations were compared to the previous literature-based results on riparian zones to determine the degree of consistency between them.

Results

Synthesis of Published Reviews on Buffer Effectiveness

We found 14 comprehensive and regional reviews of riparian buffer literature, most of which contained generalizations and recommendations based on both peer-reviewed and non-peer-reviewed research. In general, riparian forest vegetation and wetlands have been demonstrated as effective nutrient filters, particularly those between ~10-50 m wide (Belt et al. 1992, Johnson and Ryba 1992, Castelle et al. 1994, Fennessy and Cronk 1997, Fischer and Fischenich 2000, Christensen 2000). Narrower riparian buffers (5-6 m) may still reduce subsurface nitrate flows by up to ~80% (Muscutt et al. 1993, Parkyn 2004). However, extensive experimental support for buffer zones <10 m, like those used extensively on many farms, is lacking (Hickey and Doran 2004). Furthermore, riparian buffer zones >30 m were recommended for fully effective subsurface nutrient reduction (Muscutt et al. 1993, Wenger 1999). According to Wenger and Fowler (2000), “The most effective buffers are at least 30 meters, or 100 feet, wide composed of native forest, and are applied to all streams, including very small ones.” The use of riparian buffers to filter nutrients from surface flow was not recommended by Barling and Moore (1994) because dissolved nitrate was not significantly reduced.

Groundwater flow paths, soil characteristics (i.e., moisture storage, hydraulic conductivity, roughness, and slope), seasonal, and climate may significantly impact the rate and magnitude of subsurface nitrate removal. Groundwater flow above shallow, impermeable soil layers maximizes water residence time and contact with plant roots and organic-rich soils, thereby increasing the potential for nitrate removal by plant uptake and microbial activity (Hill 1996, Christensen 2000). Considerably less nitrate removal per unit distance occurred where local or regional groundwater flowed at deeper depths or through organically-poor soil (Hill 1996). Where groundwater bypassed the root zone and surface soil layers, the retention of nitrogen was minimal (Lowrance et al. 1997).

Detailed Insight into the Peer-Reviewed Literature about Buffer Effectiveness

Vegetated buffers around wetlands

Wetland buffer zones were highly variable in their effectiveness, removing from 12-80% of surface water nitrogen (Yates and Sheridan 1983, Brüsch and Nilsson 1993). However, much faster nitrate reductions can occur in the groundwater of wetlands where, in some cases, >95% of nitrate can be removed within 1 m (Burns and Nguyen 2002). Brüsch and Nilsson (1993) documented temperature and seasonal components to nitrate reductions in surface runoff across a 15-25 m wide peat wetland. Average nitrate reduction was 73.7% in the summer, 12.2% during the first winter, but ~38% during the second winter season due to higher temperatures. Despite seasonal variance in mean surface runoff nitrate concentration of 15 to 50 ppm, nitrate concentration in an adjacent stream did not exceed 5 ppm throughout the study. Seasonal patterns, but with higher percentage of nitrate reduction (>90%), also were noted in a 200-m wide reed and alder wetland within a river channel scar (Fustec et al. 1991).

Wetland buffers on soils with limited organic matter (i.e., sand or gravel) tended to show lower capacity to remove nitrogen. Cooper (1990) found that, while subsurface nitrate removal from highly organic, saturated soils was ~90%, removal from within mineral colluvial soils was much less effective. Clausen et al. (2000) observed a 52-76% reduction in subsurface nitrate concentrations (95% of all nitrate loss) across a 5-m “poorly to very poorly drained alluvium wetland.” Hanson et al. (1994) and Vellidis et al. (2003) observed similar reductions in nitrate (59% and 78%, respectively) from sandy, forested wetlands (31 and 38 m wide, respectively). Under “severely suboptimal conditions” in forested wetlands (i.e., sparsely vegetated, poorly drained, bottomland soils), riparian buffer widths <100 m were estimated to be 90% efficient at removing nutrients from agricultural runoff. However, under less severe conditions, buffer widths of 40-80 m on poorly drained soils and 15-60 m on well-drained soils were estimated to remove most nutrient runoff passing through a forested wetland, riparian zone (Phillips 1989b).

Forested buffers

The attenuation of nitrogen from groundwater flow can be rapid in forested riparian buffer zones. Schoonover and Willard (2003) found that 10-m forested buffers reduced groundwater nitrate concentration by 61%. Another study found a buffer averaging 38-m wide reduced nitrate concentration by 78% and ammonium by 52% (Vellidis et al. 2003). Others have documented more than 85% nitrate removal within the first 5 m of a buffer and 90-99% removal within 10-50 m of a buffer (Jacobs and Gilliam 1985, Lowrance 1992, Cey et al. 1999). As with wetland riparian buffers, most of the N transformation (~75%) occurred within the subsurface flow (Peterjohn and Correll 1984, Osbourne and Kovacic 1993). Furthermore, mature forests were 2-5 times more effective than "managed" (i.e., clearcut or selectively thinned) forests (Lynch et al. 1985, Hubbard and Lowrance 1997). Kuusemets et al. (2001) estimated that 85% of total nitrogen was retained in a heavily polluted 51-m wide riparian buffer, whereas only 40% of total nitrogen was retained in a buffer 31 m wide. Riparian buffers 100 m and 200 m wide in North Carolina removed from 67%-100% of groundwater nitrate entering the stream (Spruill 2004).

Effectiveness of nitrogen removal in forested riparian zones can vary widely due to characteristics unrelated to width. Extreme nitrogen loading (Lowrance et al. 1997) and increased hydraulic conductivity of the soil (Pinay and Decamps 1988, Pinay et al. 1993, Sabater et al. 2003) decrease effectiveness of forested riparian buffer zones. In some cases, these conditions can result in a net increase in nitrate concentrations in the groundwater (Sabater et al. 2003, Groffman et al. 2003) and can double the necessary width of the riparian zone for effective nutrient removal (Kuusemets et al. 2001). Spruill (2000) observed no difference in deep, "old" (>20 yr) groundwater underneath riparian zones with and without forested 30-m buffers, but 65-70% nitrate removal in shallow, "young" (<20 yr) groundwater through "reduction or denitrification." Effects of buffer width and length were mixed in a New Zealand study of forested buffers. However, oldest, longest (longitudinal), and widest (lateral) buffers had the greatest total nitrogen reductions (Parkyn et al. 2003). Saturated conditions led to removal of all nitrate within the first 30 m of forested riparian buffers in France (Pinay and Decamps 1988).

Grasslands

Grassed buffers or filter strips used alone or in conjunction with woody vegetation also can be effective at removing nitrogen. A 7.1-m grass buffer removed 80% of the total nitrogen and 62% of nitrate. Addition of a 9.2-m woody buffer to the grass buffer (total 16.3 m) increased effectiveness by 20%, removing 94% of the total nitrogen and 85% of the nitrate in runoff. However, effectiveness of the buffers in this study was negatively related to intensity of rainfall events (Lee et al. 2003). Giant cane (*Arundinaria gigantea*) reduced nitrate levels 90% in the first 3.3 m of the buffer, and 99% over 10 m, an effectiveness promoted by saturated conditions from upwelling groundwater (Schoonover and Williard 2003). In a study of seven herbaceous and herbaceous/forested riparian buffers in Canada, 90% removal of nitrate occurred 15 to 37 m into the riparian buffer depending on soil types and depth of the confining layer (Vidon and Hill 2004). Conversion of a portion of a corn field (*Zea mays* L.) to a riparian buffer of fine leaf fescue (*Festuca* spp.) decreased overland flow concentrations of total Kjeldahl nitrogen (TKN) by 70% and nitrate by 83% over the control and reduced nitrate concentrations in groundwater by 35%. Most (52%) of the nitrate decrease occurred within a 2.5-m wetland adjacent to the stream (Clausen et al. 2000).

In an Italian study, a 6-m wide grass/forest buffer (5-m grass + 1-m trees) reduced groundwater nitrate by >90% from maximum concentrations of ~25-28 ppm ($\bar{x} = 6.2$) under the application field to a level always ≤2 ppm ($\bar{x} = 0.6$) in groundwater (Borin and Bigon 2002). Grass buffers <5 m wide were ineffective in removing total nitrogen from surface runoff; those <10 m, but >5 m, wide were found to be 29-65% effective (Magette et al. 1989, Schmitt et al. 1999). Addition of a "forested" component to the grass buffer did not increase effectiveness (Schmitt et al. 1999). Grass filter strips 4.6 and 9.1 m wide reduced surface nitrate runoff from no-till cornfields by 27 and 57%, respectively. However, similar filter strips installed below animal feedlots were completely ineffective, yielding net gains in surface runoff nitrate concentrations (Dillaha et al. 1988, 1989).

Meta-Analysis of the Peer-Reviewed Literature about Buffer Effectiveness

Methods

Few peer-reviewed studies experimentally quantify nitrogen removal based specifically on riparian zone width. Rather, most studies measure nitrogen depletion at various locations throughout the riparian zone and/or in relation to biotic and abiotic variables such as vegetation or soil type. The lack of standardized field tests to quantify nitrogen removal based on buffer width sometimes makes comparisons among studies difficult. However, generalizations can be made based on the trends among 40 studies yielding 66 buffer width-effectiveness relationships (Table 1). In order to facilitate these generalizations and analyses, we grouped studies by vegetative cover type (i.e., wetland, forested, grassland) and by hydrologic flow conditions (e.g., surface vs. subsurface), factors that may influence nutrient attenuation in riparian buffer zones. We calculated nitrogen removal effectiveness (%) as 1) the % difference in nitrogen concentration between the influent into and effluent out of the riparian buffer, 2) % difference in nitrogen concentration between the terminus of the control buffer and that of the test buffer, or 3) if recalculation was impossible based on available data, the values presented by the authors were used directly (Table 1). These effectiveness data were plotted against buffer width, and linear and non-linear regression models were fitted to the data to reveal patterns of nitrogen removal based on width, buffer type, and hydrology. Though nitrate (NO_3^-) was the form of nitrogen most often measured among studies, we did not distinguish among nitrogen forms when calculating effectiveness. All buffers included in studies for which efficiencies could be calculated were included in the meta-analyses as independent data points. We then examined the relationship between loads (influents) and efficiencies to determine if thresholds existed for N removal. For studies that reported the actual influent nitrogen concentrations, we calculated the ratio of nitrogen load to buffer width as a measure of the level of impact to buffers and then used that ratio as the independent variable and nitrogen removal effectiveness as the dependent variable in a linear regression model to estimate buffer thresholds for nitrogen removal. Analyses were performed with SYSTAT version 11 (SPSS 2004).

Results

We found that nitrogen removal effectiveness varied widely among studies (Table 1) but overall, buffers were effective at removing large proportions of the nitrogen found in water flowing through riparian ecosystems (mean % ± 1SE: 74.2 ± 4.0; Table 2). A small but significant proportion of the variance in removal of nitrogen was explained by buffer width ($R^2 = 0.14$, $N = 66$; Figure 1). That is, wider buffers removed more nitrogen, but other factors also must have affected effectiveness. Additionally, greater consistency of nitrogen removal was evident with increasing buffer width (Figure 1). For example, nitrogen removal effectiveness in buffers <50 m wide was more variable than those >50 m where nearly all buffers exhibited about a 75% removal effectiveness (Figure 1). Thus, wider buffers are more likely to be efficient zones of nitrogen removal, whereas, narrower buffers may not always remove significant portions of nitrogen. Based on our non-linear regression model, 50%, 75%, and 90% removal efficiencies would occur in buffers approximately 3 m, 28 m, and 112 m wide, respectively (Figure 1, Table 2).

We found that nitrogen removal effectiveness also differed by flow pattern. Subsurface removal of nitrogen was much more efficient than surface removal (mean % ± 1SE: subsurface 89.6 ± 1.8, $N = 48$; surface 33.3 ± 7.7, $N = 18$; $t = 10.1$, $P < 0.001$; Figure 2). Furthermore, subsurface removal of nitrogen did not appear to be related to buffer width ($R^2 = 0.02$, $N = 48$; Figure 3), whereas, a small but significant proportion of the variance in surface removal of nitrogen was explained by buffer width ($R^2 = 0.29$, $N = 18$; Figure 3). That is, wider buffers removed more nitrogen in surface runoff. While some narrow buffers (1-15 m) removed significant proportions of nitrogen, three studies found that narrow buffers actually contributed nitrogen to riparian zones (i.e. had negative effectiveness values; Table 1). Such cases are likely to be short-term events due to nitrification or high rainfall events that lead to rapid inputs of particulate nitrogen. Based on our non-linear regression model, 50%, 75%, and 90% nitrogen removal efficiencies in surface flow would occur in buffers approximately 34, 118, and 247 m wide, respectively (Figure 3, Table 2).

We also found that nitrogen removal effectiveness varied by buffer vegetation type ($N = 66$; $F = 4.8$, $P = 0.002$; Figure 4 and Table 2). Grass buffers were significantly less effective than forest buffers at removing nitrogen ($P = 0.001$, Bonferroni adjustment), whereas, other buffers were equally effective (Figure 4).

Forested and wetland buffers showed no relationship between buffer width and nitrogen removal effectiveness (Figure 5). However, grass buffer effectiveness increased with buffer width in a non-linear fashion (Figure 5). Grass and grass/forest buffers were not always effective at removing nitrogen and, in three cases where buffers were <10 m, actually added to nitrogen loads (Figure 5). Based on the non-linear model results, we calculated the approximate buffer widths by vegetative types necessary to achieve 50%, 75%, and 90% effectiveness (Table 2). Nitrogen removal efficiencies of 50%, 75%, and 90% were predicted for grass buffers approximately 16, 47, and 90 m wide and for grass/forest buffers approximately 5, 20, and 47 m wide, respectively. Given the low R^2 values, buffer widths could not be predicted for effective nitrogen removal for grass or grass/forest buffers (Table 2). Note also, that the relationship between buffer width and effectiveness for forested wetlands was negative (Figure 5), suggesting that narrow forested wetland buffers are more effective than wide buffers. This non-intuitive result is likely due to the small sample size and not a cause and effect relationship. Therefore, buffer widths were not predicted for this vegetation type. Subsurface removal of nitrogen was generally high regardless of vegetation type, whereas, surface removal was less efficient and more variable among all buffer vegetation types (Figure 6).

In a similar meta-analysis with a more limited data set but fitting the same non-linear model as here, Oberts and Plevan (2001) found that nitrate nitrogen retention in wetland buffers was positively related to buffer width (R^2 values ranged from 0.35 – 0.45). Nitrogen removal efficiencies of 65-75% and 80-90% were predicted for wetland buffers 15 m and 30 m wide, respectively, depending on whether nitrate nitrogen was measured in surface or subsurface flow.

Finally, we found evidence for a threshold of nitrogen removal in buffers based on the nitrogen load entering the buffer. We calculated a ratio of nitrogen influent (pmm) to buffer width (m) for all studies that quantified influent loads and then fitted a linear model with nitrogen removal effectiveness as the dependent variable. Nitrogen removal effectiveness declined as the nitrogen load to width ratio increased ($R^2 = 0.11$, $P = 0.02$, $N = 55$; Figure 7). That is, buffer effectiveness declined when nitrogen loads were high relative to buffer width. However, five studies showed low or no nitrogen removal effectiveness even when nitrogen loads were small relative to buffer width (Figure 7), a pattern due to the ineffectiveness of nitrogen removal in surface flows. Thus, these data were highly variable but imply a threshold for nitrogen removal in buffers suggesting that reducing buffer width will risk nitrogen contamination to watersheds.

Table 1. Summary Table of Riparian Buffer Effectiveness at Removing Nitrogen by Vegetative Cover, Hydrologic Flow Path, Buffer Width and Soil Type. ("nd" = not detected; "–" = data not provided by authors)

Vegetative Cover Type	Flow Path	Buffer Width	N form	Mean Influent (pmm)	Mean Effluent (pmm)	Effectiveness(%)	Major Soil type(s)	Study
grass	surface	4.6	total N	–	–	-15	sandy loam	Magette et al. 1989
grass	surface	9.2		–	–	35		
grass	surface	7.5	total N	68	44	35	silty clay loam	Schmitt et al. 1999
grass	surface	15		68	33	51		
grass	surface	4.6	nitrate	1.86	2.37	-27	silt loam	Dillaha et al. 1988
grass	surface	9.1		1.86	2.13	-15		
grass	surface	4.6	nitrate	–	–	27	silt loam	Dillaha et al. 1989
grass	surface	9.1		–	–	57		
grass	surface	91	total N	21.6	13.3	38	–	Zirschky et al. 1989
grass	surface	27	nitrate	0.37	0.34	8	–	Young et al. 1980
grass	surface	26	NH_3	3.61	3.05	16	very fine sandy loam	Schwer and Clausen 1989
grass	surface	26	TKN	48.9	11.76	76	very fine sandy loam	Schwer and Clausen 1989
grass	subsurface	25	nitrate	15.5	6.2	60	coarse sand	Vidon and Hill 2004b
grass	subsurface	70	nitrate	1.55	0.32	80	fine sandy loam/silt loam	Martin et al. 1999
grass	subsurface	39	nitrate	16.5	3	82	silty clay loam	Osborne and Kovacic 1993
grass	subsurface	25	nitrate	12.15	1.92	84	peat/sand	Hefting and de Klein 1998
grass	subsurface	16	nitrate	2.8	0.3	89	stony clay loam	Haycock and Burt 1993
grass	subsurface	10	nitrate	7	0.3	96	entisols/histosols	Hefting et al. 2003
grass	subsurface	100	nitrate	375	<5	98	–	Prach and Rauch 1992
grass	subsurface	10	nitrate	7.54	0.05	99	silt loam	Schoonover and Williard 2003
grass	subsurface	30	nitrate	44.7	0.45	99	sand/loamy sand	Vidon and Hill 2004b
grass	subsurface	50	nitrate	6.6	0.02	100	fine sandy loam	Martin et al. 1999

Table 1. Continued.

Vegetative Cover Type	Flow Path	Buffer Width	N form	Mean Influent (pmm)	Mean Effluent (pmm)	Effectiveness(%)	Major Soil type(s)	Study
grassforest	surface	7.5	total N	68	49	28	silty clay loam	Schmitt et al. 1999
grassforest	surface	15	total N	68	40	41		
grassforest	subsurface	6	nitrate	6.17	0.56	91	loam/sandy loam	Borin and Bigon 2002
grassforest	subsurface	70	nitrate	11.98	1.09	91	loamy sand	Hubbard and Lowrance 1997
grassforest	subsurface	66	nitrate	5.8	0.17	97	gravel	Vidon and Hill 2004b
grassforest	subsurface	33	nitrate	5.7	0.11	98	sandy loam/loamy sand	Vidon and Hill 2004b
grassforest	subsurface	45	nitrate	17.8	0.18	99	peat	Vidon and Hill 2004b
grassforest	subsurface	70	nitrate	1.65	0.02	99	fine sandy loam/silt loam	Martin et al. 1999
forest	surface	30	nitrate	0.37	0.08	78	silt/stony loam	Lynch et al. 1985
forest	surface	70	nitrate	4.45	0.94	79	fine sandy loam	Peterjohn and Correll 1984
forest	subsurface	50	nitrate	26	11	58	entisols/histosols	Hefting et al. 2003
forest	subsurface	200	nitrate	11	4	64	medium-coarse sand	Spruill 2004
forest	subsurface	10	nitrate	6.29	1.15	82	silt loam	Schoonover and Williard 2003
forest	subsurface	55	nitrate	–	–	83	–	Lowrance et al. 1984
forest	subsurface	20	nitrate	–	–	83	–	Schultz et al. 1995
forest	subsurface	85	nitrate	7.08	0.43	94	fine sandy loam	Peterjohn and Correll 1984
forest	subsurface	204	nitrate	29.4	1.76	94	peat/sand/gravel	Vidon and Hill 2004b
forest	subsurface	50	nitrate	13.52	0.81	94	loamy sand	Lowrance 1992
forest	subsurface	60	nitrate	8	0.4	95	sand/gravel/clay	Jordan et al. 1993
forest	subsurface	16	nitrate	16.5	0.75	95	silty clay loam	Osborne and Kovacic 1993

Table 1. Continued.

Vegetative Cover Type	Flow Path	Buffer Width	N form	Mean Influent (pmm)	Mean Effluent (pmm)	Effectiveness(%)	Major Soil type(s)	Study
forest	subsurface	16	nitrate	6.6	0.3	95	stony clay loam	Haycock and Pinay 1993
forest	subsurface	15	nitrate	–	–	96	–	Hubbard and Sheridan 1989
forest	subsurface	165	nitrate	30.8	1	97	peat/sand	Hill et al. 2000
forest	subsurface	50	nitrate	6.26	0.15	98	peat/sand	Hefting and de Klein 1998
forest	subsurface	220	nitrate	10.8	0.22	98	peat/loamy sand	Vidon and Hill 2004b
forest	subsurface	50	nitrate	7.45	0.1	99	loamy sand	Jacobs and Gilliam 1985
forest	subsurface	10	nitrate	13	0.1	99	silt loam	Cey et al. 1999
forest	subsurface	100	nitrate	5.6	0.02	100	sandy clay/coarse sand	Spruill 2004
forest	subsurface	30	nitrate	1.32	nd	100	silt clay	Pinay and Decamps 1988
forest	subsurface	100	nitrate	12	nd	100	silt/plant debris/sand	Spruill 2004
forestwetland	surface	–	nitrate	0.34	0.07	81	sand	Yates and Sheridan 1983
forestwetland	subsurface	31	nitrate	62.7	25.9	59	sand	Hanson et al. 1994
forestwetland	subsurface	38	nitrate	30.6	6.7	78	sandy loam	Vellidis et al. 2003
forestwetland	subsurface	14.6	nitrate	–	–	84	sandy mixed mesic	Simmons et al. 1992
forestwetland	subsurface	5.8	nitrate	–	–	87	sandy mixed mesic	Simmons et al. 1992
forestwetland	subsurface	5.8	nitrate	–	–	90	sandy mixed mesic	Simmons et al. 1992
forestwetland	subsurface	6.6	nitrate	–	–	97	loamy mixed mesic	Simmons et al. 1992
forestwetland	subsurface	30	nitrate	1.06	nd	100	clay loam	Pinay et al. 1993
wetland	surface	20	nitrate	57	50	12	peat/sand	Brüsch and Nilsson 1993
wetland	surface	20		57	15	74		
wetland	subsurface	5	nitrate	6.56	1.55	76	stony silt loam	Clausen et al. 2000
wetland	subsurface	5		3	1.44	52		
wetland	subsurface	1	nitrate	1	–	96	clay loam/clay	Burns and Nguyen 2002
wetland	subsurface	200	nitrate	10.5	0.5	95	silt/sand/gravel	Fustec et al. 1991
wetland	subsurface	40	nitrate	77.48	0.31	100	fine to coarse sand	Puckett et al. 2002

Table 2. Mean and Percent Effectiveness of Riparian Buffers at Removing Nitrogen. Buffer Widths Necessary to Achieve a Given Percent Effectiveness (50%, 75%, 90%) are Approximate Values Predicted by the Non-Linear Model, y=a*ln(x)+b. Effectiveness was not predicted (np) for Models with R^2 Values <0.2

Flow Path or Vegetative cover type	N	Mean nitrogen removal effectiveness (%)	1SE	Relationship to buffer width		Approximate buffer width (m) by predicted effectiveness		
				Model	R^2	50%	75%	90%
All studies	66	74.2	4.0	y = 10.5*ln(x) + 40.5	0.137	3	28	112
Surface flow	18	33.3	7.7	y = 20.2*ln(x) – 21.3	0.292	34	118	247
Subsurface flow	48	89.6	1.8	y = 1.4*ln(x) + 84.9	0.016	np	np	np
Forest	22	90.0	2.5	y = -0.7*ln(x) + 92.5	0.003	np	np	np
Forested Wetland	7	85.0	5.2	y = -7.3*ln(x) + 104.3	0.203	np	np	np
Grass	22	53.3	8.7	y = 23.0*ln(x) – 13.6	0.277	16	47	90
Grass/forest	8	80.5	10.2	y = 18.1*ln(x) + 20.4	0.407	5	20	47
Wetland	7	72.3	11.9	y = 3.0*ln(x) + 68.9	0.005	np	np	np

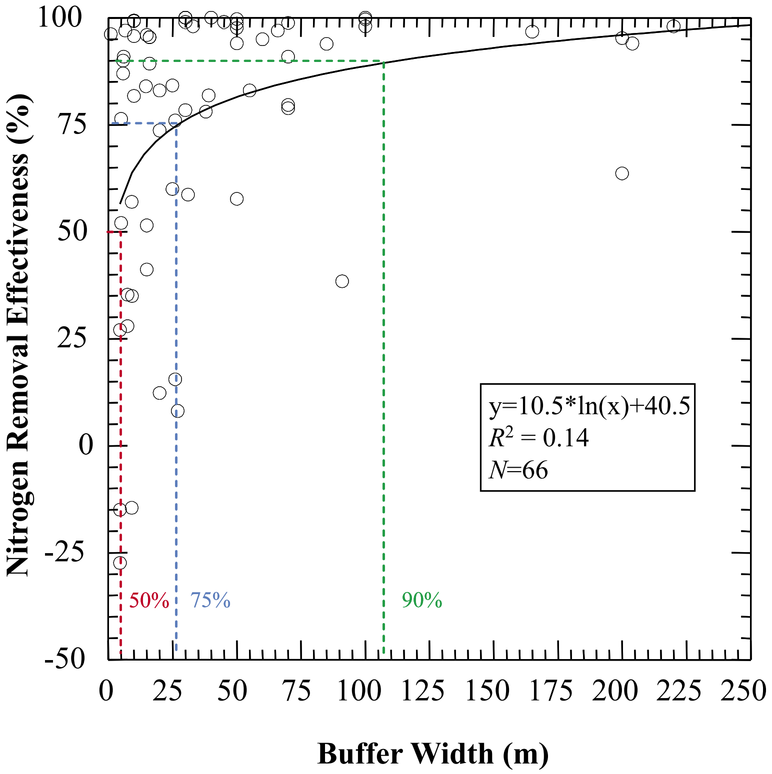

Figure 1. *Relationship of nitrogen removal effectiveness to riparian buffer width. All studies combined. Lines indicate probable 50%, 75%, and 90% nitrogen removal efficiencies based on the fitted non-linear model.*

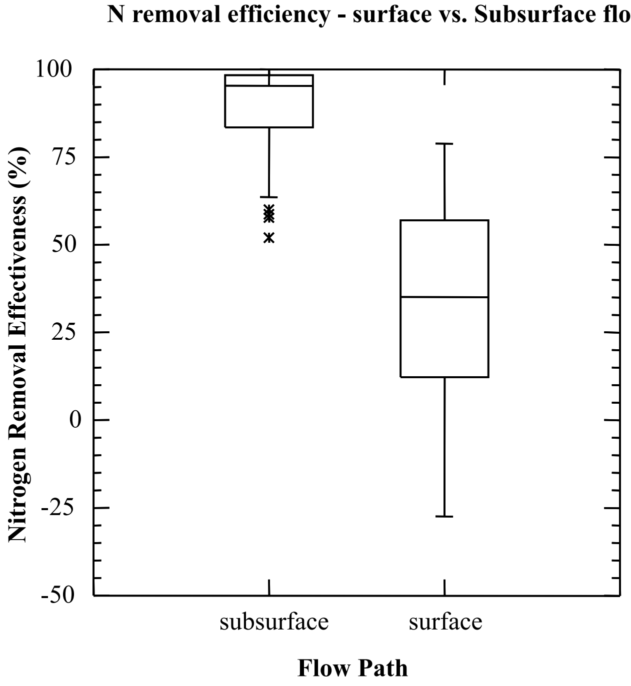

Figure 2. *Nitrogen removal effectiveness in riparian buffers by flow path. The center vertical line of the box and whisker plot marks the median of the sample. The length of each box shows the range within which the central 50% of the values fall. Box edges indicate the first and third quartiles. Whiskers show the range of observed values that fall within the midrange of the data. Asterisks indicate outside values.*

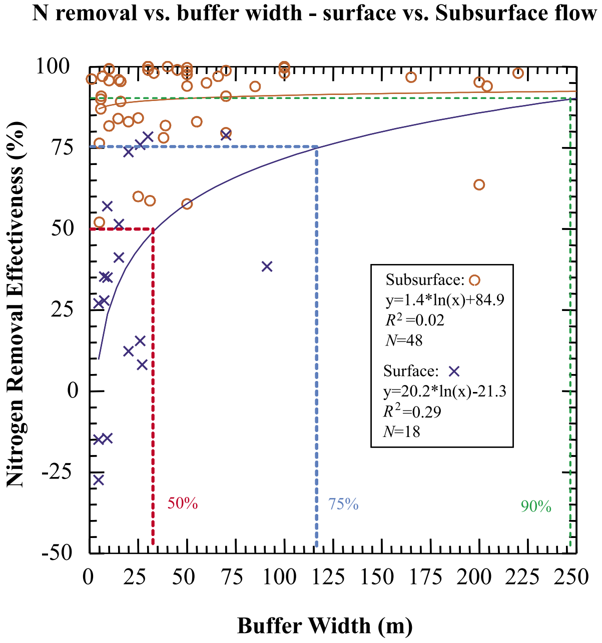

Figure 3. *Relationship of nitrogen removal effectiveness to riparian buffer width by flow path. Lines indicate probable 50%, 75%, and 90% nitrogen removal efficiencies in the surface flow path based on the fitted non-linear model.*

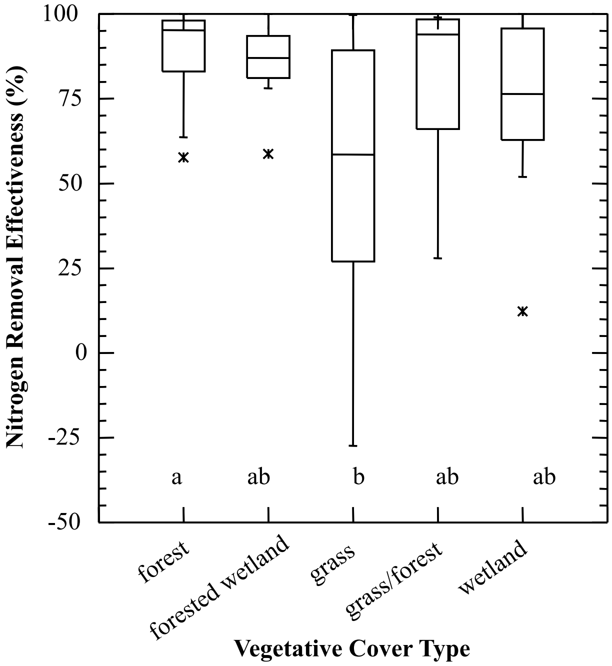

Figure 4. *Nitrogen removal effectiveness in riparian buffers by buffer vegetation type. The center vertical line of the box and whisker plot marks the median of the sample. The length of each box shows the range within which the central 50% of the values fall. Box edges indicate the first and third quartiles. Whiskers show the range of observed values that fall within the midrange of the data. Asterisks indicate outside values. Boxes identified with the same letters are not significantly different (P > 0.05).*

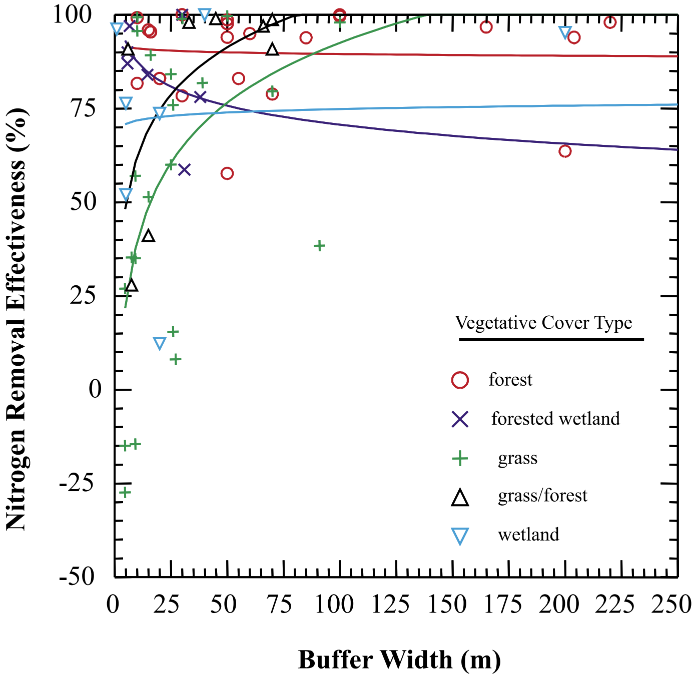

Figure 5. *Relationship of nitrogen removal effectiveness to riparian buffer width by riparian vegetation type. Curves are fitted to non-linear model: y = a*ln(x) + b*

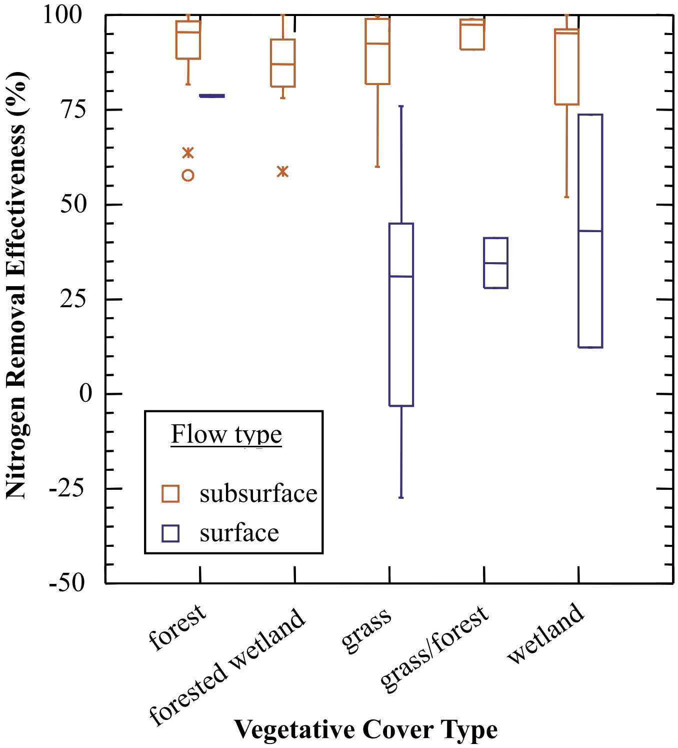

Figure 6. *Nitrogen removal effectiveness in riparian buffers by buffer vegetation type and water flow path. The center vertical line of the box and whisker plot marks the median of the sample. The length of each box shows the range within which the central 50% of the values fall. Box edges indicate the first and third quartiles. Whiskers show the range of observed values that fall within the midrange of the data. Asterisks indicate outside values.*

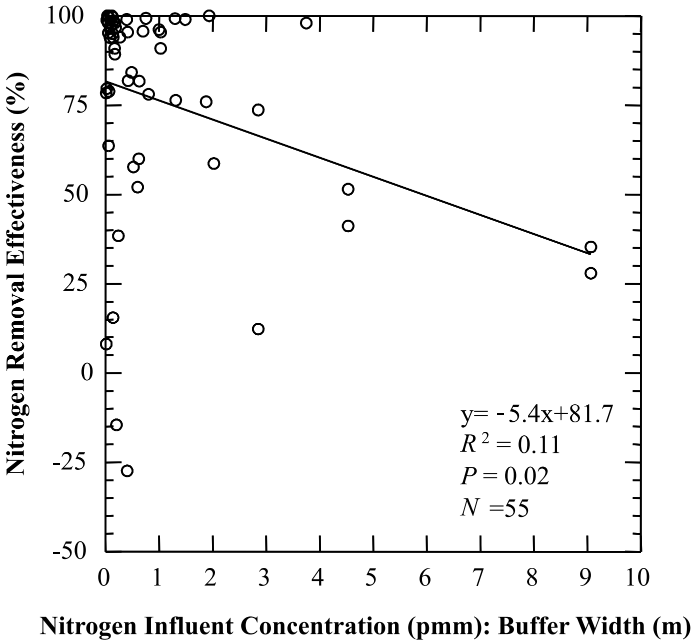

Figure 7. *Relationship of nitrogen removal effectiveness to nitrogen load:buffer width ratio. Fitted to linear model: y=a(x)+b.*

Discussion

Our meta-analysis suggests that nitrogen removal in the subsurface may be more directly influenced by soil type, watershed hydrology (e.g., soil saturation, groundwater flow paths, etc.), and subsurface biogeochemistry (organic carbon supply, high nitrate inputs) through cumulative effects on microbial denitrification activity than on buffer width per se. Surface flows bypass zones of denitrification and thus effectively remove nitrogen only when buffers are wide enough and have adequate vegetation cover to control erosion and filter movement of particulate forms of nitrogen. Grass buffers, for example, may be better at intercepting particulate nitrogen in the sediments of surface runoff by reducing channelized flow.

Federal Regulations and Recommendations

United States Code (USC)

Riparian buffers are noted in at least 14 parts within the USC (Appendix 1). Under the auspices of the 1972 Federal Water Pollution Control Act or Clean Water Act (33USC1251 et seq. as amended through P.L. 107–303, November 27, 2002), the U.S. EPA publishes lists of impaired waters for which Total Maximum Daily Loads (TMDL) are established that limit the amount of a pollutant, including nitrogen, that a water body can receive and remain compliant with State water quality standards (33USC1251.319). States are required to implement BMP's, such as riparian buffers or vegetated filter strips, to achieve compliance. U.S. EPA provides generalized recommendations and funding for riparian buffers and filter strips as part of Comprehensive Nutrient Management Plans (U.S. EPA 2001, 2003). However, site-specific BMP approaches and implementation are the jurisdiction of the States.

No comprehensive Federal statutory laws exist directly dealing with riparian buffer width even though buffers are mentioned in the USC. In some cases, site-specific legislation has been enacted that mandates protection of riparian buffers. The United States Congress has passed laws requiring vegetation to be left undisturbed on the sides of stream and river banks during specific activities. For example, in 16 USC 539(d), the National Forest Timber Utilization Program (a.k.a. the 1990 Tongass Timber Reform Act):

> "In order to assure protection of riparian habitat, the Secretary shall maintain a buffer zone of no less than one hundred feet in width on each side of all Class I streams in the Tongass National Forest, and on those Class II streams which flow directly into a Class I stream, within which commercial timber harvesting shall be prohibited…"

Timber harvesting from the National Forest System has also been regulated, in general, through the National Forest System Land and Resource Management Plan, which states, without providing strict guidelines, that harvesting plans must,

> "insure that timber will be harvested from National Forest System lands only where soil, slope, or other watershed conditions will not be irreversibly damaged" and where "protection is provided for streams, streambanks, shorelines, lakes, wetlands, and other bodies of water from detrimental changes in water temperatures, blockages of water courses, and deposits of sediment, where harvests are likely to seriously and adversely affect water conditions or fish habitat" (16 USC 1604).

Riparian conservation has been cited within the USC as one of the purposes for the establishment of National Parks and as directives to the Secretary of the Interior (e.g. 16 USC Sec. 460). As all national parks must follow the dual policy of both multiple and sustained yield, several subsections within this section of USC address riparian zones of other national parks likewise, to "contribute to public enjoyment," "protect important resource values," etc. In all cases, the statutes are site-specific, and the riparian zones discussed are between 100 and 300 ft.

Code of Federal Regulations (CFR)

Riparian buffers are noted in at least 47 parts within the CFR (Appendix 2). The CFR places blanket statutory restrictions on certain industrial practices in riparian areas. For instance, 30 CFR 816.57 and 30 CFR 817.57 prohibit surface and underground mining activities within 100 ft of perennial or intermittent streams, and 36 CFR 228.108 prohibits mining operations within the National Forest System "in areas subject to mass soil movement, riparian areas, and wetlands."

Voluntary participation programs such as the Conservation Reserve Program (CRP) and the Conservation Reserve Enhancement Program (CREP) provide landowners financial incentives to protect land and waterbodies through maintenance of buffers, wetlands, and by planting cover crops (7CFR1410). The CRP is administered through the U.S. Department of Agriculture's Farm Service Agency (USDA-FSA) (7CFR, Chap. VII) with technical assistance provided by the National Resources Conservation Service (USDA-NRCS) (7CFR, Chap. VI).

The USDA-FSA makes a distinction between filter strips and riparian buffers (7CFR1410.2). Filter strip is a "a strip or area of vegetation adjacent to a body of water the purpose of which is to remove nutrients, sediment, organic matter, pesticides, and other pollutants from surface runoff and subsurface flow by deposition, absorption, plant uptake, and other processes, thereby reducing pollution and protecting surface water and subsurface water quality and of a width determined appropriate for the purpose by the Deputy Administrator." No minimum widths are specified for construction of filter strips (NRCS 2003; practice Code 393).

Riparian buffer (NRCS 2003; practice Code 391) is "a strip or area of vegetation adjacent to a river or stream of sufficient width as determined by the Deputy Administrator to remove nutrients, sediment, organic matter, pesticides, and other pollutants from surface runoff and subsurface flow by deposition, absorption, plant uptake, and other processes, thereby reducing pollution and protecting surface water and subsurface water quality, which are also intended to provide shade to reduce water temperature for improved habitat for aquatic organisms and supply large woody debris for aquatic organisms and habitat for wildlife."

The importance of the distinction between filter strip and riparian buffer is in their implementation. For example, according to the CRP, riparian buffers should consist of three zones. Zone 1 starts at the top of the stream bank, is devoted to trees, and has a minimum width of 15 ft measured as perpendicular from the bank. Zone 2 is predominately composed of riparian trees and shrubs suitable to the site and has a minimum width of 20 ft. Zone 3 is only required for concentrated flow conditions and is devoted to native grasses and forbs (NRCS 2003). CRP limits enrollment of buffers constructed for water quality to those with less than a "maximum average width of 180 feet" and an absolute maximum width of 350 ft.

State and Provincial Regulations and Recommendations

State (USA) and Provincial (Canada) width guidelines for forested riparian buffers associated with timber harvesting were recently summarized by Lee et al. (2004). State width guidelines for buffers ranged from 15.5 – 24.2 m. Provincial guidelines generally required wider buffers (13.8 – 43.8 m). Widest buffers were recommended in northern Canada and narrowest in the southeastern U.S. In some areas, buffer widths were regulated as "one size fits all." Elsewhere, width recommendations were modified using factors including size/permanence of waterbody, slope of surrounding terrain, and presence/absence of fish.

In general, Lee et al. (2004) found that State-level "blanket" regulations addressing nitrogen attenuation and riparian buffer zone widths were non-existent. Many states have no mandatory buffer regulations and almost none regulate agriculture where buffers may have greatest potential for attenuating nitrogen fertilizer or livestock. However, many states have documented standards related to sections 303(d) and 319 of the CWA that result in site-specific maintenance of riparian zones for watershed protection, including nutrient attenuation. For resource agencies that do not yet have such regulations and wish to develop standards, numerous models and existing riparian buffer ordinances are available to serve as templates (U.S. EPA, undated; SCDHEC, undated). Many local governing bodies at the county, municipal, or district level proved additional guidance or regulation regarding riparian buffers. Wenger and Fowler (2000) indicated that establishing and enforcing regulations for variable-width buffers contingent upon local land use, slope, soil type, etc. are most difficult and suggest, rather, a model, fixed-width buffer ordinance intended to be clear and enforceable.

Other Aspects of Buffer Effectiveness

Buffer width partly accounts for nitrogen removal effectiveness of riparian buffers. However, other factors may be equally or more important in determining buffer effectiveness such as vegetation type and depth of the root zone where plants can take up nitrogen (Asmussen et al. 1979, Cooper 1990). Nitrogen also is consumed by denitrifying bacteria which convert nitrate to inert dinitrogen gas (Korum 1992). Therefore, riparian zones are particularly effective at removing nitrate where groundwater conditions favor denitrification, such as saturated soils that maintain anaerobic sites (Leeds-Harrison et al. 1999, Sloan et al. 1999, Sabater et al. 2003) and carbon supplies adequate for bacterial respiration in the subsurface (Hanson et al. 1994; Hill et al. 2000, 2004; Steinhart et al. 2001; Schade et al. 2001, 2002; Richardson et al. 2004). Therefore, narrow buffers may be effective if such groundwater characteristics promoting denitrification are present (Dillaha et al. 1989, Simmons et al. 1992) but, as our meta-analysis showed, wider buffers tended to be more effective. Streams with riparian zones that remain hydrologically connected with adjacent floodplains are more likely to function in ways that promote denitrification (Groffman et al. 2003; Groffman et al. 2005).

For maximum and long-term effectiveness, buffer integrity should be protected against a) soil compaction from vehicles, livestock, and impervious surfaces (e.g., pavement) that might inhibit infiltration or disrupt water flow patterns (Dillaha et al. 1989; NRC 2002), b) excessive leaf litter removal or alteration of the natural plant community (e.g., raking, tree thinning, introduction of invasive species) that might reduce carbon-rich organic matter from reaching the stream, and c) urbanization and other practices that might disconnect the stream channel from the flood plain (i.e., channelization, bank erosion, stream incision, and drain tiles) and thereby reduce the spatial and temporal extent of soil saturation (Paul and Meyer 2001, Groffman et al. 2003, Groffman et al. 2005). Buffer width may indirectly affect factors promoting denitrification. For example, narrow buffers that produce little vegetative biomass may not provide sufficient stocks of organic material for microbial denitrifiers.

Buffer Restoration, Planning, and Design

Creating ordinances and zoning to protect existing buffers will likely be cheaper than creating new buffers or restoring degraded ones. However, restoring buffers may be a necessary component of watershed water quality protection (FISRWG 1998, NRC 2002). An engineering approach thought to maximize nutrient removal capacity of buffers involves a multiple vegetation species or plant zone system (Welch 1991, Schultz et al. 1995, NRCS 2003). This 3-zone strategy was originally intended for protecting streams against timber harvest or agricultural use and is characterized by a zone of grasses and forbs immediately next to the area of disturbance, a middle zone of shrubs, and a zone of trees nearest to the stream channel. In theory, sediments and nutrients in surface runoff flowing from agricultural fields or timbered areas are intercepted first by the grass zone, while nutrients entering deeper subsurface pathways are taken up by shrub and tree roots (NRC 2002).

Substantial evidence exists to emphasize the importance of maintaining riparian zones in upstream headwaters or backwaters regions, which can be areas of high nitrogen removal (Perry et al. 1999, Morrice et al. 2000, Peterson et al. 2001, Seitzinger et al. 2002, Richardson et al. 2004, Bernhardt et al. 2005a). For a 10th order stream, up to 90% of the cumulative stream length consists of ephemeral, first, and second order streams (NRC 2002). Thus, the largest proportion of annual stream nutrient load enters watersheds from the headwaters where the capacity to remove nitrogen is great, while less additional nitrogen processing occurs in the main channels of higher order streams (Richardson et al. 2004, Bernot and Dodds 2005).

Many stream restoration projects are conducted to re-establish geomorphic stability (Bernhardt et al. 2005b) using approaches that potentially alter nutrient and sediment dynamics (Steiger and Gurnell 2003) in ways that may promote conditions for denitrification such as increasing supply and burial of organic matter, reconnecting flood plains, and increasing hydraulic residence time (Groffman et al. 1996). Furthermore, removal of nitrate occurs within the stream channel after nutrients have moved through the riparian zone and entered the hyporheic zone (Peterson et al. 2001, Kemp and Dodds 2002) suggesting that, in addition to establishing riparian buffers, manipulation of stream channels to support denitrification also should be considered as a means to manage nutrients (Groffman et al. 2005).

Summary and Conclusions

Based on current studies, riparian buffers of various types are effective at reducing nitrogen in riparian zones, especially nitrogen flowing in the subsurface. Buffers generally are more effective where soil type, hydrology, and biogeochemistry are conducive to microbial denitrification and plant uptake. While some narrow buffers (1-15 m) removed nitrogen, wider buffers (>50 m) more consistently removed significant portions of nitrogen probably by providing more area for root uptake of nitrogen or more sites for denitrification.

On average, State guidelines (Lee et al. 2004) recommended buffer widths that corresponded well to the minimum effective buffer widths necessary to improve water quality only if conditions within buffers are conducive to denitrification. Federal regulations do not stipulate minimum buffer widths for nitrogen removal from streams. Rather, riparian buffers represent a suggested tool to protect stream water quality and/or for removing streams from impaired listing due to nitrogen pollution under 303(d) section of the Clean Water Act. Federally recommended buffer widths vary from ~7-100 m, which encompass the width range of buffers expected to remove significant amounts of nitrogen.

Buffers extending along the length of both stream banks and in which there is prolonged contact time with the root zone will offer greater likelihood of nitrogen uptake by plants. Buffers will be most effective at controlling nitrogen through denitrification when 1) water flow (overland and subsurface) is evenly distributed and soil infiltration rates are high, 2) anaerobic (saturated) conditions persist in the subsurface, and 3) sufficient organic carbon is present. Therefore, to maintain maximum effectiveness, buffer integrity should be protected against soil compaction, loss of vegetation, and stream incision. Maintaining buffers around stream headwaters will likely be most effective at maintaining overall watershed water quality while restoring degraded riparian zones, and stream channels may improve nitrogen removal capacity. However, because streams and riparian zones have limited capacity to process nitrogen, watershed nutrient management efforts also must include control and reduction of point and non-point sources of nitrogen from atmospheric, terrestrial, and aquatic inputs. In any case, riparian buffers are a “best management practice” (BMP) that should be used in conjunction with a comprehensive watershed management plan (U.S. EPA 1995, NRC 2002). Finally, riparian buffers are often protected to achieve multiple goals (e.g. sediment trapping, aesthetics, wildlife habitat), some of which may require wider buffers, specific vegetation types, and/or other special considerations (Castelle et al. 1994, Wenger 1999, Fischer and Fischenich 2000).

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Appendices

Appendix 1. *Summary Table of United States Code Referring to "Riparian", "Buffer", "Vegetated", and "Filter Strip". (Source: http://www.gpoaccess.gov)*

United States Code			
Title	**Chapter**	**Part(s)**	
16 - Conservation	1 - National Parks, Military Parks, Monuments, and Seashores	460	
	2 - National Forests	539	
	6 - Game and Bird Preserves, Protection	689	
	36 - Forest and Rangeland Renewable Resources Planning	1604	
	41 - Cooperative Forestry Assistance	2103	2140
	58 - Land and Wetland Conservation and Reserve Program	3831	3839
25 - Indians	11 - Irrigation of Alloted Lands	381	
33 - Navigation and Navigable Waters	9 - Protection of Navigable Waters and or Harbor and River Improvements Generally	465	
	11 - Bridges over Navigable Waters	500	
	36 - Water Resources Development	2336	
42 – The Public Welfare	19 - Water Resources Planning	1962	
43 - Public Lands	23 - Grants of Swamp and Overflowed Lands	994	

Appendix 2. *Summary Table of Code of Federal Regulations Referring to "Riparian", "Buffer", "Vegetated", and "Filter Strip". (Source: http://www.gpoaccess.gov)*

Code of Federal Regulations					
Title	**Chapter**	**Part(s)**			
7 - Agriculture	VI - National Resources Conservation Service	601	610		
	VII - Farm Service Agency	718			
	XIV - Commodity Credit Corporation	1410	1467	1469	
	XVII - Rural Utilities Service	1767			
	XVIII - Rural Housing Service, Rural Business Cooperative, Rural Utilities Service, and Farm Service Agency	1940	1943	1955	
10 - Energy	I - Nuclear Regulatory Commission	51			
18 - Conservation of Power and Water Resources	I – Federal Energy Regulatory Commission	5	380		
	XIII - Tennessee Valley Authority	1304			
30 - Mineral Resources	VII - Office of Surface	15	80	84	715
		717	780	784	816
		817			
36 - Parks, Forests, and Public Property	II - Forest Service	200	228	230	292
40 - Protection of the Environment	I - Environmental Protection Agency	122	412		
43 - Public Lands, Interior	II - Bureau of Land Management	2420	2450	3420	3800
		3809	4100	4120	4130
	III - Utah Reclamation Mitigation and Conservation Commission	10005			
44 - Emergency Management and Assistance	I - Federal Emergency Management Agency	60	206	209	
50 - Wildlife and Fisheries	I - U.S. Fish and Wildlfe Service	17	36	37	
	II - National Marine Fisheries Service	222	223	226	

United States
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