Water Qual. Res. J. Canada, 2004 • Volume 39, No. 3, 311–317

REVIEW ARTICLE

A Review of the Efficiency of Buffer Strips for the Maintenance and Enhancement of Riparian Ecosystems

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Vegetative buffer strips are being widely promoted as an effective technique to protect rivers and streams from the negative impacts of adjacent land uses including forestry and agriculture. An extensive review of the literature revealed that despite the intuitive appeal of buffer strips, data demonstrating their efficacy is highly variable and most studies demonstrating significant nutrient removal in buffer zones come from studies undertaken in riparian buffers greater than 30 m wide. These buffers are much wider than what land managers can typically expect farmers to remove from active production in order to protect water quality. Research attempting to demonstrate the efficacy of riparian buffers needs to focus on buffer widths that are within the range that landowners are likely to "give up" in the name of water quality protection. Lack of experimental evidence from buffers in the 1- to 10-m width range typically encountered on farms makes it difficult to draw definitive conclusions about the efficacy of riparian buffers in agricultural areas.

Key words: **buffer zones, riparian buffers, non-point source pollution, nutrients, nitrogen, phosphorus, sediment**

Introduction

Over the past few decades, pollution associated with agricultural and forestry activities has increasingly been recognized as a serious threat to the quality of surface and ground water throughout North America (Garcia and Carignan 2000; Sovell et al. 2000; Castelle et al. 1994; Lynch et al. 1985; Owens et al. 1983; Omernik et al. 1981). Certain agricultural and forestry practices can degrade surface water quality by increasing streambank erosion, increasing the loading of contaminants, nutrients and bacteria and increasing stream temperatures (Garcia and Carignan 2000; Sovell et al. 2000; Muscutt et al. 1993; Peterjohn and Correll 1984; Younge et al. 1980). The growing concern about non-point source pollution has resulted in the development of forestry and farming practices, often called best management practices (BMPs) that minimize the impact of these activities (Aubertine and Patric 1974). Best management practices are part of the non-point source pollution control strategies of environmental groups and government (state, provincial and federal) agencies throughout the U.S. and Canada (Peterson 1983; Walker and Graczyk 1993; Lowrance et al. 1985; Haugen 1983).

Buffer strips along shorelines are a central component of most non-point source pollution programs in North America. Vegetated buffer strips can mitigate the effects of agricultural and forestry activities by acting as a physical barrier to sediment, nutrients and pesticides being carried into streams (Barling and Moore 1994; Cooper 1990). Buffer strips may also reduce the flux of soluble nutrients by uptake into growing plants or by supporting environmental conditions that favour chemical transformations such as denitrification (Haycock and Pinay 1993; Cooper and Gilliam 1987). Forested buffer strips that are sufficiently dense may also improve water quality by restricting the access of livestock to streams, thereby reducing inputs of nutrients and bacteria associated with livestock feces and reducing erosion resulting from streambank trampling (Barling and Moore 1994; Muscutt et al. 1993).

Although the potential benefits of buffer strips are intuitively appealing, the criteria for the establishment of buffer strips are often subjective and detailed monitoring after buffer zones are established is often lacking (Briggs et al. 1994). Often these criteria are set based on the discretion of individual biologists or restoration technicians. In many cases the widths of buffer strips are set based on what is politically acceptable or what landowners can reasonably be expected to "give up." Removing land from active production and converting it to riparian buffers can be expensive for farmers with extensive land area adjacent to stream systems. An accurate understanding of the real benefits of buffer zones is required if landowners are to be convinced to maintain vegetative zones.

In discussing the effectiveness of riparian buffers with professionals working to implement non-point

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source agricultural pollution control programs in eastern Ontario, it became apparent that few were aware of well-documented examples of cases where the efficacy of riparian buffers has been measured. This was despite hundreds of papers being published on the subject over the last few decades.

One of the reasons that much of the research related to riparian buffer strip design and function does not make its way to the individuals implementing restoration activities in the field, is that the literature is widely spread over a vast range of scientific disciplines. Riparian buffers can have impacts on sedimentation rates, erosion, nutrient input, stream temperature, and movement of wildlife populations. As a consequence of this wide range of ecological functions, the literature about the riparian buffers is found in journals representing a wide range of disciplines (e.g., ecology, geomorphology, population genetics, soil science, limnology and fisheries science), thus, making it difficult for those who are busy implementing projects to keep track of this growing body of literature.

The purpose of this paper was to review and synthesize the available literature about the effectiveness of buffer strips. The goal was to provide a succinct synthesis of the available information about riparian buffers that could be used by non-point source project managers, to prioritize projects, develop biologically appropriate criteria for buffer strip widths, and identify situations where buffer strips will be most effective.

The review is organized according to the following ecological functions: removal of sediment and nutrients, streambank stabilization, effects on water temperature, and importance as habitat corridors.

Many studies are underway concerning the use of buffer strips to improve or protect water quality. More than 100 papers were reviewed and evaluated and even this was not exhaustive. The purpose of this review is to produce a succinct document that can be used by those undertaking non-point source pollution control projects, thus we have not attempted to summarize each study reviewed. Instead, specific studies were selected to illustrate the range of results obtained. A complete list of the papers reviewed is available from the authors.

Definitions and Terminology

Different authors have used a variety of definitions and terminology related to riparian buffer strips. For the purpose of this review, a buffer strip is defined as any strip of vegetation between a river, stream or creek and an adjacent upland land use activity, that is maintained for the purposes of protecting or improving water quality, or enhancing the movement of wildlife among habitat patches. Buffer strips may be composed of native vegetation (e.g., pre-existing native forest) that is intentionally left intact when land is cleared for other land uses (forest harvesting, agriculture or urban development) as well as vegetative buffers that are re-established where original vegetation has previously been removed. The latter may include forested or herbaceous buffer zones. The terms buffer strips, riparian buffers and vegetative buffer strips are used interchangeably.

Results and Discussion

Sediment and Nutrient Removal

Degradation of surface water quality in areas where native forest has been replaced by intensive agriculture has been well documented (Barling and Moore 1994; Muscutt et al. 1993), but whether vegetative buffer strips along streambanks can mitigate these effects is less clear. The results of some studies clearly show nutrient removal in buffer strips (Cooper 1990; Lowrance et al. 1984), and in some cases removal of phosphorus (P) and nitrogen (N) approaches 90 to 100%. Other studies show poor removal efficiencies of these nutrients (Groffman et al. 1991; Magette et al. 1989; Table 1).

Omernik et al. (1981) compared water quality in watersheds with similar degrees of conversion from forest to intensive agriculture. In some of the watersheds, the deforestation and land conversion to agriculture was predominantly in riparian areas. In other watersheds, the extent of the deforestation was similar, but the agricultural activity was located away from riparian areas. Their results indicated that the proximity of agricultural activity to riparian areas did not influence water quality in the

TABLE 1. A comparison of nutrient and sediment removal efficiencies by riparian buffers in agricultural areas[a]

Author	*Parameter measured*	*Buffer width*	*Percent reduction*
Cooper et al. (1987)	Sediments in surface water	Variable (woodlots)	84–90%
Groffman et al. (1991)	Nitrates in soil pore water	Plots (3 x 5 m)	1–29%
Haycock and Pinay (1993)	Nitrates in groundwater	Approx. 20–25 m	84–99%
Lowrance et al. (1984)	Nitrogen in surface water	No set values	68%
Magette et al. (1989)	TSS, P and N in surface runoff	4.6 and 9.2 m	0–66%
Young et al. (1980)	N and P in surface runoff	0–25 m	67–83%

[a] Studies were selected to illustrate a wide range of outcomes based on an extensive review of the literature. See the text for more details of the individual studies summarized in the table.

streams they studied (Omernik et al. 1981). Instead, they found that the total proportion of land converted to agriculture was a better predictor of water quality than proximity of agricultural activity to riparian areas.

The conflicting results of these studies (Groffman et al. 1991; Cooper 1990; Lowrence et al. 1983; Omernik et al. 1981) clearly illustrate that the functions of riparian buffer strips are complex. The efficacy of buffer strips as nutrient filters may depend on the specific characteristics of the buffer strip (soil chemistry, type of vegetation, successional stage) as well as the nutrients involved.

Nitrogen

Much of the nitrogen that moves from agricultural land into rivers and streams is in the form of nitrate. Processes within riparian zones, wetlands and streams are capable of nitrate removal under appropriate conditions but the relative importance of these processes is highly variable (Cooper 1990).

Riparian buffers can remove nitrogen via a variety of mechanisms. Nitrogen can be removed by uptake into growing plants or by conversion of nitrate to nitrogen gases (NO, N_2 and NO_2) by denitrifying micro-organisms. Sediment-bound nitrogen can be effectively removed when riparian vegetation physically slows the movement of water allowing increased sedimentation rates. Atmospheric nitrogen (N_2) can also be converted back to nitrate by nitrogen-fixing micro-organisms associated with the roots of some plants (e.g., Leguminosae), further complicating the situation for nitrogen exchange (Haycock and Pinay 1993; Lowrance 1992; Groffman et al. 1991; Cooper 1990; Magette et al. 1989; Jacobs and Gilliam 1985).

Reported nitrate removal efficiencies are highly variable and much of the variation may be related to the many different mechanisms involved in nitrogen removal as well as variation in the balance between nitrogen fixation and denitrification rates (Philips 1989a,b; Warwick and Hill 1988). Magette et al. (1989) found that experimental buffer strips (4.6 and 9.2 m in width) were ineffective in removing total nitrogen. They found that nitrogen losses from experimental plots with buffer strips varied from 45 to 184% compared to losses from plots without buffers.

In contrast, several studies have shown that buffer strips can be effective in the removal of nitrates from surface runoff (Cooper 1990; Lowrance et al. 1983). Cooper (1990) observed nitrate removal efficiencies varying from 88 to 97% for riparian organic soils at his study site. Removal efficiencies of mineral soils were less spectacular and in some months these sites served as net exporters of nitrate (Cooper 1990). Organic soils accumulate in low-lying areas that receive disproportionately large volumes of runoff, therefore these organic soil deposits can still be important sites of nitrate removal even if they occupy only a small area of the riparian zone. For example, Cooper (1990) found that between 56 and 100% of denitrification occurred in organic soils even though organic soils covered only 12% of the study area.

One key difference between the experiments of Magette et al. (1989), and those of Cooper (1990) and Lowrance et al. (1983), is that Magette et al. (1989) measured nitrate removal in small herbaceous riparian buffer strips established in agricultural fields. In contrast, the studies by Cooper (1990) and Lowrance et al. (1983) were conducted in intact riparian ecosystems. Although the latter two studies were conducted in buffer strips that were much wider than those used by Margette et al. (1983), buffer width alone is not sufficient to explain the difference between these studies since denitrification often occurs within the first 10 m of riparian forest (Lowrance 1992).

Both forested and herbaceous buffer strips can be effective sites of nitrogen removal but whether herbaceous or forested buffers are more effective in removing nitrogen varies. Haycock and Pinay (1993) found that forested buffers were more effective in promoting nitrogen removal in winter months compared to grass buffers. In contrast, Groffman et al. (1991) found higher nitrate removal rates in grass buffers compared to forested buffers.

Taken together, these studies illustrate the importance of maintaining the ecological integrity of riparian buffers. Some studies have shown that buffers consisting of herbaceous vegetation or forests in early successional stages can increase the efficiency of nitrate removal (Lowrance et al. 1984). This may be effective when plant uptake is the primary route of nitrate removal but nitrate removal by plant uptake is only a short-term solution since the nitrogen becomes available again when the plants senesce. Denitrification by microbial communities in soil, on the other hand, results in long-term nitrogen removal from riparian zones. Removing vegetation to maintain buffers in an early successional stage may promote sustained nutrient removal via plant uptake, but may also remove carbon that is essential for denitrification.

Phosphorus

In contrast to the situation for nitrogen, there is no mechanism to remove phosphorus to the atmosphere (Cooper and Gilliam 1987). Phosphorus in agricultural runoff can be removed by sorption onto soil particles, by sedimentation, or through uptake by plants (Cooper and Gillian 1987). In contrast to nitrogen, the capacity for phosphorus removal is finite (Cooper and Gilliam 1987) and the capacity for riparian areas and wetlands to remove phosphorus may become saturated (Omernik et al. 1981). Whether riparian buffers serve only as short-term sinks for phosphorus is unclear. Most studies follow phosphorus removal over too short a time span to draw conclusions about the long-term potential for phosphorus removal. Nonetheless, several studies have shown that buffer strips can remove phosphorus from both surface water and shallow groundwater (Osborn and Kovacic 1993; Cooper and Gilliam 1987). Osborn and Kovacic (1993) found that grass buffers removed more phosphorus than forested buffers.

Many of the studies demonstrating long- or short-term phosphorus removal involved buffer widths that were much greater than what can be expected in agricultural areas. Magette et al. (1989) measured phosphorus removal by 4.6- and 9.2-m buffers. Their results were highly variable but phosphorus removal was generally poor compared to other studies involving wider buffers.

Sediment

Several studies have shown that buffer strips can assist in the retention of sediments, thereby reducing sediment loads to rivers and streams (Heede 1990; Cooper et al. 1987; Lowrance et al. 1986). Large heavy particles are most efficiently removed by buffer strip vegetation. Reducing sediment transport may also reduce nutrient export from riparian zones because nutrients are often bound to sediment particles. Unfortunately, fine particles such as clay that bind a disproportionate amount of the sediment-bound nutrients are less effectively removed compared to larger, heavier particles.

Sediment retention alone (i.e., even without significant quantities of bound nutrients) is desirable because increased sedimentation can degrade spawning sites for fish and other aquatic animals. Riparian vegetation can also reduce sediment loads by stabilizing streambanks and minimizing streambank erosion (Kemper et al. 1992; Schlosser et al. 1981).

Whether sediment removal is effective over the long term is a matter of debate. Cooper et al. (1987) used cesium dating to examine sediment deposition over a 20-year period. They found that the riparian zone was a sediment sink over the 20-year period they studied. Lowrance et al. (1986) reached a similar conclusion (using different methods) examining sediment deposition over a 100-year period. Both of these studies were conducted in watersheds that were characterized by >50% forest cover. Whether narrow buffers are able to retain sediments over the long term is not clear. Most studies have been too short in duration to detect remobilization of sediments during infrequent intense floods.

In addition to trapping sediment and nutrients moving into the stream from upland areas, riparian buffers may also reduce sedimentation that results from the erosion of the streambank itself (Bowie 1995; Kemper et al. 1992).

Effects of Tile Drainage

Nutrient removal requires contact between runoff water and soil containing micro-organisms (denitrification) or the roots of plants (plant uptake). Much of the agricultural land in eastern Ontario is tile drained, therefore, much of the nutrient load can bypass the plant root zone and denitrifying soils. Concentrating agricultural runoff in narrow tile drains or surface ditches may reduce the efficacy of nutrient removal by overloading the assimilation (e.g., plant uptake) and transformation (e.g., denitrification) processes. Buffer zones, therefore, may be most effective in preventing the deterioration of water quality in areas where the natural drainage patterns are intact.

Stream Temperature

Several studies have documented increases in stream temperatures associated with removing riparian forest (Hotlby 1988; Barton et al. 1985; Rishel et al. 1982). Rishel et al. (1982) found that average temperatures increased by 4.4°C following the removal of riparian forest. The increase in maximum temperature was even more dramatic: 32°C in the clear-cut stream compared to 22°C at a nearby reference site. Lee and Samuel (1976) observed similar increases in stream temperature associated with timber harvesting.

Stream temperature is a critical factor for some fish, especially salmonids, which are important sport fish. Barton et al. (1985) found that temperature was the most important factor distinguishing between trout and non-trout streams.

Even narrow riparian buffers are sufficient to reduce stream temperatures. The proportion of the streambank that is buffered by vegetation is more important than buffer width in determining effects on stream temperature (Barton et al. 1985). Vegetation height is also important since the buffer vegetation must be sufficiently high to shade the water surface. Although buffer width is not critical for regulating stream temperature, narrow buffers may be more susceptible to wind damage that may compromise the long-term integrity of the riparian buffer.

Habitat Corridors

Numerous studies have demonstrated the use of riparian forest as wildlife habitat (Skagen et al. 1998; Crompton et al. 1988). Riparian buffers may serve as corridors for dispersal among larger patches of forest habitat (Rich et al. 1994). Although many studies have reported the use of corridors by forest-dwelling species (Skagen et al. 1998; Crompton et al. 1988), it is less clear whether these corridors provide for sufficient movement of animals to significantly influence the dynamics of the populations of animals living in these forest patches (Beier and Noss 1998). For example, knowing that a particular species that is found in two isolated patches also occurs in a corridor connecting the two patches, is not conclusive evidence that the presence of the connecting corridor will reduce the probability of local extinction of that species in one or both patches.

While it is theoretically possible that riparian buffers may provide corridors to facilitate movement of wildlife among forest patches, there is little evidence to indicate that buffers in the size range typically found in agricultural areas are effective at promoting gene flow among populations or reducing local extinction probabilities. Narrow corridors may allow the movement of some small mammals (insectivores and rodents) but most species require larger corridors.

The presence of riparian corridors between two isolated forest patches will increase the proportion of edge habitat, potentially exposing nesting birds to increased predation and nest parasitism. Keyser et al. (1997) found that predation on artificial bird nests increased as forest fragmentation increased. Haegen and DeGraaf (1996) compared the frequency of predation on artificial nests located in riparian buffer strips to those located in intact forest patches. In their experiment, the frequency of nest predation was twice as high in riparian buffers compared to nests in intact riparian forest. These studies clearly demonstrate that riparian buffers may not always be beneficial and that their efficacy may vary among sites.

For many area-sensitive species, buffer widths of at least 100 m are required to maintain breeding populations. For example, Lambert and Hannon (2000) found that Ovenbirds (*Seiurus aurocapillus*) were absent from 20-m buffers following a clear-cut. Larger buffers (100 and 200 m) were sufficient to maintain Ovenbird populations (Lambert and Hannon 2000). Pearson and Manuwal (2001) found that buffers 30 m wide on each side of a third-order stream in the Pacific Northwest was sufficient to maintain pre-logging bird communities.

Further Research Requirements

The one outstanding feature of most of the papers we reviewed is the large degree of variation both within and among studies. This variation was a conspicuous feature of most of the parameters we considered (e.g., N, P, sediments, habitat corridors, etc.). Much of this variation probably reflects the wide range of conditions under which studies were conducted. For example, some authors examined forested buffer strips whereas others focussed their attention on herbaceous buffer strips. Forested buffers ranged from remaining native riparian forest to forest plantations established specifically for the purpose of reducing nutrient and sediment export to adjacent watercourses. The studies we reviewed included buffers ranging from vegetative strips less than 10 m wide surrounded by agricultural land to 100-m buffers in landscapes dominated by forest.

The wide range of approaches and conditions makes it difficult to make site-specific conclusions about how vegetative buffer strips will perform in a given location. Many of the papers we reviewed suffered from one or more serious methodological deficiencies. Because of the difficulties associated with undertaking large landscape-level studies, most studies lacked sufficient replication. Few studies have adopted an experimental approach, once again reflecting the challenges of working at landscape level.

A more serious limitation is the lack of research involving buffer widths within the size range typically found in eastern Ontario. In areas dominated by agriculture, buffer strips are often less than 5 m. When farmers in the Raisin Region Conservation Authority (RRCA) watershed are required to establish buffer zones in return for subsidies for fencing or the establishment of alternate water sources, the buffer widths are typically much less than 10 m (C. Chritoph, RRCA, pers. comm.). Only a few studies examined buffers in this size range and the results of those studies were highly variable.

Much more research needs to be focussed on buffers in the 1- to 10-m range since this is the size of buffer strip typically encountered in many agricultural settings. Where possible, carefully controlled field experiments should be conducted. The experimental approach of Magette et al. (1989) offers a useful model. They compared buffers of three different widths under simulated rainfall events where they could control and manipulate nutrient content in the runoff. Their study also included adequate replication but unfortunately their statistical analysis was insufficient to draw conclusions.

Conclusions

Despite the enormous variability that characterized most of the literature we reviewed, it is possible to draw some general conclusions. Numerous studies have demonstrated that vegetative buffer strips can reduce non-point source pollution to streams but the results, both within and among studies, are highly variable, making site-specific predictions difficult. Wide buffer strips (30–100 m) provide the best protection from non-point source pollution, but few studies have focussed on buffer strips within the 1- to 10-m size range typically encountered in areas dominated by agriculture.

Experimental studies of nutrient and sediment removal efficiencies of narrow buffers (1–10 m) typically established on farms are badly needed. Given the large number of buffer programs underway at conservation authorities and other management agencies, there should be abundant opportunities to conduct this type of research. Funding agencies should ensure that monitoring and research are integral components of the riparian buffer programs they fund.

Narrow buffers may reduce non-point source pollution in some situations, and even narrow buffer strips are sufficient to provide other benefits such as shading streams, thereby reducing water temperature, which is critical for some fish species including salmonids.

Farmers who remove valuable land from production to establish protective buffer strips may incur significant economic losses. In order to justify these losses, more research needs to be devoted to demonstrating the efficacy of buffers of a width likely to be achieved in an agricultural setting (e.g., 1 to 10 m).

Acknowledgements

We are grateful for financial support from the Eastern Ontario Model Forest (EOMF). We thank the EOMF's Forest Science Committee for their constructive comments on an earlier version of the manuscript. The comments of two anonymous reviewers improved the quality the final manuscript.

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Received: December 12, 2003; accepted: June 25, 2004.