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Setting Priorities for Research on Pollution Reduction Functions of Agricultural Buffers

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ABSTRACT / The success of buffer installation initiatives and programs to reduce nonpoint source pollution of streams on agricultural lands will depend the ability of local planners to locate and design buffers for specific circumstances with substantial and predictable results. Current predictive capabilities are inadequate, and major sources of uncertainty remain. An assessment of these uncertainties cautions that there is greater risk of overestimating buffer impact than underestimating it.

Priorities for future research are proposed that will lead more quickly to major advances in predictive capabilities. Highest priority is given for work on the surface runoff filtration function, which is almost universally important to the amount of pollution reduction expected from buffer installation and for which there remain major sources of uncertainty for predicting level of impact. Foremost uncertainties surround the extent and consequences of runoff flow concentration and pollutant accumulation. Other buffer functions, including filtration of groundwater nitrate and stabilization of channel erosion sources of sediments, may be important in some regions. However, uncertainty surrounds our ability to identify and quantify the extent of site conditions where buffer installation can substantially reduce stream pollution in these ways.

Deficiencies in predictive models reflect gaps in experimental information as well as technology to account for spatial heterogeneity of pollutant sources, pathways, and buffer capabilities across watersheds. Since completion of a comprehensive watershed-scale buffer model is probably far off, immediate needs call for simpler techniques to gage the probable impacts of buffer installation at local scales.

Buffer practices have become widely accepted as important management tools in the effort to reduce agricultural nonpoint source (NPS) pollution of streams and lakes. Agricultural cropland is a major source of pollutants that include sediment, nutrients, and pesticides (US EPA 2000, USDA 1997). Large financial incentive programs have been established by the US Department of Agriculture (USDA) to encourage widespread installation of buffer practices on crop lands in order to reduce NPS pollution among other conservation objectives (e.g., Conservation Reserve Program, Environmental Quality Incentive Program, Conservation Reserve Enhancement Program). The USDA has also enlisted nongovernmental organizations, corporations, and producer groups in the National Conservation Buffers Initiative to help promote enrollment of farm land in these programs.

Despite the magnitude and breadth of buffer programs and initiatives, there remains substantial research to be done to ensure that buffers are effectively applied and that expectations for the amount of pollution reduction are accurate (Dosskey 2001). Buffer installation involves converting portions of crop fields to permanent vegetation. Within a new buffer area, soil becomes stabilized, fertilizers and pesticides are withheld, and pollutants entering in runoff from adjacent crop fields can become trapped among the vegetation and soil (USDA 1999). The weight of existing scientific evidence clearly favors a general inference that widespread buffer installation will significantly reduce agricultural NPS pollution. However, the evidence is qualified for more-specific geographical locations: agricultural land must be a major source of pollutants to streams and lakes; site conditions must be appropriate for buffers to address the specific pollutant problems that exist there; buffers must be properly located, designed (size and vegetation), and managed to address those specific problems. If conditions are not right, the result may be negligible or possibly worsen the pollution problem.

While the existing body of evidence has been convincing enough to justify creation of national initiatives and programs, those programs have created subsequent demand by local land planners for more detailed information required to put buffers on the ground with substantial and predictable results. Faced with major information gaps and immediate needs, some prioriti-

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zation of future research is prudent. The objective of this paper is to propose priorities for future research that will lead more quickly toward better planning and application of buffers for reducing agricultural NPS pollution.

Importance of Predictable Impacts

The most important information that land planners and managers need is reliable estimates of how much impact buffers will have. Accurate prediction is critical in the process of developing acceptable buffer designs and ensuring that they will achieve pollution reduction objectives. Accurate prediction also enables proper evaluation of costs and benefits of investments in individual installations, local watershed projects, and national programs. Given that farm enrollment in US federal programs is voluntary, such information is important to inform and motivate millions of landowners and taxpayers.

Accurate predictions of water pollution reduction may be more important for local projects than national programs. Local planners typically work with limited budgets and may face severe resource, economic, and political consequences if buffers fail. For example, a public works official seeking to avoid a costly drinking water treatment system will need to know with a high degree of certainty what the pollutant levels in the community water supply will be after implementing a pollution-reduction alternative emphasizing buffer installation. A landowner who is reluctant to convert valuable cropland to permanent buffer vegetation may seek assurances that a recommended design uses the minimum amount of land necessary to achieve watershed water quality objectives. In contrast to this local perspective, it may be enough to simply know that widespread enrollment of farmland in buffers will likely, on the average, improve the nation's water quality, in addition to advancing other program objectives. The information requirements for local implementation are far more specific and require greater certainty of the magnitude of the results.

Currently, there is a large uncertainty regarding the level of water quality improvement that can be achieved through installation of buffers on agricultural land. A recent review of the research literature highlighted several major information deficiencies (Dosskey 2001). Among the prominent shortcomings: there has yet to be a study published that directly quantifies the response of pollutant levels in streams to the installation of buffers; few indirect plot-scale studies have employed proper experimental designs for yielding probable estimates; some potentially important buffer processes and impact-governing variables are not well understood; modeling capabilities are very limited for integrating the numerous known variables that govern buffer impacts.

Large uncertainty makes it difficult to set realistic planning goals and develop buffer programs, projects, and installations that can achieve them. For the local planner, the consequences of underestimating impacts of buffers can include: (1) overestimation of buffer design requirements resulting in rejection of a project for being too expensive, (2) overspending on buffers that diverts funds away from other approaches and projects, and (3) installation of extravagant designs that overachieve a planning target. In this latter case, obtaining results beyond the planning goals may be desirable, but come at unacceptably higher cost to the taxpayer and/or the landowner. On the other hand, overestimating buffer impacts can lead to (1) other approaches being considered unnecessary to achieve a planning target, (2) underestimation of buffer costs so that inadequate funding is obtained to achieve the planning target, and (3) installation of buffer designs that fail to achieve the planning target. The larger the error of prediction, the more severe these consequences become.

Sources of Uncertainty

Experimental Data

The most direct estimate of the impact that buffer installation would have on NPS pollution would be a watershed study that measured stream pollutant levels (concentration and/or load) before and after installation of buffers. A study of this kind has not been reported in any of several reviews of research on pollution control functions of buffers (Barling and Moore 1994, Castelle and others 1994, Dosskey 2001, Fennessy and Cronk 1997, Haycock and others 1997, Hill 1996, Lowrance and others 1995, Muscutt and others 1993, US Department of the Army 1991, Vought and others 1994, Wenger 1999). An important role in maintaining low pollutant levels in streams has been shown for existing buffers (e.g., Lowrance and others 1985, Yates and Sheridan 1983), but a change in water quality in response to buffer installation has not.

Most evidence that a change should occur comes from site-scale studies of individual pollution control functions of buffers, including: (1) reduce surface runoff of pollutants from fields, (2) filter surface runoff that flows from fields, (3) filter groundwater that flows from fields, (4) reduce bank erosion, and (5) filter pollutants from stream water. The term "filter" is used

Table 1. Range of site-scale impacts of buffers on selected pollutants[a]

Function	Pollutant type	Reduction observed in outflow (%)	
		Nonbuffered plot outflow vs buffered plot outflow[b]	Buffer inflow vs buffer outflow[c]
		By mass	
		9 studies, grass	
Surface runoff reduction	sediment	47–98	
	water	2–73	
		3 studies, mostly grass, 6–30 m wide, 5–14% slope	14 studies, mostly grass, 0.5–18 m wide, 2–16% slope
Surface runoff filtration	sediment	12–82	40–100
	total P	(−50)–60	27–96
	dissolved P	(−245)–14	(−64)–93
	water	(−163)–66	(−42)–100
		By concentration	
		1 study, grass, 35 m wide	11 studies, mostly forest, 25–125 m wide
Groundwater filtration	nitrate	35	29–100

[a] Reported in research literature for studies based on two different experimental designs: (1) comparison of outflow from buffered cultivated plots with outflow from nonbuffered cultivated plots, and (2) comparison of inflow with outflow from buffers accepting runoff from cultivated land (summarized from Dosskey 2001).

[b] % reduction = [(nonbuffered plot outflow − buffered plot outflow) / nonbuffered plot outflow] × 100%.

[c] % reduction = [(buffer inflow − buffer outflow) / buffer inflow] × 100%.

here to encompass the range of specific processes that act to reduce pollutant amounts in runoff flow. The first function applies to in-field buffers such as contour buffers, vegetative barriers, and grassed waterways. The latter four functions encompass field margin processes associated with filter strips and riparian forest buffers. Stream water filtration can occur during out-of-bank flows across a vegetated floodplain, and by various chemical processes occurring within channel sediments that are promoted by organic debris contributed from buffer vegetation.

Theoretically, if buffer installation improves these functions, then pollutant levels in streams should decrease. Only a minor fraction of the existing body of research studies, however, has compared cultivated sites before and after buffer installation, mainly by way of an experimental analogy comparing pollutant runoff from buffered field plots to that from similar plots without buffers (Table 1). Most of this kind of work has been conducted on in-field buffers.

The largest body of experimental work has concerned filtering processes within buffers themselves and identification of numerous site and design variables that can affect them (Table 1). These experiments consist of comparing pollutant flow into and out of buffers that differ in specific conditions. Results from these studies reveal a high degree of variability, including negative impacts, revealing the sensitivity of impacts to field site and buffer design variables that differ between the studies. Examples of important impact-governing variables that have been clearly identified include pollutant type, amount of inflow, size of buffer, and extent of bypass flow (Table 2). In general, studies of surface runoff filtration have focused on sediment trapping by 3- to 20-m-wide grass buffers, while those of groundwater filtration have focused on nitrate reduction in 25- to 75-m-wide forest buffers. The importance of vegetation type to either of these functions has yet to be clearly established.

Streambank erosion reduction and stream water filtration functions of buffers have received much less research attention. While their existence is well established, the degree to which they can be enhanced in an agricultural setting by installing buffers and contribute to pollution reduction in streams remains to be experimentally addressed.

Any estimate of pollution reduction in streams inferred from existing research is highly uncertain. Observed buffer impacts have ranged from almost complete elimination of pollutant runoff to substantially adding to the problem (Table 1). The tendency will be to overestimate benefits of buffer installation on pollutant runoff for several reasons. First, values for pollutant filtration within buffers are generally greater than val-

Table 2. Major functions of buffers and their impact-governing variables[a]

	Variables	
Function	Field and buffer site conditions	Buffer design and management
√ Surface runoff reduction	√ pollutant type and load	√ distance between contour strips
	√ sediment particle sizes	√ width of buffer strip
	√ surface runoff depth	√ vegetation type and density
	√ slope of buffer	● vegetation harvest
	√ soil permeability of buffer	● sediment removal
	● flow–concentration pattern	
√ Surface runoff filtration	[Same factors and judgement (√) as for surface runoff reduction, except distance between strips does not apply to a field margin buffer.]	
√ Groundwater filtration	√ pollutant type and load	● width of buffer strip
	√ groundwater depth	● vegetation type
	● tile bypass flow	● vegetation harvest
	● groundwater flow velocity	● groundwater depth control
	● soil organic matter content	● tile by-pass flow control
	● flow–concentration pattern	
● Bank erosion reduction	√ stream size	● vegetation type and density
	● stormflow size	● width of buffer strip
	● rate of bank erosion	
	● rate of channel incision	
● Stream filtration	√ pollutant type and load	● vegetation type
	● stream size	
	● flood plain size and access	
	● bed sediment porosity	
	● bed organic matter content	

[a] Summarized from Dosskey (2001). Relatively more experimental information exists for functions and factors that are checked (√). The remainder (●) have received relatively less experimental study or only theoretical assessment in the research literature.

ues obtained by the difference between buffered and nonbuffered sites. Second, runoff filtration experiments have generally been conducted under conditions that would yield a relatively high level of benefit. For example, surface runoff filtration studies have been typically conducted on small plots having low input volume, shallow uniform flow, and high infiltration. Groundwater filtration studies have been predominantly conducted on sites where shallow groundwater flows slowly through the root zones of wetland soils. Third, several potentially important variables that remain to be elucidated most likely will cause estimates to be revised downward. For example, the extent of field runoff flow that bypasses buffer zones or does not contact the entire buffer has not been accounted for in existing research results, and remains largely unquantified. For these reasons, the aggregate of values reported in the research literature may be biased toward the upper limit of benefits that we can expect from widespread installation of buffers.

Modeling Capabilities

Mathematical models present an alternative way to develop predictions of impacts that buffer installation will have on pollutant levels in streams. Both mechanistic and empirical models have been produced. Mechanistic models, based on an understanding of key processes that govern the system, have been created from a foundation of studies that identify important functions (e.g., surface runoff filtration) and elucidate the critical processes and variables that determine their magnitude (Figure 1). Such models help account for numerous impact-governing variables and enable predictions of buffer impacts in different situations. Limitations in the amount and kind of experimental data available have generally favored the development of mechanistic types of buffer models to describe filtration of surface runoff and groundwater at the field margin. Empirical models, based directly on many observations of buffer installation and impact, have been developed for in-field buffers.

Buffer modeling has typically started with site-scale representation of an individual function. Then, site scale function models can be combined, followed by scaling up to watersheds, or vice versa. Scaling up to watersheds involves describing and accounting for spatial patterns of important processes and impact-governing variables throughout a watershed.

At this time, a comprehensive watershed model that predicts buffer impacts on pollutant levels in streams is not available. Modeling of each of the component buffer functions is at a different stage of development

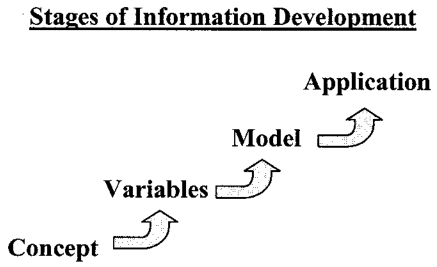

Figure 1. Progression of information and model development on buffer functions. These stages have feedback loops not shown. Models can be just as valuable for identifying important factors needing further experimental research as in predicting benefits from buffer application.

(Figure 2). Models have been developed and used to design in-field buffers and filter strips (e.g., Flanagan and others 1989, Renard and others 1997) and to predict their impact on surface runoff from fields and surface runoff filtration (e.g., Hamlett and Epp 1994, Munoz-Carpena and others 1999, Williams and Nicks 1988). A site-scale model, REMM, has been developed recently that couples surface and groundwater filtration functions of buffers, but remains to be widely validated (Lowrance and others 2000). Some attempts have been made to scale-up predictions of individual buffer functions to watersheds (e.g., Tim and Jolly 1994, Prato and Shi 1990). Streambank erosion and stream filtration functions have yet to be modeled in a way that allows quantitative prediction of impacts from buffer installation.

A substantial amount of model development and experimental work remains to be done to produce a model capable of reliable prediction of stream response to installation of buffers. The accuracy of buffer models increases as we expand our knowledge of impact-governing variables and incorporate that knowledge into mathematical models. While modeling of buffer impacts on surface runoff from fields and filtration of surface runoff at field margins is relatively well advanced, there still remain potentially important site and design variables for all component functions that are incompletely understood (e.g., Table 2).

How Should Future Research be Prioritized?

The information gaps summarized above cast substantial uncertainty over the level of pollution reduction to expect from existing programs and projects that involve installation of buffers. Given the immediacy of information needs, priority should be given to research avenues that can quickly yield the greatest advances in predictive capability.

A two-step screening process was used here to identify priority research avenues. The first step was to rank individual functions for their probable universal contribution, or importance, to the amount of pollution reduction from buffer installation. Then, each function was ranked on degree of uncertainty associated with predicting that level of pollution reduction. Highest priority for research was assigned to important functions that also have high uncertainty. Results of this process were further subdivided by pollutant type. Variables associated with important functions that create substantial uncertainty are topics of greatest research value.

The rankings are based on a what is believed to be a consensus interpretation of research results published in the peer-reviewed scientific literature. There is substantial subjectivity associated with these judgements. However, this approach should facilitate identification of broad categories of topics that have particularly high research value and guide further discussions of research priorities.

Research Priorities

Experimental Studies

The most universally important pollution reduction functions of buffers are surface runoff reduction from crop fields and surface runoff filtration at field margins (Table 3). Surface runoff erodes and transports cultivated surface soil along with its content of nutrients and pesticide amendments. Surface runoff transports all sediment and sediment-bound pollutants to streams along with major portions of dissolved pollutants. Buffers have the greatest potential for preventing surface transport of pollutants from fields and for intercepting and trapping them at field margins.

Of these two functions, the magnitude of surface runoff filtration is the least certain. Numerous site and design variables have already been identified that govern the ability of buffers to filter pollutants from runoff, but mathematical models designed to integrate them are not complete. Some additional, potentially important variables remain little studied. Almost all the previous studies of this function have been conducted under ideal conditions for filtering pollutants: small runoff events, sheet flow, and short-term studies. However, most pollutants are transported in large storm events (Larson and others 1997), concentrated runoff flows through buffers may greatly reduce their effectiveness (Dillaha and others 1989), and accumulations of sediment and nutrients in buffers may reduce subsequent longer-term filtering capability (Dillaha and

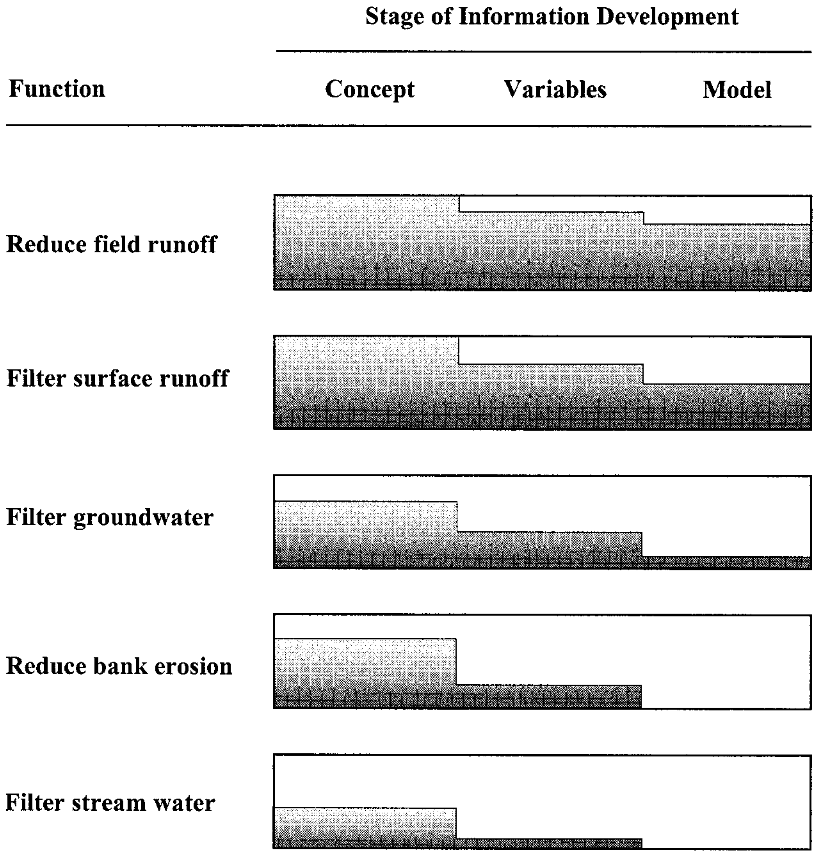

Figure 2. Status of information and predictive model development for each component pollution reducing function of buffers. Shaded area represents the relative degree of completion (based on the review of literature by Dosskey 2001).

others 1988). Theoretically, each of these variables will limit buffer effectiveness in some relation to the magnitude of their extent. Beyond that, it remains uncertain how to account for these unknowns when designing buffers and estimating the likely impact of their installation on the level of pollutants in streams. A better understanding of long-term accumulation of pollutants also has important implications for management of buffers to maintain filtering capability.

There is greater predictive certainty for surface runoff reduction from fields, coming from decades of field erosion control research and empirical modeling that includes strip cropping, a practice similar to contour buffers. Furthermore, in-field buffer studies have exclusively compared outflow from buffered plots with that from unbuffered plots, an experimental comparison that simulates the impact of installing buffers better than by observing buffered plots alone. In contrast, studies of filtering by field margin buffers has focused dominantly on buffered plots alone. A few remaining sources of uncertainty regarding in-field buffers include quantifying their capability to reduce gully erosion and to retain dissolved nutrients and pesticides.

Other functions of buffers are less universally important than surface runoff control. In some regions, conditions may lend themselves to substantial reduction of stream pollution by groundwater filtration of nitrogen and stabilization of eroding streambank sources of sediments (Table 3).

Groundwater flow is likely to be a major transport pathway for nitrate-nitrogen in intensively farmed regions where fields have relatively coarse-textured soil and low slope, so that rainfall is more likely to infiltrate and percolate to the groundwater. For field margin buffers to address groundwater nitrate, the subsequent groundwater flow to streams must occur mainly in or near the root zone of buffer plants. High infiltration and confined shallow groundwater flow conditions occurs widely along the eastern US Coastal Plain (Lowrance and others 1995, 1997), and may occur locally in other regions. Since root zone groundwater is generally incompatible with good crop growth, however, it is likely that artificial drainage systems have been constructed to lower the water table. For conversion of cropped areas to buffer vegetation to work effectively in such areas, removal of the drainage system is probably also required. Little work has been done to quantify the groundwater contributions of nitrate to overall levels of

Table 3. Comparison of the probable level of impact that each individual buffer function can contribute to NPS pollution reduction nationwide (level of importance) by pollutant type, and the relative degree of uncertainty associated with that estimate[a]

	Level of importance, degree of uncertainty					
Function	Sediment	P	N	Pesticides	Constraints on benefits	Major sources of uncertainty
Surface runoff reduction	H	H	M	M-H	Extensive cultivation	Flow-concentration of runoff
	l	l	m	m	Flow–concentration of runoff	Limited data on dissolved pollutants
					Limits on enhanced infiltration	
					Sediment buildup	
					Site nutrient saturation	
Surface runoff filtration	H	H	M	M-H	Flow–concentration of runoff	Comparison to unbuffered condition
	h	h	h	h	Limits on enhanced infiltration	Flow–concentration of runoff
					Sediment buildup	Pollutant accumulation
					Site nutrient saturation	Long term impacts
Groundwater filtration	O	L	M	L	Deep groundwater and tile bypass flow	Comparison to unbuffered condition
	l	h	h	h	Aerobic conditions in buffer soil	Extent of applicable sites
					Short residence time of groundwater in buffer	Site nutrient saturation
					Site nutrient saturation	Comparison of vegetation types
Stream bank erosion reduction	M	L	L	O	Channel incision	Identify excessive bank instability
	h	h	h	h	Excessive bank instability	Limited data
						Extent of applicable sites
Stream water filtration	L	L	L	L	Noncropland sources of pollutants	Comparison to unbuffered condition
	m	m	m	m	Course of bed sediments	Limited longer-term data
					Existing sources of organic matter	Intermittent and ephemeral channels
					P saturation of sediments	
					Scour by large storm flows	
					Access to floodplain	

[a] H, M, L, and O refer to high, medium, low, and negligible impact, and h, m, and l refer to high, medium, and low uncertainty, respectively. For each function, some major constraints on the upper limit of impact and major sources of uncertainty are listed. P = phosphorus; N = nitrogen.

nitrogen in agricultural streams outside of the eastern US Coastal Plain and to describe the extent of artificial drainage systems and deeper groundwater flow to channels that would circumvent buffer installations. Groundwater nitrate filtration is commonly associated with riparian forests. The importance of trees to this function is uncertain. Since there is substantial resistance by farmers to planting trees adjacent to streams in intensively agricultural regions like the central United States, it is important to understand the capabilities of alternative vegetation types. Included here are longer-term vegetation management requirements for maintaining these capabilities. Contrasting nitrate removal in riparian buffer zones with cultivated crops in those same zones is critical for accurately estimating how much the nitrate filtration process can be enhanced by buffer installation.

Erosion of streambanks is a major source of sediment to streams in some regions, particularly where there are deep loess soils (e.g., in Iowa, Mississippi). Highly erodible channel materials in these regions have been exposed to elevated erosional forces through a combination of bank clearing, channel straightening, and increased runoff flows from land converted to cultivated agriculture. Buffer installation in eroding riparian zones can add protection and stability to bank soils. However, the effectiveness of buffers to halt bank erosion may be limited. Buffers may not be capable of stabilizing stream reaches undergoing rapid incision and widening. The degrees of stream instability that buffers are capable of addressing effectively have yet to be clearly defined, as well as their extent in farming regions. Another difficulty of deriving estimates of stream sediment reduction through bank stabilization is the relative dearth of information on what proportion of stream sediment load comes from banks compared to field erosion.

Stream water filtration by deposition of sediment on floodplains and denitrification in channel sediments are probably universal functions but probably exert a low impact on long-term stream loads. Opportunities to enhance these functions through installation of buffers appears limited. In intensely farmed regions, many streams are disconnected from their floodplains, and there are other sources of organic matter to channel sediments. There may be opportunities for local enhancement of these processes through installation of buffers, but research on the streamwater filtration function of buffers is less likely to bring major universal advancements in buffer application than research on other functions.

Modeling

A comprehensive, watershed-scale prediction model remains a desirable longer-term goal for buffer research. It may represent the only practical way to integrate numerous site and design variables and enable planners to make accurate predictions of buffer impacts on pollutant levels in streams in many different agricultural settings. Substantial work remains, however, to complete the development of component models that adequately describe surface and groundwater filtration, create models that describe streambank erosion reduction and stream water filtration, and spatially integrate them into one watershed-scale model. Furthermore, some watershed-scale experimental data must be collected in order to fully validate a comprehensive model.

In the interim, models that enable useful approximations are needed. Completion of a surface runoff filtration model that accounts for concentrated flow and pollutant accumulation variables will greatly improve our capability to address a universally important, but currently unpredictable function of buffers. Dramatic improvement is also possible by expanding field-scale runoff models with geographical information systems (GIS) to identify locations of prominent pollutant sources (e.g., Endreny and Wood 1999), then coupling with buffer models that quantify surface runoff filtration and reduction. Tools of this kind would enable planners to effectively locate, design, and predict impacts of buffer installation in most watersheds. Models that are made available, however, must be easy to use. Generalized models and scoping tools, in place of precise parameter-intensive simulation models, will probably gain wider acceptance and use by local planners. Different modeling approaches may be possible for this purpose. For example, a reference-based index approach may offer a useful alternative to mathematical modeling (e.g., Rheinhardt and others 1999).

Collection of watershed-scale experimental data are still important for testing the accuracy of any stream pollution prediction model. Watershed-scale experimental studies, however, have proved to be time consuming and particularly difficult to conduct successfully (Addiscott and Mirsa 1998, Gale and others 1993, Sutton and others 1996). Nevertheless, production of stream response data is critical to confirm that buffer installation indeed reduces agricultural NPS water pollution of streams and to validate a watershed-scale impact prediction model when it becomes available.

Conclusions

The existing body of research clearly indicates potential for buffer installation to substantially reduce agricultural NPS pollution of streams. In order to realize that potential, however, local planners require detailed information on which to base buffer designs and ensure acceptable and effective installations. Information that enables accurate prediction of local impacts is critical to the success of local installations, watershed projects, and national programs and initiatives.

Priorities for future research and model development are proposed that will lead more quickly toward better planning and application of buffers to achieve pollution reduction goals. Research that improves our understanding of surface runoff filtration by field margin buffers represents the greatest opportunity to quickly advance predictive capabilities for the broadest range of agricultural pollutants and in most watersheds. Quantitative assessment of the extent and consequence of runoff flow concentration and pollutant accumulation in buffers are key variables that remain to be clarified in order to remove substantial uncertainty regarding how much pollution reduction buffer installation will yield and identify management actions that may be necessary to maintain a high level of impact.

In some regions and locales, buffer filtration of groundwater and stabilization of eroding streambanks may be able to substantially reduce stream pollution by nitrate and sediment, respectively. Information is still needed that will enable a planner to identify site-specific conditions where buffers can effectively function in these ways.

Completion of an accurate comprehensive watershed-scale buffer model is probably far off. Deficiencies in predictive models generally reflect gaps in experimental information and in technologies for describing spatial heterogeneity of pollutant sources, pathways, and buffer capabilities across watersheds. Immediate needs call for simpler techniques that account for the major functions and variables. Generalized models and scoping tools can be developed more quickly than comprehensive simulation models, and will likely gain wider acceptance and use by local planners.

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