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:IMPRINT: Oxford, Eng., Blackwell Scientific Publications.
:ARTICLE: Osborne L.L.; Kovacic D.A. "Riparian vegetated buffer strips in water-quality restoration and stream management"
:VOL: 29 :NO: 2 :DATE: 1993 :PAGES: 243-258
:VERIFIED: OCLC ISSN: 0046-5070 [Format: Serial]
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Freshwater Biology (1993) **29**, 243–258

Riparian vegetated buffer strips in water-quality restoration and stream management

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SUMMARY

1. A review is presented of the literature on riparian vegetated buffer strips (VBS) for use in stream-water-quality restoration and limitations associated with their use are discussed. The results are also presented of recent investigations on the effectiveness of a forested and a grass vegetated buffer strip for reducing shallow subsurface inputs of nutrients from agriculture to a stream in central Illinois, U.S.A.
2. Because riparian zones link the stream with its terrestrial catchment, they can modify, incorporate, dilute, or concentrate substances before they enter a lotic system. In small to mid-size streams forested riparian zones can moderate temperatures, reduce sediment inputs, provide important sources of organic matter, and stabilize stream banks.
3. Several questions on the utility and efficiency of vegetated buffer strips for stream restoration still remain unanswered, including: what types (grass *v* forest) are most efficient; do they become nutrient saturated; are they only temporary sinks; how does species composition influence effectiveness; and, what is the optimal width of buffer to facilitate nutrient reduction under different conditions?
4. Water samples were collected (1989–90) from lysimeters located at three depths (60, 120, and >120 cm) in an upland area planted in conventional row crops (corn and soybean) and in three adjacent riparian buffer treatments, a 39 m wide grass buffer, a 16 m wide mature forested buffer, and a buffer planted in row-crops to the stream bank. Concentrations of dissolved and total phosphorus and nitrate-N in each sample were determined following major precipitation events over a seventeen month period.
5. Both the forested and grass VBS reduced nitrate-N concentrations in shallow groundwater (up to 90% reduction). On an annual basis the forested VBS was more effective at reducing concentrations of nitrate-N than was the grass VBS, but was less efficient at retaining total and dissolved P.
6. During the dormant season, both grass and forested buffer strips released dissolved and total P to the groundwater. The VBS apparently acted as a nutrient sink for much of the year, but also released accumulated nutrients during the remaining portion of the year. Periodic harvesting of plant biomass may reduce the amount of P released during the dormant season.
7. VBSs are not as effective in agriculture areas with tile drained fields. Alternative restoration practices such as discharging drain tiles into wetlands constructed parallel to the stream channel may prove to be a more effective means of controlling non-point-source agricultural inputs of nutrients in such areas.

Introduction

Humans are only beginning to appreciate and understand the costs and global implications associated with past land-use practices, the demands of a continually increasing human population, and the cumulative impacts (*sensu* Preston & Bedford, 1988) of local modifications to the landscape and their influence on fundamental ecological processes. Recognition of such impacts on aquatic ecosystems and the need to 'sustain' these systems has stimulated interest and research in the areas of restoration and protection. Restoration and protection of physical and chemical conditions are fundamental to all water-quality regulation in North America (Novotny, 1988). Water-quality restoration has been defined as 'returning the concentration of substances to values typical of undisturbed conditions' (Herricks & Osborne, 1985) and implicitly assumes that an impact or a disturbance (Pickett & White, 1985; Resh *et al.*, 1988) has occurred.

For any lotic system, a continuum of environmental conditions can exist ranging from a 'natural or pre-impacted' state to a degraded 'impacted' state. Water-quality impacts originate from point and diffuse sources and each successive insult pushes conditions to a more degraded state. Recognizing that even poor conditions can get worse promulgated the institutionalization of protection programmes that attempt to maintain the environmental condition of a system. Alternatively, restoration forces environmental conditions in the opposite direction from that of impacts.

Ideally, a restoration programme should return water-quality concentrations to a close approximation of a system's pre-impacted or natural condition (National Research Council, 1992). Such a goal is difficult, if not impossible to achieve because humans have extensively modified the land cover in most catchments, thereby altering important landscape processes. Often, there are limited empirical data on what pre-impact or natural conditions and concentrations were. Therefore, a more practical water-quality restoration goal is the reduction in the intensity, magnitude, or frequency of disturbance. Reduction can involve treatment, conversion, or alteration of substances prior to their entry into the aquatic system (e.g. denitrification, incorporation into plant biomass, retention), or a reduction in the amount of the substance being discharged.

Existing restoration strategies

The most commonly used restoration strategies are isolation, removal, transfer, and dilution of a pollutant through space and time (Herricks & Osborne, 1985). Historically restoration strategies have been tied to engineering disciplines (Warren, 1971) and usually require that the target substance be concentrated in a centralized location before treatment. The economics associated with centralized treatment necessarily limits the application of many technology-based removal, isolation, and transfer procedures to point-source disturbances. Similarly, dilution requires sufficient space or time to permit natural cleansing processes to occur, without which it too will become unsuccessful.

Unlike point-source-pollution control programmes, no single strategy is likely to be effective in restoring water-quality conditions in streams suffering from diffuse source impacts. Diffuse-source water-quality pollution occurs because human activity has altered the structure of the landscape and increased the quantity of substances (e.g. nitrogen, phosphorus) in the catchment (natural pools or external inputs) thereby altering the rate at which natural processes operate and cycling occurs. Therefore, a catchment strategy is advocated that uses best-management practices and techniques that incorporate natural physical and biological processes to reduce, convert, or store pollutants on the land before they enter the aquatic system (e.g. Ritter, 1988; Lynch & Corbett, 1990; Petersen, Petersen & Lacoursiere, 1992) combined with a rational input management policy (see Odum, 1987, 1989). This is referred as a bioassimilation strategy, and is believed to be the only ecologically sound, sustainable, and cost-effective approach for restoring water-quality conditions in lowland streams.

In the United States, agriculture-derived contaminants (e.g. sediment, nutrients, pesticides) constitute the single, largest diffuse source of water quality degradation (Maas *et al.*, 1984; U.S. Department of Agriculture, 1985; Baker, 1985). Numerous approaches have been adopted for mitigating the adverse impacts of agriculture practices within the context of a bioassimilative strategy. These include the use of riparian vegetative buffer strips (VBS). Although riparian VBS have recently become an accepted management practice under the Conservation

Reserve Program in the United States (Prato & Shi, 1990), several important and fundamental questions regarding their efficiency, composition, necessary width, and structure still need to be addressed. The use of riparian VBS can be expected to increase; thus, it is imperative that resource managers, catchment planners, and economic and ecological modellers be provided with detailed information on their efficiency, capabilities and limitations. Within this paper a brief summary is provided of the riparian VBS literature for use in stream-water-quality restoration. Additionally, the results are presented of a recent investigation on the effectiveness of forested and grass VBS for reducing shallow subsurface inputs of agriculture nutrients to a stream in Illinois, U.S.A. We also identify some potential limitations to the use of VBS.

Water-quality function of vegetated buffer strips

Riparian ecosystems link stream environments with their terrestrial catchment. Because of this physical proximity, riparian ecosystems influence the structure of both aquatic and upland terrestrial communities and affect important functional processes in the stream channel. For instance, the riparian ecosystem can influence: hydrological condition by modifying storage capacity and aquifer recharge; in-channel primary and secondary productivity and organic-matter quality and quantity; biodiversity and migratory patterns; and, biogeochemical pathways and rates (Sharitz *et al.*, 1992). Regarding the latter, riparian zones can modify, incorporate, dilute, or concentrate substances before they enter a lotic system. For these reasons, riparian buffer strips have been adopted as a viable and useful tool for restoring and managing streams and rivers. In small to mid-size streams, narrow bands of forested vegetation paralleling the stream can moderate temperatures, reduce sediment input, provide important sources of organic matter to lotic communities, and stabilize stream banks.

Moderating stream temperature

Forested VBS can reduce inputs of solar radiation and thereby minimize temperature fluctuations of the stream water. In small, heavily shaded streams, removal of riparian vegetation can dramatically increase stream temperatures (Burton & Likens, 1973; Karr & Schlosser, 1977; Feller, 1981). The amount of influence that riparian vegetation will have on stream temperature is dependent upon geographical location, groundwater input, and VBS width, composition, and density. From a restoration perspective, VBS width, composition, and density are economically modifiable. In North America VBS widths between 10–30 m have been shown to maintain effectively stream temperatures (Table 1).

Sediment reduction

Sediment loading and deposition constitutes one of the most serious water-quality problems throughout the world. There is general agreement from both experimental and field studies that fairly narrow VBS that maintain shallow sheet flows can protect streams from excessive sediment loading (Table 2). Gough (1988) argued that efforts by many land managers to establish singular, generic standards for VBS widths are inappropriate as they are based on an over-simplification of complex physical processes. Factors other than width and sediment input that are important in dictating the efficiency of VBS for reducing sediments are micro- and macro-relief, vegetation density and type which dictates hydraulic resistance, litter characteristics, soil characteristics (especially infiltration), particle size distribution of

Table 1 Width of forested vegetated buffer strips that maintained ambient stream temperatures and their geographic location. *Source U.S. Department of the Army (1991)

Buffer width (m)	Geographic location	Authors
10–20	West Virginia	Aubertin & Patric, 1974
12	North Carolina mountain stream	Corbett, Lynch & Sopper, 1978
31	Pennsylvania	Lynch & Corbett, 1990
10	Oregon mountain stream	Brazier & Brown, 1973

Buffer width (m)	Geographic location	Upland disturbance	Authors
9	Idaho	Logging road	Haupt & Kidd, 1965
15–45*	New Hampshire	Logging road	Trimble & Sartz, 1957
10–20	West Virginia	Clearcut	Aubertin & Patric, 1974
19	Maryland	Agriculture	Peterjohn & Correll, 1984
19	Illinois	Agriculture	Kovacic & Osborne (unpublished data)

* Range dependent on slope; see Karr & Schlosser, 1977.

Table 2 Results from field studies on the width of vegetated buffer strips that removed a substantial portion of sediments in overland flow from a variety of disturbances and geographic locations. (Source Karr & Schlosser, 1977 and Gough, 1988)

incoming sediments, subsurface drainage, slope, and temporal distribution of contributed sediment loads (Gough, 1988). Several management models for estimating sediment erosion have been suggested for specific conditions, and geographical locations including those by Trimble & Sartz (1957), Haupt (1959), Tollner *et al.* (1976), Foster (1982), Wong & McCuen (1981), Barton & Taylor (1985), and Barfield, Tollner & Hayes (1979).

Despite the obvious complexity of the sediment-filtering process, the results from numerous field studies, including those reviewed by Karr & Schlosser (1977), indicate that fairly narrow strips of riparian vegetation can reduce sediment input to surface water (Table 2). More research is needed on the long-term fate of this material as some controlled experimental results have indicated that the effectiveness for sediment removal decreased with time because of sediment accumulation in the filters (Dillaha, Sherrard & Lee, 1986).

While these results demonstrate that VBS can reduce sediment inputs, it should be emphasized that their effectiveness will be dependent on a complex interaction between numerous environmental factors. Also, many of the models developed to date assume shallow sheet flow (Dillaha *et al.*, 1986), a condition that is difficult to maintain in the field.

Nutrient reduction

In areas dominated by agriculture, a major goal of stream restoration is reducing the amount of nutrients entering the stream. Planting and/or preserving riparian VBS has been recommended as an effective and economically feasible procedure for reducing inputs of nitrogen and phosphorus. Among the processes involved are: retention of sediment-bound nutrients in surface runoff; uptake of soluble nutrients by vegetation and microbes; and, absorption of soluble nutrients by organic and inorganic soil particles (U.S. Department of the Army, 1991).

In a review of the literature Petersen *et al.* (1992) reported that forested VBS reduced N in groundwater by 68–100% and in surface runoff by 78–98%. They also concluded that the amount of reduction was dependent on initial concentrations of N in subsurface and surface water before passing through the VBS, the width of the VBS, and the soil type. We conducted a similar review, but also included studies that examined the effectiveness of grass VBS and those that measured total P (Table 3). This review indicated N reductions of 40–100% in subsurface waters due to forested VBS. The limited information on grass VBS reveals N reductions of 10–60% (Table 3). Data on the influence of VBS on P concentrations in subsurface waters were also limited and no clear pattern of effect was evident (Table 3). Peterjohn & Correll's (1984) study indicated that P concentrations increased in subsurface waters. Forested VBS 30–50 m in width reduced nitrate concentrations in surface runoff by 79–98% while grass buffers 4.6–27 m in width reduced nitrate concentrations by 54–84% (Table 3). Forested VBS 16–50 m in width reduced P concentrations in surface waters by 50–85% while grass VBS 4.6–27 m in width reduced P concentrations by 61–83% (Table 3).

These data demonstrate that fairly narrow forested VBS effectively remove nitrate from both surface runoff and groundwater. In any study the nutrient removal efficiency of VBS will probably be dependent upon many factors, including, sedimentation rates, surface and subsurface drainage characteristics, soil characteristics (i.e. oxidation–reduction potential), organic matter content and type (James, Bagley & Gallagher, in press), temperature, successional status

Table 3 General results from previous studies on the efficiency of removal of nitrate-N and P from surface and subsurface waters by forested and grass vegetated buffer strips. A range in the per cent indicates that seasonal mean values were reported. Negative percentages indicate that concentrations increased rather than decreased

Width (m)	Parameter	% Reduction	VBS type	Reference
Subsurface				
10	N	60–98	Forest	James, Bagley & Gallagher, in press
16	N	93	Forest	Jacobs & Gilliam, 1985
19	N	93	Forest	Peterjohn & Correll, 1984
19	N	40–90	Forest	Schnabel, 1986
25	N	68	Forest	Lowrance, Todd & Asmussen, 1984
30	N	100	Forest	Pinay & Decamps, 1988
50	N	99	Forest	Peterjohn & Correll, 1984
27	N	10–60	Grass	Schnabel, 1986
19	P	33	Forest	Peterjohn & Correll, 1984
50	P	−114	Forest	Peterjohn & Correll, 1984
Surface				
30	N	98	Forest	Doyle, Stanton & Wolf, 1977
50	N	79	Forest	Peterjohn & Correll, 1984
9	N	73	Grass	Dillaha *et al.*, 1989
5	N	54	Grass	Dillaha *et al.*, 1989
27	N	84	Grass	Young, Huntrods & Asmussen, 1980
16	P	50	Forest	Cooper & Gilliam, 1987
19	P	74	Forest	Peterjohn & Correll, 1984
50	P	85	Forest	Peterjohn & Correll, 1984
9	P	79	Grass	Dillaha *et al.*, 1989
5	P	61	Grass	Dillaha *et al.*, 1989
27	P	83	Grass	Young, Huntrods & Asmussen, 1980

of vegetation, and nutrient loading rates from the upland and slope (U.S. Department of the Army, 1991). The efficiency of grass buffer strips in removing nutrients from groundwater is less well known, while both forested and grass VBS appear to remove substantial proportions of P from surface runoff. There is no clear evidence as to their efficiency for removing soluble P in subsurface waters.

Because of the differences in study designs, it is not possible to assess whether forested VBS are more efficient than grass VBS from these data. Although there are exceptions, nutrient removal efficiency increases with width of the VBS as reported by Petersen *et al.* (1992). The long-term effectiveness of VBS as nutrient filters remains unknown, however. Studies have indicated that riparian areas are long-term sinks for total P, while soluble forms are released during periods of increased discharge (e.g. Cooper, Gilliam & Jacobs, 1986). Mineralization of biologically bound phosphorus and nitrogen (Lowrance, Todd & Asmussen, 1984) and subsequent transport to the stream channel also occurs seasonally. For these reasons, Omernik, Abernathy & Male's (1981) concern over the long-term effectiveness of VBS needs to be addressed through controlled experiments and detailed nutrient-budget analyses.

Despite the extensive work completed on this topic, several questions and controversies regarding the utility and efficiency of VBS for stream-restoration programmes still remain unanswered or unresolved. For instance, what types of riparian VBS are most efficient at reducing land-use impacts to streams? Do VBS become saturated with sediment and nutrients, thereby becoming ineffective? Are they only temporary sinks? Does species composition make a difference? What is the necessary width of a VBS for specific regions and conditions? Such questions are important in all restoration programmes and particularly in areas dominated by row-crop agriculture where, historically, the natural riparian vegetation was removed to facilitate drainage and reduce shading of crops and sources of nuisance weeds.

Any proposed restoration strategy, regardless of its ecological merits, needs to be economically feasible and socially acceptable if it is to be adopted and implemented on a landscape level. Large-scale acceptance and implementation may involve changing age-old practices and approaches that is only possible through comprehensive education and extension programmes and well-conceived government policies and support programmes. Because the economic costs of such programmes can be high, it is imperative that decisions be based on sound scientific information. Below we present data from our study site in central Illinois to add to this growing body of literature.

Study design and methods

The study was conducted along a 1-km reach of the East Branch of the Embarras River, in southeastern Champaign County, Illinois (Fig. 1). This area is dominated by row-crop agriculture and characterized by low-relief glacial till plain overlain with loess. Stream density is typically 0.62 km km^{-2} with numerous constructed ditches and channelized natural waterways to assist land drainage. Drummer–Kendall–St Charles is the dominant soil association overlying a dense basal till. Adjacent to the Embarras River the dominant soil is Colo silty clay loam. The soil structure facilitates downward water penetration on the cropped uplands to the basal till where the flow is directed laterally toward the Embarras River. With the exception of the forest and grass riparian VBS noted below, the majority of the area is drained by subsurface tiles.

The site was divided into an upland zone planted in a corn–soybean rotation (1988 and 1989, respectively) and a riparian zone that was divided into three treatments that paralleled the west bank of the channel: row crops planted to the stream bank; a riparian forest (approximately 16 m wide) dominated by mature cottonwood (*Populus deltoides*) and silver maple (*Acer saccharinum*); and, a 39-m-wide buffer of reed canary grass (*Phalaris arundinacea*) between the stream and row crops (Fig. 1). We investigated the effects of these riparian treatments on concentrations of nitrate-N, dissolved (DP) and total phosphorus (TP) in solutions collected from shallow (60 cm) and deep (120 cm) ceramic cup (#653X01-B2M2, Soil Moisture Equipment Corporation, Santa Barbara, California) lysimeters (7.6-cm-diameter PVC; Kovacic, Osborne & Dickson, 1990) and piezometers (>120 cm) from January 1989 to May 1990 (Fig. 1). Piezometers (length dependent on depth to aquiclude) were constructed from 5.1-cm-diameter PVC pipe (ASTM 2665). The bottom 30 cm of pipe, perforated with 1-cm-diameter holes, was covered with a fibreglass screening to prevent soil movement into the sampler.

Lysimeters were placed in hand-augured holes and the ceramic cup set into a silica slurry. To mini-

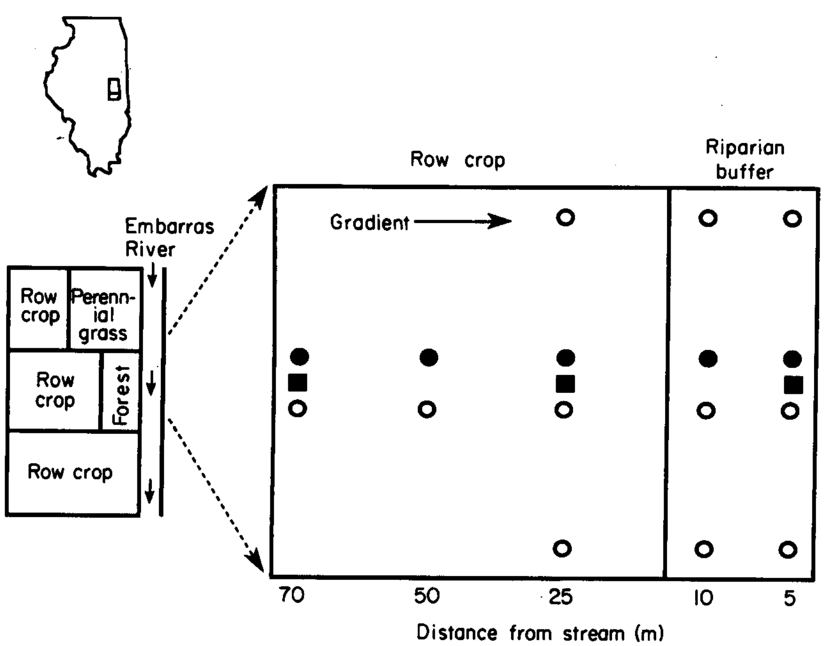

Fig. 1 Location of Embarras River study site in east-central Illinois and details of study showing location of shallow (○) and deep (●) lysimeters and piezometers (■).

mize vertical movement of water and contamination from the surface a 15-cm collar of bentonite clay was tampered around the bottom (5 cm above the ceramic cup) of each lysimeter. The remainder of the hole was backfilled with the augured soil to retain the original soil-profile structure.

Water samples were collected on roughly a monthly basis following precipitation events of sufficient magnitude and duration to initiate surface runoff and allow soil infiltration to track nutrient movement. One to two days before sample collection all lysimeters and piezometers were cleared of water and each lysimeter evacuated to approximately 50 centibars. Water samples were analysed for nitrate-N, total and dissolved P according to Standard Methods (APHA, 1985). Nitrogen analyses were performed on a Technicon GTpc Auto Analyzer II. Transformed (natural logarithm) concentrations in solution at each sampling depth were analysed for the effects of zone (upland crop *v* riparian) and buffer type (crop, grass, and forest) using analysis of variance.

Results and Discussion

Forest v grass vegetative buffer strips

A basic question for those concerned with the restoration of lowland streams is: are forested VBS more effective than grass VBS at reducing nutrients? Much previous research has concentrated on the ability of VBS to reduce nutrient and sediment inputs to streams via surficial water transport. Because the discharge in many streams is dependent on groundwater, it follows that a substantial portion of the total annual nutrient load entering streams could do so via subsurface pathways. Kovacic, Osborne & Dickson (1990) estimated that 29% of the total phosphorus and 35% of the total nitrate-N loads in the Embarras River entered via subsurface sources. Because they were unable to account for potential denitrification in the stream channel (Hoare, 1979), it is likely that these are underestimates.

Significant interactions occurred when the effects of buffer type (crop, grass, forest) and zone (upland and riparian) on shallow (60 cm) subsurface concentrations of nitrate-N, TP, and DP were examined suggesting a non-linear response of buffer types within zones. No significant differences were found in the concentrations of DP ($F_{2,69} = 1.3137$; $P = 0.2754$), TP ($F_{2,58} = 1.368$; $P = 0.2626$), and nitrate-N ($F_{2,95} = 0.811$; $P = 0.448$) in the upland zone reflecting the homogeneous environmental and land-use conditions (e.g. fertilizer application rates, soil types, and crop cover) in this zone.

Dissolved and total P in shallow groundwater

In the riparian zone, cover type had significant effects on the concentrations of nutrients in shallow lysi-

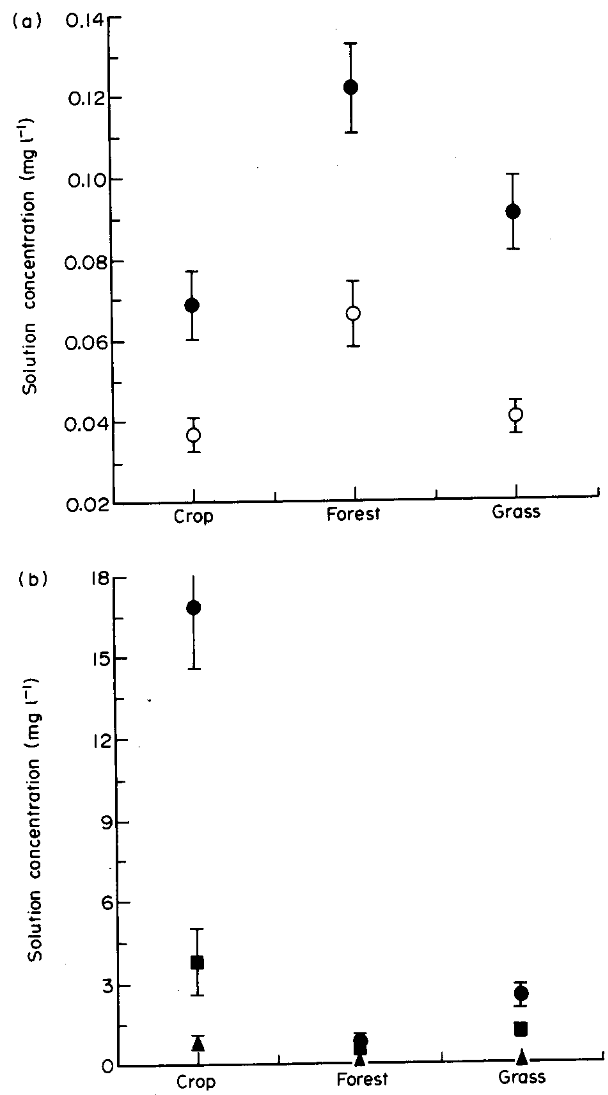

Fig. 2 Mean concentrations of (a) dissolved (○) and total (●) phosphorus (±standard error) in shallow lysimeters, and (b) nitrate-N in shallow (●) and deep (■) lysimeters and piezometers (▲) in the crop, forest, and grass riparian vegetated buffer strips.

meters (Fig. 2). Significantly higher concentrations of DP and TP occurred in lysimeter solutions in the forest than occurred in the crop or the grass buffers (Fig. 2). No significant differences were found in TP and DP concentrations between the crop and grass VBS. The higher concentrations of P in the groundwater in the forest VBS suggest that mature riparian forests may accumulate P to a greater extent than grass VBS but also leak it through shallow groundwater at a greater rate. Significantly higher concentrations were also found of TP ($0.122 \pm 0.011\,mg\,l^{-1}$) and DP ($0.066 \pm 0.008\,mg\,l^{-1}$) in the riparian forest compared to the upland crop area (0.058 ± 0.010 and $0.013 \pm 0.001\,mg\,l^{-1}$, respectively). No significant differences were found in DP and TP concentrations between the grass and upland crop sites (Fig. 3) suggesting that the grass VBS did little to reduce P in shallow groundwater.

Because the slope, soil types, climatic conditions and upland land use near the forested and grass VBS were similar, it was assumed that the flows of subsurface water through these VBS were also similar. Further, the lack of a significant difference in DP and TP concentrations in lysimeters in the upland crop zone suggests that P loading via shallow subsurface water into the grass and forested VBS should also be similar. The higher concentrations of DP and TP in shallow subsurface groundwater samplers in the forested VBS therefore suggest that the mature riparian forest may be a less efficient P sink than the grass VBS on an annual basis.

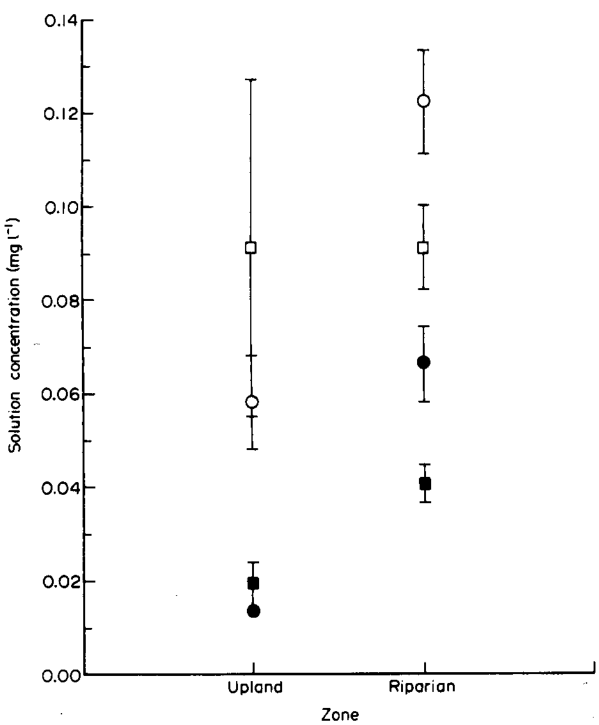

Fig. 3 The mean concentrations of dissolved and total phosphorus from shallow lysimeters in the upland crop zone and in the riparian forest and grass vegetated buffer strips. ■, grass DP; □, grass TP; ●, forest DP; ○, forest TP.

Seasonal variation in P

Omernik *et al.* (1981) have suggested that forested VBS can become saturated with nutrients and become ineffective filters on an annual basis. While the results of others are inconsistent with this idea (e.g. Lowrance, Todd & Asmussen, 1983) this question still remains inadequately addressed. Our results suggest that forested VBS leak P to the adjacent stream channel to a greater degree than the grass VBS. Significant seasonal differences may also exist in the effectiveness of grass and forest VBS that may provide insights into the differential effectiveness of grass *v* forested VBS in relation to P. Therefore, the influence of season on TP and DP concentrations in shallow groundwater was examined.

Because agriculture was the dominant land-use activity in the region, the year was divided into three periods that corresponded with the primary agricultural activity: the dormant season (1 November–15 April); the planting season (16 April–30 May); and, the growing season (1 June–31 October). Significantly higher mean concentrations of DP occurred in lysimeters located in the riparian grass VBS ($F_{2,79} = 3.649$; $P = 0.030$) during the planting season than occurred during the dormant season (Fig. 4). No effect of season was detected on the mean concentration of DP in the forest ($F_{2,54} = 0.925$; $P = 0.403$) or in the riparian crop site ($F_{2,49} = 0.993$; $P = 0.378$).

TP concentrations were significantly higher during the planting season than during the growing and dormant seasons in both the riparian crop and riparian forest 60 cm samples (Crop, $F_{2,38} = 10.36$, $P = 0.0003$; Forest, $F_{2,47} = 11.23$, $P = 0.0001$). TP concentrations in riparian grass samples were significantly higher ($F_{2,70} = 5.45$, $P = 0.0063$) during the planting season than during the dormant season (Fig. 4). No other seasonal differences were detected in the grass VBS

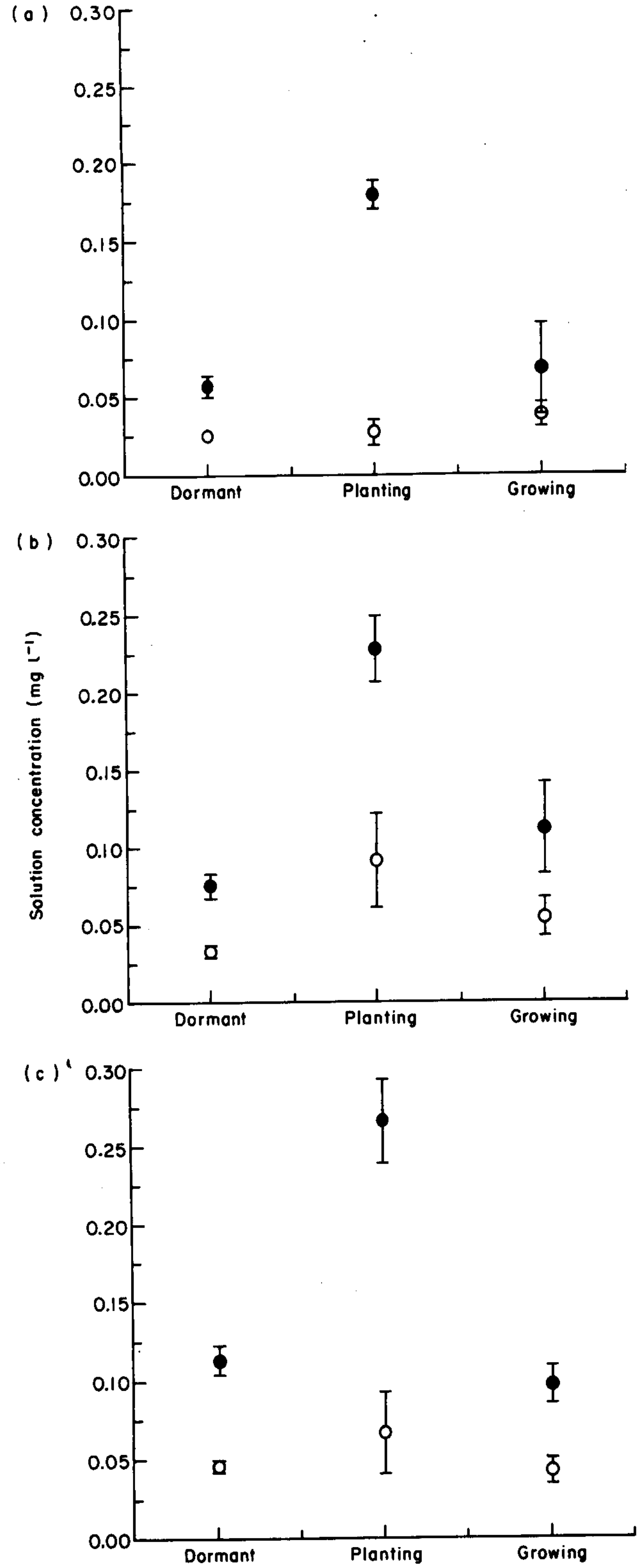

Fig. 4 Mean concentrations of total (●) and dissolved (○) P in shallow lysimeters from the riparian (a) crop, (b) grass, and (c) forest sites during the study with respect to season (dormant, planting, and growing).

(Fig. 4). The higher P concentrations in groundwater samples during the planting season coincided with fertilizer application to agriculture fields. The different spatial and temporal concentrations further suggest that phosphorus is actively moving from the upland to the riparian zone in shallow groundwater.

During the planting season DP and TP concentrations were significantly higher in the forest and grass VBS than in the riparian crop site (Fig. 4) although fertilizer was not applied to the forest and grass VBS but was applied to the riparian crop site. The lower concentrations of TP and DP in the riparian crop-site samples were probably due to the more rapid transport of water in tile drains running through this treatment. The more rapid flow of water probably flushed P in solution more rapidly to the stream channel. In the forest DP and TP concentrations in shallow groundwater were substantially higher than in the grass VBS and in the riparian crop site during the dormant season. This suggests that the loss of P to groundwater was greater in the forest during this period than in the other two riparian treatments (Fig. 4). Higher concentrations of P during the dormant season in the forest may be due to the leaching and decomposition of organic matter (leaves) on the forest floor. Thus, while some have suggested that forest VBS function as sinks for nutrients (Lowrance *et al.*, 1983), the significant seasonal variation reported here indicates that P is only temporarily retained by forested VBS, as postulated by Omernik *et al.* (1981). Additional work is needed on the fate of P in both surface and subsurface water in VBS.

Obviously, it is not possible for nutrients such as phosphorus to be continually added to a riparian buffer without some loss to the stream. In the present study, the trees in the forested site were relatively mature (>40 years); thus, cropping of grass VBS and select harvesting of the mature forested buffers may have enhanced the P filtering efficiency of both VBS. Care must be taken in cropping forested vegetation however, as too great a removal can increase P and N loading relative to background levels (James *et al.*, in press).

Nitrate-N in shallow groundwater

There was no significant difference in nitrate-N concentrations among shallow lysimeters in the upland and riparian crop sites. In the two other cases (i.e. the forest and the grass sites) the concentrations of nitrate-N in groundwater in the upland crop areas were significantly higher than were mean concentrations at comparable sampling depths in the riparian zone (Fig. 5). The significant reductions in nitrate-N concentrations from the upland crop zone to the riparian VBS suggest that nitrates were being removed from the system. Denitrification in VBS has been suggested as the primary mechanism for the reduction of nitrate concentrations in solution (Cooper *et al.*, 1986; Jacobs & Gilliam, 1985; Peterjohn & Correll, 1984; Pinay & DeCamps, 1988; Pinay, Roque & Fabre, 1993). Others have also provided evidence that denitrification is an important mechanism contributing to the loss of NO_3^-. Schnabel (1986) estimated that on an aerial basis the potential denitrification rate into 0.5 m of the stream bottom was $0.01\ mg\ m^{-2}\ s^{-1}$. This rate is substantially higher than rates estimated by Hill (1983) and Wyer & Hill (1984). Just as important, Schnabel (1986) and Pinay *et al.* (1992) found that denitrification rates did not decrease with distance laterally away from the stream channel and into the stream bank through the riparian area where solutions travel en route to the stream.

Because Cl^- is not actively taken up by organisms it can be used as a conservative marker. We measured

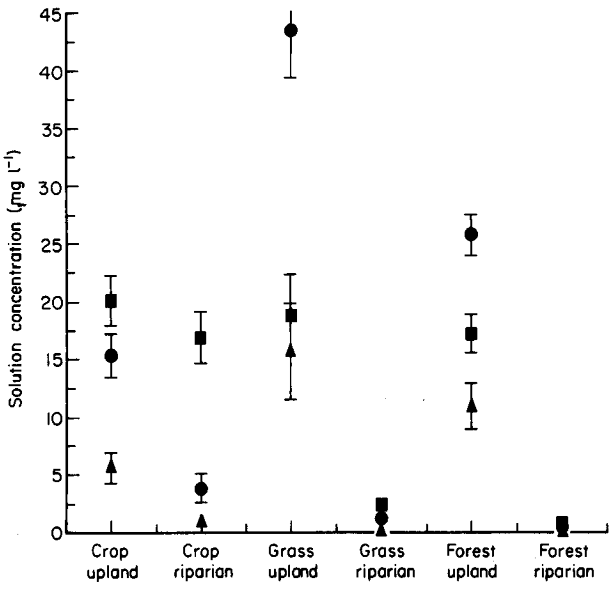

Fig. 5 Mean concentrations of nitrate-N in solution from shallow (■) and deep (●) lysimeters and piezometers (▲) in each upland region planted in row crops and each riparian (crop, grass, and forest) zone during the study.

Cl^- in lysimeters throughout the study and found significantly lower nitrate-N:Cl^- ratios at all depths in the organically enriched forested and grass VBS relative to those in the riparian crop site and the upland crop areas (D.A. Kovacic & L.L. Osborne, unpublished data). These results support denitrification as the most plausible mechanism for the removal of nitrate-N in groundwater. Thus, these results suggest that both the grass and forested buffers were effective filters for nitrate-N in shallow groundwater.

In the riparian zone, concentrations of nitrate-N in shallow lysimeters were significantly greater in the grass VBS ($2.43 \pm 0.43\ mg\ l^{-1}$) than in the forested VBS ($0.87 \pm 0.23\ mg\ l^{-1}$, Fig. 5). There were no significant differences in nitrate-N concentrations in solution between the forest and grass VBS at 120 cm and >120 cm (Fig. 5). Unlike the phosphorus results, these data suggest that forested VBS are more efficient at filtering nitrate-N in shallow groundwater than grass VBS.

It is noteworthy that between the 60- and 120-cm depths the greatest proportional decrease in nitrate-N concentration (77.5%) occurred in the riparian crop site (i.e. from 16.86 ± 2.29 at 60 cm to 3.79 ± 1.22 at 120 cm, Fig. 5). The proportional decreases between the 60 and 120 cm depths in the forest and grass VBS (34 and 51.0%, respectively) were substantially lower than in the riparian crop site (Fig. 5). In the riparian crop site the greater loss of nutrients in solution between the 60- and 120-cm depths is attributable to subsurface transport in drainage tiles directly to the stream channel, rather than to denitrification and plant uptake.

Seasonal variation in nitrate-N

No significant seasonal variation occurred in nitrate-N concentrations in either the forest VBS ($F_{2,57} = 0.932$; $P = 0.399$; mean $= 0.87 \pm$ S.E. $= 0.23\ mg\ l^{-1}$) or in the upland crop area ($F_{2,70} = 1.10$; $P = 0.339$; mean $= 16.86 \pm 2.29\ mg\ l^{-1}$). Beginning in the dormant season, the nitrate-N concentrations in shallow lysimeters generally decreased throughout the year in the riparian crop zone (dormant season $= 22.06 \pm 3.40$, planting season $= 18.47 \pm 4.77$, and growing season $= 4.60 \pm 1.39\ mg\ l^{-1}$) and in the riparian grass VBS (dormant season $= 3.27 \pm 0.69$, planting season $= 1.95 \pm 0.77$, and growing season $= 1.07 \pm 0.58\ mg\ l^{-1}$).

These results again suggest that both VBS remove nitrate-N from shallow groundwater, but on an annual basis the grass VBS was less effective than the forest VBS. The low NO_3-N concentrations in shallow groundwater during the dormant season also suggest that denitrification was an important process during the winter and are consistent with more recent results (Haycock & Pinay, 1992; Pinay *et al.*, 1992).

Observed limitations of VBS

The available evidence suggests that VBS can reduce N inputs to streams. Osborne & Wiley (1988) concluded that the mitigating benefits of VBS will be maximized if they are instituted in smaller headwater streams whose lengths dominate any drainage network. In much of the mid-western United States most lands in the headwaters of a catchment are privately owned. Undoubtedly, government supported incentives will be required for large-scale adoption of VBS in many regions of the United States.

Because large volumes of water and nutrients in solution can by-pass riparian VBS in areas that are tiled, the effectiveness of VBS for mitigating streamwater quality by themselves will be greatly reduced, but not completely lost (Cooper *et al.*, 1986). For instance, we found a significant positive correlation (Spearman rank) in nitrate-N ($R = 0.80$; $P = 0.006$) and TP concentrations ($R = 0.77$; $P = 0.043$) between drainage tile outlets and Embarras River surface water. On the basis of these results we can expect a decrease in the filtering efficiency of VBS in agriculture regions that are tile drained. An obvious solution in such situations is to plug the tiles. This, however, is not generally feasible. These results support the proposition of Petersen *et al.* (1992), that no single method or technique is universally applicable in every stream restoration programme. Rather, alternative techniques and options must be considered and investigated. We have begun to examine the feasibility and efficiency of small artificial wetlands separated from the stream channel by a grass VBS as a possible alternative strategy for use in lowland streams with minimal 1–2% relief and that are tile drained. Essentially, a small depression is excavated and the drainage tiles within the area are outlet (sunlighted) into the re-vegetated depression (Fig. 6). These wetlands are similar to the horseshoe concept recently proposed by Petersen *et al.* (1992) but may be less susceptible to in-channel erosion forces and bank slumping during high-discharge events. It is anticipated that nutrient removal will occur in a fashion similar to that of natural wetlands (Lee, Bentley & Amundson, 1975).

Both forested and grass VBS will require periodic maintenance to maintain maximum performance. We observed the formation of small gullies, particularly in the forested VBS and immediately up-slope of this point following major precipitation events. Failure to maintain shallow sheet flow and promote infiltration within the VBS will greatly reduce their sediment trapping (Gough, 1988; Dillaha *et al.*, 1989) and nutrient removal (Dillaha *et al.*, 1986, 1989) efficiencies. Although limited, the evidence from this study suggests that both the grass and forest VBS leak P, possibly due to saturation. While additional research is needed in this area, it should be possible to further minimize the loss of nutrients by selective cropping of VBS and maintaining the vegetation at an intermediate successional state.

The species composition of the vegetation will also dictate nutrient removal efficiency. For instance,

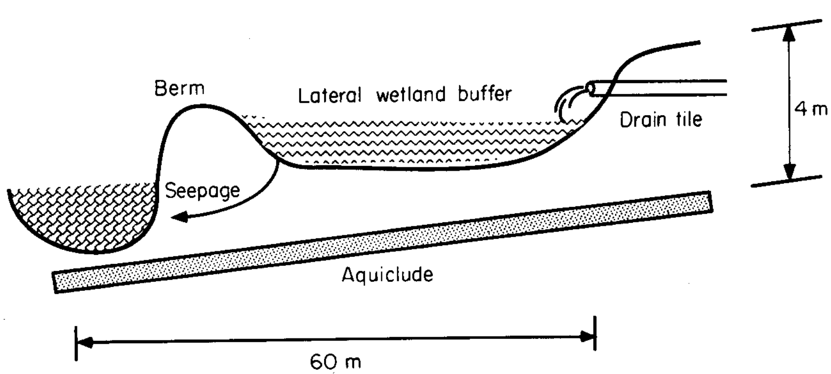

Fig. 6 Proposed lateral wetland for facilitating the removal of nutrients from groundwater carried by drainage tiles. (After Kovacic, Osborne & Dickson, 1990.)

James *et al.* (in press) have demonstrated that non-leguminous trees were significantly more effective as nutrient filters than black locust (*Robinia pseudoacacia* L.), a legume. Perkey (1990) presents a brief summary on the biological uptake of nutrients by tree species applicable to the northeastern region of the U.S.A. Other regional summaries may also exist.

The results of our study indicate that VBS can reduce nitrate-N concentrations in shallow groundwater. These data also suggest that forested VBS are more efficient than grass VBS for reducing NO_3-N but forested VBS are less efficient at reducing P in shallow groundwater. Thus, selection of the appropriate cover type should be dependent upon the specific water-quality problem at hand.

In low-order streams, forested buffer strips can provide a moderating influence on temperatures (Burton & Likens, 1973; Aubertin & Patric, 1974; Lynch & Corbett, 1990), more effectively stabilize banks (Erman *et al.*, 1977; Beschta & Platts, 1986), provide the principle energy source (Vannote *et al.*, 1980; but see Wiley, Osborne & Larimore, 1990), and more efficiently reduce subsurface concentrations of NO_3-N than grass VBS (Kovacic *et al.*, 1990). Grass VBS are not without merit, however. For instance, Gough (1988) has suggested that herbaceous vegetation may be more desirable for use in VBS than larger woody vegetation because the greater stem density increases the hydraulic roughness, thereby decreasing the velocity of the water flow, and hence, its sediment carrying capacity (Meyer & Wischmeier, 1969). Further, this study has demonstrated a greater efficiency of grass for reducing DP and TP in shallow groundwater. Because grass was the native riparian vegetation in many agricultural areas of the mid-western United States its reestablishment in sufficient widths along stream channels may return stream function to a more natural state. Further, some riparian landowners now cite the adverse impacts that shading from forests have on crop yields and decry the tendency for fallen trees and branches to interfere with the flow of the channelized and manicured stream channels. Concern over the effects of riparian trees and shrubs on flooding needs further clarification. In highly modified landscapes such as the agriculture-dominated midwestern U.S.A., failure to retain riparian vegetation and floodplains in the headwaters has resulted in increased water levels downstream during flood events (Sparks *et al.*, 1990). Essentially, flood damage will occur at the first restriction, or unmodified reach, along the drainage network.

In some areas the stream channels themselves must be accessible to large equipment for periodic maintenance (dredging and straightening). While we question the long-term wisdom of such practices, forested VBS do not allow such access without potentially serious damage to the vegetation. Therefore, modified designs that use both forested corridors with interspersed buffers of grass to permit channel maintenance (Fig. 7) may provide an acceptable compromise and alternative to simple grass VBS.

Finally, herbaceous vegetation is generally more compatible with the short-term nature of many government agriculture support programmes. Alternative forage crops such as oats and clover are commonly advocated and planted in these temporary set-aside programmes (e.g. Payment in Kind Program). Thus,

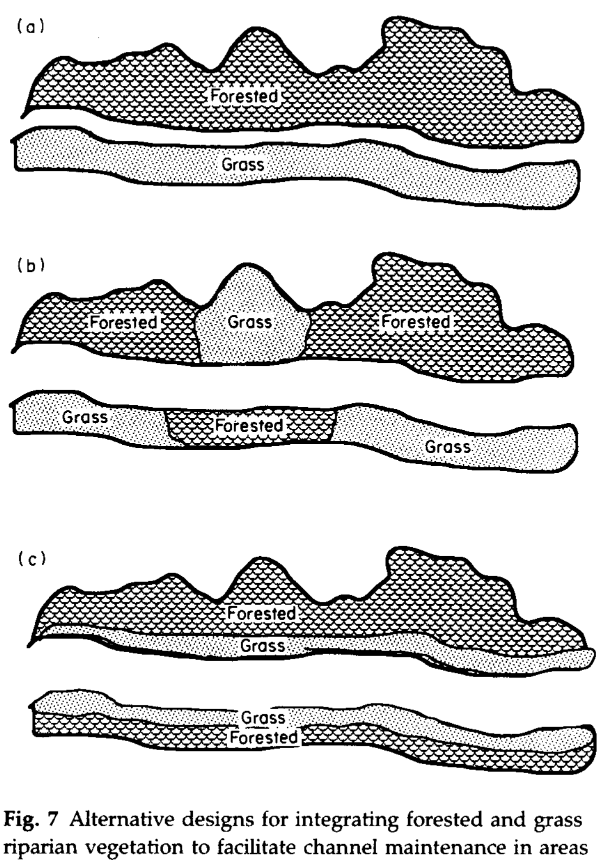

Fig. 7 Alternative designs for integrating forested and grass riparian vegetation to facilitate channel maintenance in areas dominated by agriculture land use. Design (a) is for narrow stream channels while designs (b) and (c) are for moderate width stream channels. See text for details.

the continued use and possible expansion of riparian grass VBS can be anticipated; but, research on the most effective size, shape, and composition of vegetated buffers for specific situations is still needed. Although we have concentrated on water-quality benefits derivable from VBS, similar information is needed on the beneficial aspects of VBS for increasing biodiversity, modifying hydrographs and groundwater recharge, reducing bank erosion, and as an energy source for stream organisms.

Rye grass *v* oats vegetated buffer strips

We have recently initiated a study that examines the efficiency of three different buffer widths of rye grass (10, 20, and 30 m) and a 20-m buffer of oats for reducing stream inputs of TP from surface runoff in agricultural fields. The buffers were planted in 1990 and allowed to establish for 1 year. Surface runoff collectors were placed in each of the three rye treatments, the oat treatment and in a fifth treatment planted in corn to the stream bank. Collectors were constructed from plastic rain trough (length 1 m) connected to a 6.4-mm plastic tubing attached to a buried collection bottle (4 l) located downslope. An apron made from plastic siding was attached to the upslope portion of the trough to allow surface runoff from an enclosed 4.65 m^2 area (partially buried retainer wall made from aluminum siding) to enter the collector (Kovacic *et al.*, 1990).

A one-way analysis of variance on the May 1991 data demonstrated that cover type had a significant effect on TP retained within the buffer ($F_{4,10} = 20.215$; $P = 0.00009$). The amount of TP removed from the oats plot in surface flow was not significantly different from the amount removed in the plot planted in corn (Fig. 8), suggesting that the 20-m oat VBS had no significant mitigating influence on TP in surface runoff during this period. Concentrations of TP in surface runoff from 10- and 20-m rye grass plots were significantly lower than TP concentrations in runoff from the corn and oat sites (Fig. 8), suggesting that rye grass was acting as an effective nutrient filter. Mean concentration of TP in the 10-m rye grass plot was also less than the mean concentration in the 30-m rye grass plot (Fig. 8). This unexpected result was attributable to the fact that the 30-m rye plot was completely inundated for several days during a flood. As flood waters subsided large quantities of

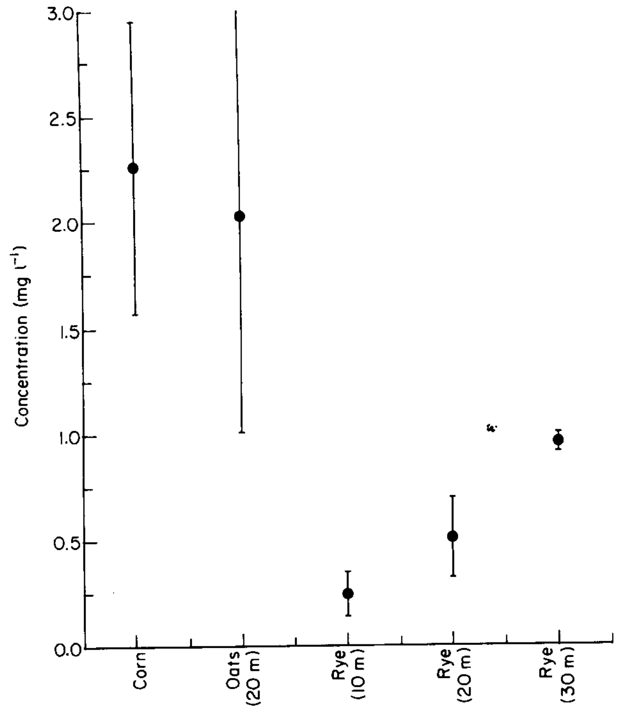

Fig. 8 Mean concentration of total P in surface runoff in May, 1991, in different crop and grass riparian vegetated buffer strips in east-central Illinois.

nutrients bound to sediments were deposited. All of these sediments were not permanently retained in the riparian area. Some were transported in the surface runoff during subsequent precipitation events.

Although these results are only preliminary, and time is needed to examine the long-term efficiency of these buffers, they do suggest that many of the present agriculture support programmes may not be recognizing their full potential for improving stream water quality by advocating the planting of oats or other forage crops. Even a 10-m-wide buffer of rye grass can significantly reduce the concentration of TP in surface runoff subsequently improving stream water quality.

Summary of Embarras River results

We have shown that riparian VBS can significantly reduce the concentrations of nitrate-N in shallow groundwater before its entry into a stream channel. The evidence also suggests that riparian forests are more efficient at removing nitrate-N in shallow subsurface water than are grass VBS. Reasons for the difference in the N removal efficiency between the grass and forest VBS may be associated with the form of carbon available for denitrification (B.R. James, unpublished data). Because grass VBS are generally more socially acceptable in agriculture areas, mechanisms responsible for this difference need further investigation. Both the forest and grass VBS appeared to be temporary sinks for TP and DP, but the forest VBS appeared to be less efficient at retaining P than the grass VBS. Analyses of preliminary results also suggest that a 20-m VBS of oats does not reduce TP concentrations in surface runoff but a 10-m-wide VBS of rye grass significantly reduces TP in surface runoff.

Despite the many benefits of VBS for stream restoration there are limitations associated with their use, not the least of which is the apparent reduction in nutrient removal efficiency in agricultural areas that are tile drained. In such instances, incorporation of VBS with alternative strategies such as lateral wetlands may be necessary to improve stream-water quality.

Acknowledgments

Information for this paper was supported by funds from the University of Illinois Water Resources Center, the Illinois Department of Energy and Natural Resources, the United States Forest Service, and the Illinois Natural History Survey. Numerous individuals contributed to field and laboratory efforts including P. Bayley, B. Dickson, J. Sanberger, and J. Wagner. We thank Drs G. Pinay, C. Rabeni, B. Petersen, B. Higler, P. Bayley, R. Sparks, and a special thanks to Dr J. Meyer for their valuable comments on earlier versions of this manuscript. Finally, we acknowledge the support and enthusiasm of Drs L. Petersen and R. Petersen for organizing and hosting the SIL-sponsored Lowland Streams Restoration Conference held in Lund, Sweden and for inviting us to present this paper.

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(*Manuscript accepted September 1992*)