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Design and placement of a multi-species riparian buffer strip system*

R. C. SCHULTZ[1], J. P. COLLETTI1[2], T. M. ISENHART[1], W. W. SIMPKINS[2], C. W. MIZE[1] and M. L. THOMPSON[3]
[1] *Department of Forestry;* [2] *Department of Geological and Atmospheric Sciences;* [3] *Department of Agronomy, Iowa State University, Ames, IA 50011, USA*

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Abstract. A multi-species riparian buffer strip (MSRBS) system was designed and placed along a Central Iowa stream in 1990. Bear Creek, is typical of many streams in Central Iowa where the primary land use along the stream's length is row crop (corn and soybeans) production agriculture or intensive riparian zone grazing. The Bear Creek watershed is long (~ 35 km), narrow (3–6 km), and drains 7,661 ha of farmland. The MSRBS system is a 20 m wide filter strip consisting of four or five rows of fast-growing trees planted closest to the stream, then two shrub rows, and finally a 7 m wide strip of switchgrass established next to the agricultural fields. The 1.0 km long system is located on an operational farm and is laid out in a split block design on both sides of Bear Creek. An integral part of this system is a streambank stabilization soil bioengineering component and a constructed wetland to intercept NPS pollutants in field drainage tile water flow. It is hypothesized that this system will function effectively as a nutrient, pesticide, and sediment sink for NPS pollutants coming from the upslope agricultural fields. Prior to establishment of the MSRBS system, the riparian zone along Bear Creek was grazed and row cropped to the stream edge. Since 1990 there has been dramatic alteration in the appearance and functioning of this riparian zone. After four growing seasons, the fast-growing tree species (cottonwood, silver maple, willow, and green ash) range in height from 2.4 m to over 5.5 m. Mean (four-year) biomass production of silver maple was 8.4 dry Mg ha^{-1}, more than twice to seven times the yield from other silver maple research plots in Central Iowa. The shrub species, selected because of desired wildlife benefits, have done well in terms of survival and growth with ninebark, Nannyberry viburnum and Nanking cherry doing the best. The switchgrass has developed into a dense stand that effectively stops concentrated flow from the agriculture fields and allows for infiltration rates well above the field rate. Early root biomass data indicate significantly more roots below the MSRBS than agricultural fields. This suggests better soil stabilization, absorption of infiltrated water, and soil-root-microbe-NPS pollutant interaction characteristics within the MSRBS system than the cropped fields. Nitrate-nitrogen concentrations in the MSRBS never exceed 2 mg l^{-1} whereas the levels in the adjacent agricultural fields exceed 12 mg l^{-1}. The water quality data collected suggest that the MSRBS is effective in reducing NPS pollutants in the vadose and saturated zone below the system. The soil bioengineering revetments have stabilized the streambank and minimized bank collapse. Initial results (from 4 months of operation) from the constructed wetland (built in summer 1994) indicate nitrate-nitrogen concentrations of the tile inflow water > 15 mg l^{-1} whereas the outflow water had a nitrate-nitrogen concentration of < 3 mg l^{-1}. Over time this wetland should become more effective in removing excess nitrogen moving with the tile flow from the agricultural fields because of the accumulation of organic matter from the cattails. Overall the MSRBS system

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seems to be functioning as expected. This MSRBS system offers farmers a way to intercept eroding soil, trap and transform NPS pollution, stabilize streambanks, provide wildlife habitat, produce biomass for on-farm use, produce high-quality hardwood in the future, and enhance the aesthetics of the agroecosystem. As a streamside best management practice (BMP), the MSRBS system complements upland BMPs and provides many valuable private and public market and non-market benefits.

Introduction

Most agricultural landscapes are a mosaic of crop and pasture lands and human habitations superimposed on natural prairie, wetland, and forest ecosystems. In the Corn Belt of the Midwestern United States most of these natural ecosystems have been cleared for agricultural purposes. In Iowa, for example, 99% of the prairie and wetlands and more than 80% of the forests have been converted to other uses [Bishop and van der Valk, 1982; Thomson and Hertel, 1981]. Highly efficient production agriculture has produced many intended benefits such as great quantities of high quality and relatively inexpensive food stuffs and industrial raw materials. The production-oriented function of this landscape also has produced unintended and undesirable environmental consequences that include non-point source (NPS) pollution of water, hydraulic alterations of waterways, and disruption of wildlife habitats and populations.

Nationwide, NPS pollution of our water resources is a serious problem. Soil sediment eroded from cropland contributes about 1.4 billion Mg annually to our waterways. In total, over 2.7 billion Mg of soil enters water as NPS pollution each year [Welsch, 1991]. In Iowa, it is estimated that 240 million tons of rich Iowa topsoil enters the Missouri River each year [Kelley, 1990]. Two Army Corps of Engineers reservoirs in Central Iowa are reported to receive thousands of metric tons of soil sediment daily. For example, Saylorville Lake on the Des Moines River receives an estimated 4,000 Mg of sediment per day whereas Lake Red Rock, farther downstream from Saylorville and with three additional uncontrolled drainages entering its conservation pool receives about 15,000 Mg per day [Kelley, 1990].

Pesticides and fertilizers also contribute NPS pollution to our nations waters. Atrazine and alachlor, two pesticides used in row crop production, have been found in Midwestern surface waters for some time [Kelley, 1990]. Phosphorus (P) and nitrogen (nitrate-nitrogen) are major fertilizers that can enter the surface and groundwater resources in great quantities. It was estimated that in 1989, nearly one million Mg of P entered our Nation's waterways. In 1980, an estimated 2.6 million Mg of nitrate-nitrogen became NPS pollution [Welsch, 1991]. Kelley [1990] reported that in 1991 many Iowa surface waters had nitrate-nitrogen levels exceeding 10 mg l^{-1}. Kelly also reported water flowing from tile lines entering various waterways having nitrate-nitrogen levels of 70 to 80 mg l^{-1}.

Removal of fertilizer/pesticide NPS pollutants is expensive and is borne by downstream users of surface and groundwater. For example, the City of Des Moines, IA has invested over $ 4 million in new equipment to filter nitrates from the drinking water extracted from the Des Moines and Raccoon rivers. And, it is considering another $ 13.5 million investment for an advanced filtration system to remove atrazine from the polluted river water [Hubert, 1992]. Welsch [1991] reported that it costs about $ 10 to $ 15 per month for a family of three to remove excess nitrate from groundwater with a community water facility.

The primary way in which the agricultural community has addressed this dispersed and pervasive NPS pollution problem is to develop upland soil conservation practices (reduced tillage, no-till and fertilizer/pesticide (more accurate and better timed applications) management practices). These agricultural best management practices (BMPs) have included vegetative filter strips on watersheds where there is substantial potential for movement of pollutants to drainageways. However, these filter strips have been comprised primarily of introduced cool-season grass species and have been applied along ephemeral channels in crop fields. Most of these introduced cool-season grasses develop limited above- and below-ground biomass when compared to other native species and therefore may not be as effective trapping sediment from surface runoff nor at removing agricultural chemicals from the soil solution (unpublished data). Even with these BMPs in place substantial quantities of sediment and chemicals can still make their way into the riparian zone along streams and lakes. However, in those watersheds where the riparian vegetation is maintained as a well-managed plant community most of the sediment and agricultural chemicals from the upland are filtered before they reach the stream [Lowrance et al., 1985]. Major water quality problems develop when riparian zones are converted to intensive row crop cultivation or heavy grazing.

The mitigating influence of naturally vegetated riparian zones in reducing the delivery of NPS pollutants from agricultural land to stream channels has only recently been perceived as an important element in overall agroecosystem management [Lowrance, 1992; Lowrance et al., 1985, 1984a–c; Heede, 1990; Magette et al., 1989; Phillips, 1989; Cooper and Gilliam, 1987; Cooper et al., 1987; Jacobs.and Gilliam, 1985; Peterjohn and Correll, 1984; Schlosser and Karr, 1981a, b, McColl, 1978). The utility of such buffers as sediment traps has been documented [e.g. Brinson et al., 1981; Mahoney and Erman, 1984]. Although not much is known about the nutrient uptake and cycling capabilities of vegetated buffers, long-term storage of nutrients and gaseous loss of nitrogen tends to be high in riparian areas [Lowrance et al., 1992, 1985]. In Illinois, Kovacic et al. [1991] found that an 80% to 90% nitrate reduction could be achieved in subsurface water after passage through grass and forest buffer strips, respectively. Very little is known about the effects of buffer systems on the fate and transport of pesticides, but it has been suggested that they may at least immobilize or retard movement of pesticides until they naturally detoxify [Pionke and Chesters, 1973; Schlesinger, 1979].

Riparian buffer strips have been recommended as a means to enhance habitat for both aquatic and terrestrial wildlife populations within agricultural ecosystems [Osborne and Kovacic, 1993; Armour et al., 1991; Hehnke and Stone, 1978; Karr and Schlosser, 1978]. Thus, there is much interest among wildlife managers in rehabilitating riparian zones, especially by enhancing their interconnectedness with each other and with upland natural ecosystem remnants.

Within agricultural watersheds, several general land use or land cover conditions occur adjacent to drainage ways: cultivated fields or bare soil, pasture/rangeland, human habitations, and semi-natural areas which may support grassy to wooded vegetation. Each condition may be expected to have characteristic physical, chemical, and biological buffering capabilities relative to NPS pollutants and potentials or constraints as wildlife habitat. Similarly, a variety of BMPs to enhance the environmental utility of these areas may be devised according to site-specific and economic conditions.

One of these BMPs is restoration of riparian buffer strips that can be designed to function similar to or even more efficiently than natural riparian communities. Combinations of trees, shrubs, and grasses can be developed that function effectively as nutrient, pesticide, and sediment sinks for NPS pollutants. The design can take advantage of the different above- and below-ground structure of each species to provide maximum year-round interception of surface runoff and vadose zone soil solution with their associated sediment and/or agricultural chemicals. Innovative designs that use specially selected fast-growing tree species can be grown as short-rotation woody crop systems (SRWC). SRWC systems produce biomass for energy in 5–8 years and timber products in 15–20 years [Colletti et al., 1991]. These frequent harvests help to maintain active nutrient and pesticide sequestering by the woody plant community. These riparian sites do not have to be replanted for 3 to 4 harvests because the selected species reproduce vegetatively by stump or root sprouts. The large root systems allow very rapid regrowth that provides continuity in water and nutrient uptake and physical stability of the soil throughout the life of the stand.

SRWC systems also can include native shrubs which can provide biomass if harvested and demonstrate coppice regeneration. The addition of shrubs will increase species diversity and wildlife habitat, provide yet another rooting pattern which will hold soil, intercept shallow groundwater nutrients, and provide organic matter for soil microbes. Finally, the addition of native prairie grasses to the reconstructed multi-species buffer strip will provide additional species diversity, a very high frictional surface for intercepting surface runoff and a deep and fibrous root system that will play an important role in improving soil quality.

Although forested riparian buffer strips have been shown to be effective there are still major questions on whether forests or grass buffers are best and what optimal widths of strips are needed to provide a specific nutrient and sediment load reduction [Osborne and Kovacic, 1993]. Even less information exists on the design, technical capabilities and appropriate management approaches for reconstructed riparian buffer strips in agricultural landscapes [National Research Council, 1993].

This paper presents a model for a multi-species riparian buffer strip (MSRBS) system that will intercept eroding soil and agricultural chemicals from adjacent crop fields, stabilize channel movement, and improve in-stream environments, while also providing wildlife habitat and biomass for energy and high quality timber. This agroforestry model has been developed by an interdisciplinary team of researchers, members of the Iowa State Agroforestry Research Team (IStART) with specialists in forage crops, soils, hydrogeology, forest hydrology, forest ecology, wetland ecology, economics, biometrics, wildlife management, and extension.

The recommended model tree/shrub/grass buffer strip

The following figure demonstrates the MSRBS design that is recommended by IStART. Figure 1 shows the general concept of a 20 m-wide filter strip. Starting at the stream, four or five rows of trees, two rows of shrubs and a 7 m-wide band of switchgrass (*Panicum virgatum*) are recommended. Other native prairie grasses could be mixed with the switchgrass as long as the switchgrass dominates the site. Fast-growing trees species such as cottonwood

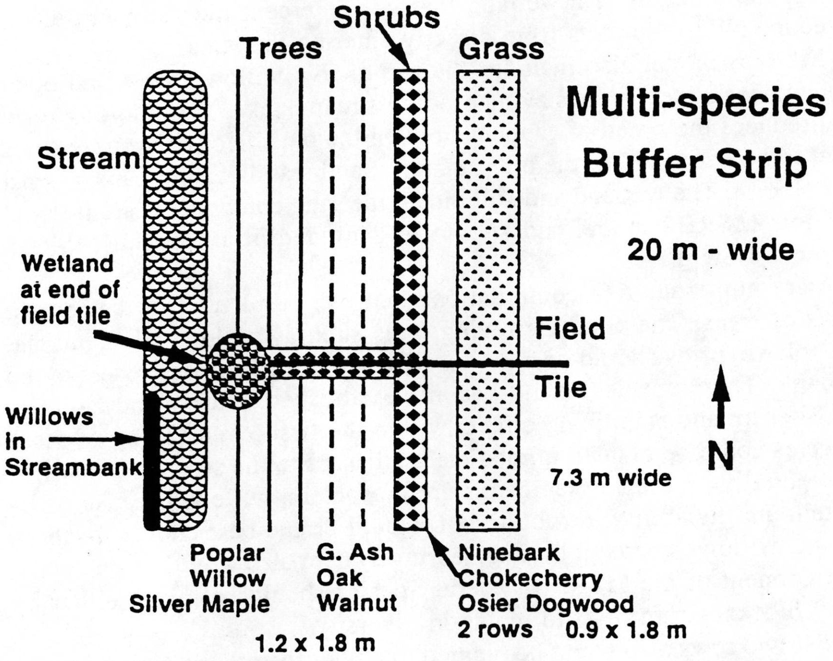

Fig. 1. Layout for a multi-species riparian buffer strip management system that includes streambank bioengineering and small constructed wetlands at the end of field drainage tiles.

hybrids (*Populus* spp., e.g., *Populus clone* NC-5326, a designated clone by the North Central Forest Experiment Station), silver maple (*Acer saccharinum* L.), willow (*Salix* spp), and green ash (*Fraxinus pennsylvanica* Marsh.) are used in this model. Also, slower growing species such as black walnut (*Juglans nigra* L.), red oak (*Quercus rubra* L.), bur oak (*Quercus macrocarpa* Michx.), white oak (*Quercus alba* L.), swamp white oak (*Quercus bicolor* Willd.) and hackberry (*Celtis occidentalis* L.) may be planted if the soils are moderately well drained and the seasonal water table does not stay above three feet for more than one month during the early growing season.

If an underground drainage tile runs through the filter strip, tree roots from cottonwood hybrids, silver maple and willow are likely to plug these tiles. Moreover, the efficacy of the buffer strip to transform NPS pollutants moving with the sub-surface water flow is eliminated. To alleviate problems with tree roots, the portion of the tile which passes under the filter strip could be replaced with a solid PVC pipe. Alternatively, a strip of grass (or even shrubs) might be used in the vicinity of the tile. This grass strip should be 4.5–6 m wide and centered over the tile. To alleviate the problem of the tile flow bypassing the 'living filter' actions of the soil-roots-microbial zone beneath the buffer strip, the model includes a small, constructed wetland at the outflow end of a field drainage tile and sized at a ratio of 1 ha of wetland per 100 ha of drained agricultural land. With this size criterion only a small space is needed for the creation of a wetland that will intercept tile flow and effectively reduce NPS pollutants from directly entering the stream.

The MSRBS model also includes the use of live willow stakes and other soil bioengineering techniques along eroding streambanks. The resulting plant material reduces the speed of channel flow on the outside of the bend, causes sediment to be deposited in the plant material and stabilizes the bank against further collapse. The wetland and soil bioengineering components are integral parts of this MSRBS model and should be included in an overall MSRBS management system.

There are numerous tree combinations that can be planted in the four or five rows of trees. The fastest growing trees such as willow, silver maple, and/or poplar hybrids should occupy the first two or three rows closest to the stream bank. These species would become established quickly and begin to provide filtering and stabilizing effects within the first 3 years. Any of these three species could be planted immediately adjacent to the stream. But where steep, potentially eroding streambanks are a problem, willow, because of its root system and its ability to root sprout, would be the best choice. In these situations, a willow-stake/soil bioengineering system also would be an appropriate component of the MSRBS system. Species should be mixed either by row or by blocks within rows to maintain diversity.

The next two rows also could be planted to any of the other species already mentioned. These species can be slower growing species because they are placed further from the streambank where soil stability is less of a concern. Figure 1 shows a 1.8 m spacing between tree and shrub rows. That spacing could be increased to 2.4 m between rows which would reduce the number of tree rows to four. At this spacing, it is easier to get between the rows for maintenance and the cost of establishment is reduced because fewer seedlings are needed.

The two rows of shrubs could include a wide variety of species. Past experience dictates planting at least two different species of shrubs for diversity and to reduce the risk of losing all the shrubs to a pest or drought. Common ninebark (*Physicarpus opulifolius* L.), common chokecherry (*Prunus virginiana*), Nannyberry viburnum (*Viburnum lentago*), Nanking cherry (*Prunus tomentosa*), and red osier dogwood (*Cornus stolonifera* Michx.) are well suited to these buffer strips.

Spacing between trees in the rows is 1.2 m and between shrubs is 1 m. A 20 m wide by 500 m long MSRBS on one side of a stream occupies 1.0 ha of land. Five rows of trees would include ~2,085 trees per 1.0 ha (4 rows of trees would need ~1,667 trees). For two rows of shrubs at 1.0 m between shrubs, there would be an additional 1,000 plants for a total of 3,085 woody plants (2,557 for the 4 row design) per 1.0 ha or 500 m of length on one side of a steam. This MSRBS model assumes designing and placing the system on both sides of a stream.

If there are specific tree density requirements for governmental and non-governmental organizations (NGO) cost-share programs, the numbers of trees can be increased by not planting shrubs or by making the grass strip 6 m wide and adding an additional row of trees. The grass strip should not be any narrower than 6 m.

Materials and methods

The multi-species riparian buffer strip (MSRBS) system was planted in the Bear Creek Watershed located in north-central Iowa within the Des Moines Lobe, the depositional remnant of the late Wisconsinan glaciation in Iowa. The total length of Bear Creek is 34.8 km and it has 27.8 km of major tributaries before it empties into the Skunk River. The watershed drains 7,661 ha of farmland, most of which has been subjected to field tile-drainage during the last 40 years. About 87% of the watershed is devoted to corn and soybean agriculture. Prairie vegetation originally dominated most of the undulating to level topography, with the exception of forests that occurred along the lower end of the creek. Soils are well drained to poorly drained and formed in till or local alluvium and colluvium derived from till. Roland, a town of 1,100 people, is the only community in the watershed and there are no major recreational areas.

Two different levels of research activity are taking place in the Bear Creek Watershed. The Leopold Center for Sustainable Agriculture Agroecology Issue Team (AIT) is using the watershed to study the condition of the riparian zone at the watershed level. The AIT is developing a model to identify critical riparian reaches along the creek that need restoration and/or modified management to reduce the impact of NPS pollution on Bear Creek. The long term goal of the project is to help farmers who own land along this and other streams to develop riparian zone management systems that will intercept surface runoff and subsurface flow and remove or immobilize sediment and agricultural chemicals before they enter the creek.

The Iowa State Agroforestry Research Team (IStART) has been working on one farm in the watershed and is developing the MSRBS model system for use along the critical reaches of Bear Creek. This model can be adapted to other waterways in Iowa and the midwest. An integral part of that system includes soil bioengineering features to stabilize streambanks and small wetlands placed at the outlets of field drainage tiles to denitrify the tile flow before it enters the creek. The AIT will use this model to help demonstrate the MSRBS concept to farmers and to provide design specifications for similar buffer strips on their farms.

The MSRBS system lies along a 1,000 m reach of Bear Creek on a private farm approximately 2.4 km north of Roland, Iowa. At this location the creek is a third order stream with average discharge rates varying between 0.3–1.4 m^3 sec^{-1}. The farm has been owned by the Risdal family for several generations. As expected, there is a gentle topographic slope down to the creek. Corn, soybeans, and alfalfa hay are produced on this farm and the corn and soybeans are rotated on an annual basis. During the past five years, pesticides applied on the farm have included Commence (chlomazone) in 1989 and 1991, Extrazine (atrazine and cyanazine) in 1990, 1992, 1993, and 1994 and Eradicane (EPTC) in 1990 and 1992. During the past twelve years, impregnated urea pellets have been applied at the rate of 134 kg ha^{-1}. On legume fields, 90 kg ha^{-1} of 120-60-60 (N-P-K) are applied annually. Until 1988, livestock also were allowed to graze along parts of the creek riparian zone, which caused severe stream bank erosion and impacted the riparian plant and animal community.

The MSRBS system site is set in Pleistocene sediment deposited by the Des Moines Lobe (Alden and Morgan Members) and Holocene age sediment overlying Mississippian age bedrock, which is composed of primarily limestone, dolomite, sandstone and shale. Perhaps the most surprising feature of the geology at the site is the depth to bedrock. Although maps provided by the Iowa Department of Natural Resources-Geological Service Bureau (GSB) indicated that the Pleistocene sediment is probably less than 30 m thick and there are no visible bedrock outcrops near here, bedrock was encountered at depths of 6.7 m near the stream entrance to the farm and at depths of 3.7 to 4.6 m below the alluvium. Excavations of the creek bed for the weir installations indicated that weathered limestone and siltstone lie only 1.5 m below the channel. Shallow bedrock complicates the hydrogeology of the site to the extent that much of the hydrogeological research has been directed towards distinguishing groundwater flow in the shallow unconfined and the deeper bedrock aquifer.

To objectively evaluate the MSRBS, sections of the Bear Creek riparian zone reach were divided according to a split block statistical design. The reach of the creek under study was divided into three blocks: inside bend, outside bend, and straight reaches (Fig. 2). Five 90-m plots were located within each block. Treatments consisting of three combinations of planted trees, shrubs, grass, and two controls, were randomly assigned to the plots within each block. The planted treatments consisted of five rows of trees planted closest to and parallel to the creek at a 1.2 × 1.8 m spacing. Different species of trees were used in each of the three treatments. One treatment consisted of a poplar hybrid (*Populus* × *euramericana* 'Eugenei') which has been extensively field tested and is readily available in Iowa. The second treatment contained green ash and the third treatment contained a mixture of four rows of silver maple with

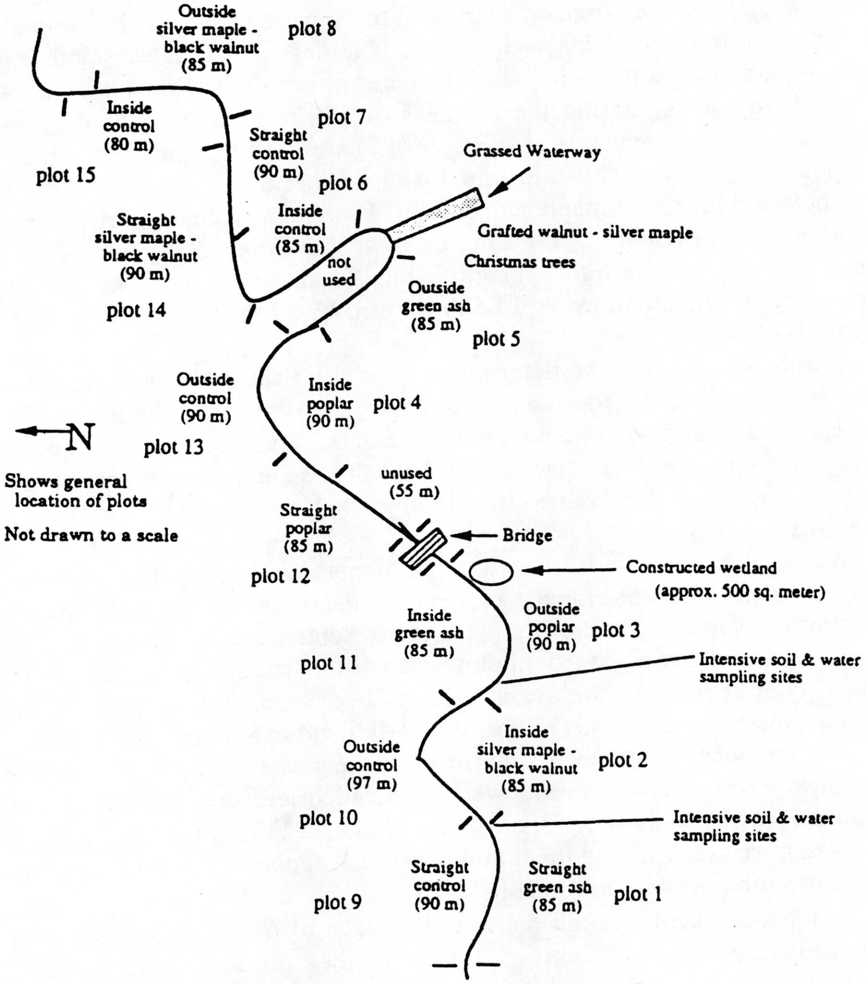

Fig. 2. Plot layout of the MSRBS project located on Bear Creek in Story County, IA.

a center row of black walnut. Upslope from the trees are a row of red-osier dogwood and a row of ninebark. The shrubs were planted at a 1.0 × 1.8 m spacing. Finally, a 7.3-m-wide strip of switchgrass was planted upslope from the shrubs. Controls consist of pasture grasses similar to those that were present on areas that were grazed prior to the study. Most trees are being grown on a 8- to 10-year rotation, depending on the species. Black walnut is being grown on a 45- to 55-year rotation.

Above-ground plant growth and biomass production are measured using permanent measurement plots in each of the treatment plots. Two permanent measurement plots were established in each of the 90 m long tree and shrub plots during the summer of 1990. The measurement plots consist of 4 trees in each of the 5 consecutive rows of trees and 4 shrubs in each of the 2 consecutive rows of shrubs. The height and diameter at 20 cm above the ground of each surviving tree have been measured annually during the dormant season. The tree measurements are used to estimate average height, diameter, biomass, and survival for each species. Biomass is estimated using regression equations and the height and diameter of each tree. Equations that were developed for estimating the biomass of poplar in a study at the nearby Hickory Grove Biomass project (Colo, IA) are used to estimate the biomass of poplar and green ash while equations for silver maple are used to estimate the biomass for silver maple and walnut. There is a probable bias in the estimation of the ash and black walnut biomass, but the trees are so small at this time that the error is likely insignificant. As the ash and walnut get larger, species specific equations will be developed by harvesting some of the trees in the MSRBS.

Shrub biomass will be determined after the fifth growing season during the 1994 dormant season when subsamples of shrubs will be measured for stem numbers and stem diameters and heights. Subsamples will be coppiced and dry weights will be determined. Switchgrass and pasture grass (control plots) biomass are determined by clipping 1 × 1 m plots and determining dry weights.

A preliminary study of below ground biomass was conducted to determine the differences in root biomass production under the various plant species in the buffer strip and the crop fields. During September, 1993, two 6,000 cm^3 soil cores were extracted from below each of the tree species, shrubs, switchgrass, cool season pasture grass, corn, and soybeans. Cores were separated into depths of 0–45 cm, 45–75 cm, and 75–110 cm to approximate soil horizon depths and because these were multiples of the bucket on the extraction corer. Soils were wet sieved and roots were collected, dried, and weighed. Although the number of cores is very small, the differences in root (dry kg ha^{-1}) are so great that we are reporting them in this paper. A replicated study is in progress to substantiate these initial results.

Water movement through the MSRBS reach of Bear Creek is sampled in the vadose zone (the unsaturated zone of the soil above the water table including the rooting zone), the unconfined shallow aquifer located in the alluvium and glacial till, the bedrock aquifers, the drainage tiles, and the stream channel itself. Various kinds of sampling equipment have been installed to access these different sources of water. Piezometers, 'mini-piezometers', and zero-tension and tension lysimeters were installed. In addition, soil tensiometers are also installed to monitor soil water tension in the vadose zone. The southwest quadrant of the MSRBS project site (plots 1–3) has been established for intensive monitoring to examine the physical and chemical processes that take place in the buffer strip during the capture, retention, and processing of the products of overland and subsurface movement. In this area five transects, with three nests of instruments each, are installed one at the crop field-switchgrass interface, one at the switchgrass-shrub interface, and the last near the tree-streambank interface. Each nest of instruments contains porous cup tension lysimeters at depths of 45 cm and 90 cm, a zero-tension lysimeter at 45 cm depth [Thompson and Scharf, 1994], a soil tensiometer at 45 cm, and a minipiezometer at 3 m. During the growing season an additional set of tension lysimeters is installed in the crop field at a horizontal distance of 15 m from the end of each of the five transects. Stream, tile, and groundwater samples also are collected. Only the water quality results from the transects will be presented in this paper as the major emphasis of the paper is to describe the design function of the MSRBS system.

Water samples are analyzed for nitrate, ammonia, atrazine, and pH. The present protocol calls for monthly sample collection between growing seasons, and twice-monthly collections during the growing season (March–October). The twice-monthly sampling is needed during the growing season to follow the flush of the chemicals added during that period. Nitrate and ammonia concentrations are determined using electrodes (Hach Chemical Co, Colorado Springs, CO). Samples are screened for atrazine using an Ohmicron Rapid Assay System (Ohmicron, Newtown, PA).

Two 80–100 m long soil bioengineering structures have been developed as part of the MSRBS system. These structures use live staking and dead tree fascines to stabilize severely eroding banks on two outside streambanks. Dormant willow (*Salix* spp.) posts were installed on the outside bend along plot 2 in the spring of 1992. From the original time of planting of the MSRBS in early 1990 until spring of 1992 at least 3.6 m of bank, 90 m in length, had collapsed into the creek in this bend. Two newly planted rows of silver maple had been lost. In the spring of 1992, up to 1 m long and 5–7.5 cm diameter cuttings of willow were pounded into the creek bottom along the toe of the bank of the first two thirds of the collapsed area. Three or four rows of posts were pounded in at a spacing of about 0.5 × 0.5 m. Also, smaller cuttings were pushed into the bare bank wall at a similar spacing. Most of these cuttings took root and grew. The planting was extended in the spring of 1993 after more cuttings became available. Record floods occurred in the watershed in June 1992 and especially July 1993. Although the plantings withstood the 155 cm of rainfall (79 cm is normal), the record 500 year flood plus at least 5 other over-bank floods of 1993, a dead fascine system, using bundles of harvested, 6 year old silver maple was added to this planting in spring 1994. Two or three complete trees were wired together and placed in cribs of 3–4 bundle heights. Additional willow stakes were added to the system. An additional system was also developed along 200 m of the outside bend of plots 4 and 5 in 1994. The stability of these two bends are being compared to bends in plots 6 and 10.

An approximately 500 m^2 wetland was constructed to process field drainage tile water from a 4.9 ha cropped field. The wetland is 0.5–1 m deep and is surrounded by a low berm. The bottom of the wetland was sealed with clay because it contained alluvial sand. Organic soil was then replaced as the top layer. The agricultural drainage tile was excavated and rerouted to enter the wetland at a point in the wetland furthest from the creek, forcing the water to travel through the wetland before entering the surface waters. A gated water level control structure at the wetland outlet provides complete control of the level of water maintained within the wetland. Cattail (*Typha glauca*) rhizomes were collected from a nearby wetland during the early spring when the shoots had just begun to elongate, and stored in a cooler until planting. The wetland was planted in early June at a spacing of approximately 0.6 × 0.6 m. Willow cuttings were planted on the stream side of the berm and native grasses and forbs were planted on the constructed berm for stabilization and to provide vegetation diversity.

Results and discussion

This buffer strip project differs from many that have been reported in the literature because this system was established on previously cultivated and heavily grazed ground. It is inherent on such sites that time is required before the system begins to function as it is ultimately expected to function. Early results from restoration projects such as this one do not accurately reflect the remediation potential of the plant community. However, it is important to report early results of such systems to demonstrate the potential of the system. Visual contrasts also are useful to demonstrate the changes that have taken place on the site over time. Although these visible changes are difficult to quantity, it is often the visual impact that results in landowner adoption of a demonstrated technology.

The plants for this demonstration MSRBS were selected to serve multiple purposes. Those purposes included rapid growth, dense rooting habits, coppice regeneration ability for the trees and shrubs, stiff stems for the grass, cover and/or food for wildlife, and a potential for being used as biomass for energy or fiber. The desire was to develop an effective buffer in as short a time as possible to effectively trap sediment and process chemicals and to demonstrate to landowners that a buffer strip with woody plants grows rapidly.

Survival of the trees, shrubs, and switchgrass in the MSRBS has generally been very good. Only red-osier dogwood has shown significant mortality.

After the first growing season (1990) 50% of the dogwood seedlings died. The mortality showed an interesting pattern with some plots having good survival and others almost 100% mortality. The seedlings were replanted in 1991 and most of these also died during the first season. This would suggest that there might be a soil problem that has, as of yet, not been identified. Nannyberry viburnum and Nanking cherry have now been replanted in those locations and are showing better survival.

Silver maple and green ash have had the highest survival over the life of the project (Table 1). Poplar survival was adversely influenced on plot 12 by the two major floods of 1990 and 1991. Seedlings in over one-half of the plot were washed away in 1990 and the replanted seedlings were washed away again in 1991. There also has been some mortality, possibly related to residual herbicides, in plot 3 where survival and growth on the portion of the plot that had been cultivated prior to establishment of the MSRBS, have not been very good. These two incidents account for most of the mortality in the poplars.

Black walnut survival was adversely influenced in the second year of growth because of intense grass competition. Strips of pasture grass into which the trees were planted were treated with glyphosate (Roundup™) herbicide at the time of establishment. The survival of walnut was 96% after the first growing season. No herbicides were used in the second year because of the desire to keep the surface covered with vegetation. Walnut seedlings are very susceptible to grass competition and that effect can be seen in the second-year survival and growth of the trees on this site. Once the seedlings had completed their third growing season they were able to compete more effectively with the grass but still did not grow very rapidly.

Of the tree species that were planted in the MSRBS plots, poplar hybrids are the tallest after four growing seasons, averaging 4 m in height. The poplars are followed in height by silver maple, green ash, and black walnut. The poplars show very rapid initial growth that has been maintained throughout the four growing seasons. Diameter responses for the trees has been similar to the height responses with poplar and silver maple again the largest trees. Most of the trees on the site have single stems, except for silver maple whose individuals have an average of 1.8 stems per plant. These added stem numbers produce a denser canopy structure than for poplar which is taller and single stemmed. The result is a different habitat opportunity for wildlife and a different distribution of biomass per plant.

Although willow was not planted as part of the design, two plots of 15 Austree® willow trees each are planted on the project site. One is planted on the end of a sandbar in plot 11 and the other is planted near the creek parallel to plot 3. The trees in plot 11 were coppiced in the spring of 1992 while those in plot 3 were not. At the end of the 1993 growing season the trees in plot 3 averaged almost 5.5 m in height and 10 cm in diameter while the trees which were coppiced in spring of 1992 averaged 5 stems per stump with diameters greater than 3.8 cm and average heights of 5 m.

Table 1. Mean and standard deviation (SD) of % survival, height, diameter at 20 cm, biomass and number of stems for poplar, green ash, silver maple, and black walnut in 1990, 1991, 1992, and 1993. Means and SDs are calculated from individual tree measurements, not plot means.

Poplar	1990 (140)[a]		1991 (140)		1992 (120)		1993 (120)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
% Survival	87.00	–	85.00	–	83.00	–	87.00	–
Height (m)	1.03	0.36	2.08	0.87	3.42	1.32	4.00	1.67
Diameter (mm)	11.50	4.80	25.20	12.10	46.00	22.90	55.00	28.80
Biomass (kg)	0.04	0.04	0.33	0.25	1.44	1.35	2.43	2.52
# of stems per seedling	1.2	0.50	1.10	0.30	1.10	0.30	1.00	0.17

Green ash	1990 (100)		1991 (100)		1992 (120)		1993 (120)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
% Survival	96.00	–	95.00	–	97.00	–	92.00	–
Height (m)	0.45	0.14	0.84	0.23	1.12	0.36	2.40	1.59
Diameter (mm)	5.80	1.80	10.90	3.60	14.00	5.30	31.00	16.30
Biomass (kg)	0.01	0.00	0.03	0.02	0.07	0.07	1.02	1.80
# of stems per seedling	1.10	0.30	1.00	0.10	1.20	0.40	1.10	0.30

Silver maple	1990 (96)		1991 (96)		1992 (96)		1993 (96)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
% Survival	98.00	–	97.00	–	98.00	–	98.00	–
Height (m)	0.82	0.19	1.26	0.37	1.89	0.60	3.02	0.75
Diameter (mm)	10.10	2.80	18.80	6.80	28.00	11.50	44.00	17.50
Biomass (kg)	0.03	0.02	0.14	0.11	0.46	0.40	1.82	1.40
# of stems per seedling	1.00	0.20	1.00	0.00	1.50	0.80	1.80	1.00

Black walnut	1990 (24)		1991 (24)		1992 (24)		1993 (24)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
% Survival	96.00	–	71.00	–	75.00	–	75.00	–
Height (m)	0.61	0.12	0.61	0.18	0.63	0.21	1.14	0.43
Diameter (mm)	6.90	1.50	8.40	3.10	10.00	4.40	20.00	9.20
Biomass (kg)	0.01	0.00	0.04	0.01	0.04	0.02	0.15	0.14
# of stems per seedling	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00

[a] Numbers in parentheses represent number of seedlings initially planted in permanent tree plots. The means for size and number of stems are based on measurements of survivors. Willow data are not available because they are not planted in replicated plots.

Based on four year growth in this MSRBS, biomass per plant and per hectare is less for the *Populus* clone but more for silver maple than in the SRWC experimental plots at the Hickory Grove Energy Plantation site, near Colo, IA. For example, the MSRBS mean biomass for poplar was 11.25 Mg

ha^{-1} and for silver maple 8.43 Mg ha^{-1}. Leaves and twigs for these adds approximately 1 Mg ha^{-1}. From the Hickory Grove SRWC plots, the mean biomass after four growing seasons for the same *Populus* clone was 29.3 Mg ha^{-1} (1.8 × 0.9 m system) and 25.5 Mg ha^{-1} (1.8 × 1.8 m system) [Colletti et al., 1991]. For silver maple at Hickory Grove, the four-year mean biomass was 2.9 Mg ha^{-1} (1.8 × 0.9 m system) and 1.1 Mg ha^{-1} (1.8 × 1.8 m system) [Colletti et al., 1991]. At the Hickory Grove site the same *Populus* clone produced roughly twice the biomass.

The MSRBS site seems to yield substantially better in terms of silver maple biomass. Part of the reason for the hybrid poplar differences is that the MSRBS is managed for multiple uses whereas the SRWC system is managed mainly for biomass. As a result, more attention is given to weed control in the SRWC system and those plantations are more weed free. In the MSRBS the objective is to maintain a continuous cover of grasses on the ground for sediment trapping and these grasses compete heavily with the trees, especially in the early years of establishment of hybrid *Populus*. The apparent *Populus* biomass trade-off of the MSRBS may be necessary to meet the major objective of reducing NPS pollution. Silver maple growing along Bear Creek seems to have at least 2 to 7 times the biomass production compared with the biomass from the upland (and non-irrigated) Hickory Grove site. Silver maple casts a denser shade than the poplar hybrids which may reduce the grass competition. Given the early performance of silver maple in this model there may not be a biomass trade-off for the MSRBS at all.

Clipping plots in the switchgrass and the control plots of mixed pasture grasses show that the switchgrass has about 9.4 Mg ha^{-1} of dry biomass while the pasture grasses have about 5.1 Mg ha^{-1}. The switchgrass biomass is almost twice as great as that of the pasture grasses and much larger than that of the trees. Although samples were not collected to test the following, the pasture grasses growing between the tree and shrub plots would contribute enough biomass to the poplar plots to provide a total above-ground weight similar to that of switchgrass (4.4–5.1 Mg ha^{-1}). However, it would not be economical to try to harvest the pasture grasses in the tree strips. This system of narrow strips of trees and shrubs provides enough light to the ground vegetation that grasses and herbs are able to grow providing excellent sediment trapping.

The preliminary root biomass data from a very small number of samples cores are very encouraging. The dry weights were used to estimate the weight of roots in each depth category on a per hectare basis (Fig. 3). Except for the corn and soybean crops (adjacent fields are planted on a corn-soybean rotation), the vegetation in Fig. 3 is arranged in the order that it is planted in the MSRBS to show root distribution in relation to the stream channel.

The implications of these root data are profound. Plant roots increase soil stability by mechanically reinforcing soil and by reducing the weight of wet soil through evapotranspiration [Waldron and Dakessian, 1982]. Deeper rooted plants extract more water from greater soil depths than shallow rooted plants. Woody plant roots provide superior soil stabilization when compared

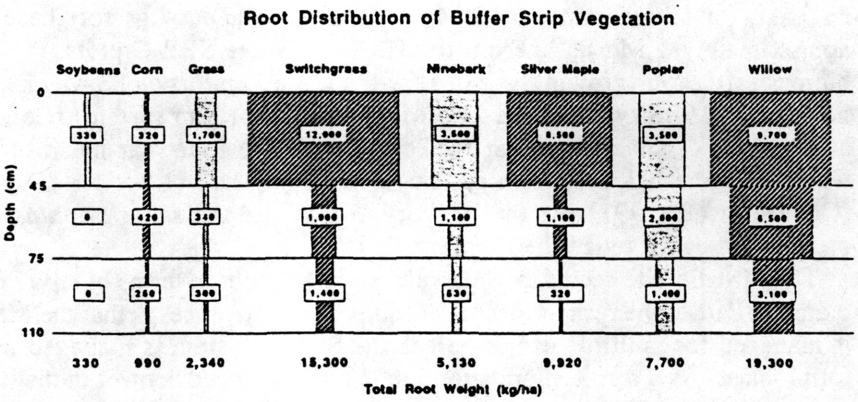

Fig. 3. Preliminary root distribution of MSRBS vegetation by depth and arrangement. Data is based on a limited sample of two large soil cores per species.

to herbaceous plants because of their deeper rooting habit and their larger perennial roots [Waldron et al., 1983].

Corn and soybeans have only minimal root biomass and that is probably only present during and shortly after the growing season, a period of 5–6 months. Cool season pasture grasses provide significantly more roots in the top 43 cm of the soil and are similar to corn at lower depths. The grass roots are present for a longer time during the year and provide organic matter for maintaining soil tilth. The limited biomass of these grasses below 43 cm reduces their ability to stabilize soil and extract water and associated agricultural chemicals. The limited influence of shallow roots can be seen along collapsing streambanks of grazed riparian pastures. Even when these pastures are abandoned, bank stability is minimal because of the lack of root mass at depth. The riparian buffer strips or filter strips recommended by a number of federal and state agencies consist primarily of these cool season grasses with their limited root biomass. It would seem that the MSRBS design developed in this project provides superior rooting to filter or buffer strips consisting of only cool season pasture grasses. The switchgrass has a much larger root mass than the cool season grasses. This coupled with an above ground biomass which is almost twice that of the pasture grass makes the switchgrass superior for trapping sediment and absorbing the water which infiltrates into the soil as a result of the slowed surface water movement.

The tree strip adjacent to the creek also provides a large root biomass both at the surface and with depth. Willow and silver maple with their large deep root biomass would seem to be best suited for planting next to the creek, especially in those areas where bank stability is needed. In areas such as straight reaches poplar could also be planted along the streambank. In both cases at least two rows of these species should be planted to provide the root mass necessary for soil stability. Silver maple and willow also would help reestablish higher soil infiltration rates and provide a large root volume to absorb the infiltrated water. It is expected that the root biomass for the trees will continue to increase at each depth over the next few years.

The frictional surface, and above-ground and below-ground biomass of the MSRBS are superior to that of the pasture grass buffer strips. These are the major attributes needed for a buffer strip to function effectively in reducing NPS pollution. The diverse MSRBS also provides the additional benefits of wildlife habitat, improved aesthetics, and potential fiber and biomass energy crops.

One of the best ways to demonstrate the results of a restoration project is to keep a visual record of the progress of restoration from the beginning of the project. To that end a series of three sets of photos are provided to show visible changes on the site. Because this site was devoid of any significant plant cover other than closely grazed grass and cultivated fields, the change in vertical and horizontal structure of the vegetation community over the past four growing seasons has been very dramatic. This change in structure serves both as a physical barrier to water and wind movement across the buffer strip, provides a diverse wildlife habitat, dramatically changes the aesthetic impressions that visitors have of the site, and suggests that significant biomass can be produced that could provide potential commercial products for the landowner.

The photos also are evidence that the buffer strip can withstand large volumes of water that can move through the system during major storm events. There were no areas along the MSRBS that were breached by concentrated flow from the uplands during 1993, one of the wettest years on record. A large portion of the MSRBS was inundated by flood waters from the creek itself and was subjected to movement of large debris which floated with the water. There is no evidence that any major damage was done by either the flood water or the debris.

The two of photos shown in Fig. 4 were taken from the bridge, looking down stream to the southwest into plot 11. For reference note the old cottonwood tree stump in the center of A and the bottom right corner of B. The bridge in A was washed out by the flood of 1990. Numerous planks from the replaced bridge also have been washed out by subsequent floods. The bridge is substantial enough to support large tandem wheeled gravel and concrete trucks as well as large combines. Photo A was taken in March, 1990. Note the bare streambanks of this area which was previously grazed.

Photo B was taken in June of 1994. Plot 11 is an ash plot with an Austree® willow plot planted at the end and soil bioengineering live willow stakes pounded into the bank. At the end of the 1993 growing season the ash and willow were 2.4 m and 5.0 m tall, respectively. All of the grass and herbaceous plants that are seen in the photo were either already on site or seeded in naturally. Only trees, shrubs, and willow cuttings were planted. The switchgrass strip which was planted is hidden by the trees in photo B. This site was

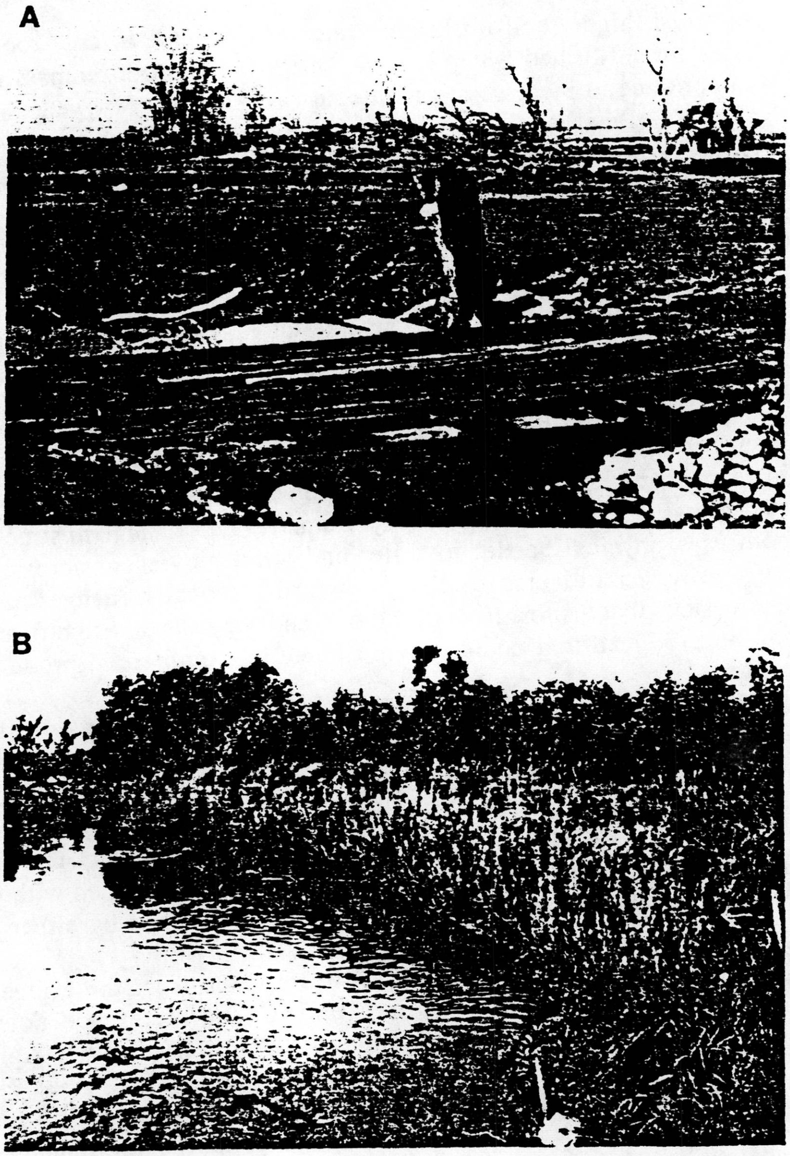

Fig. 4. Looking downstream to the southwest from the bridge across plot 11 (green ash) (A) before planting, March 1990; (B) June, 1994.

subjected to a 500 year and 5 other out-of-bank floods during the 1993 growing season. The results show how effective the MSRBS is as a frictional buffer.

The two photos shown in Fig. 5 also were taken looking downstream toward the bridge (toward the southwest) from the east end of plot 12 on the north-

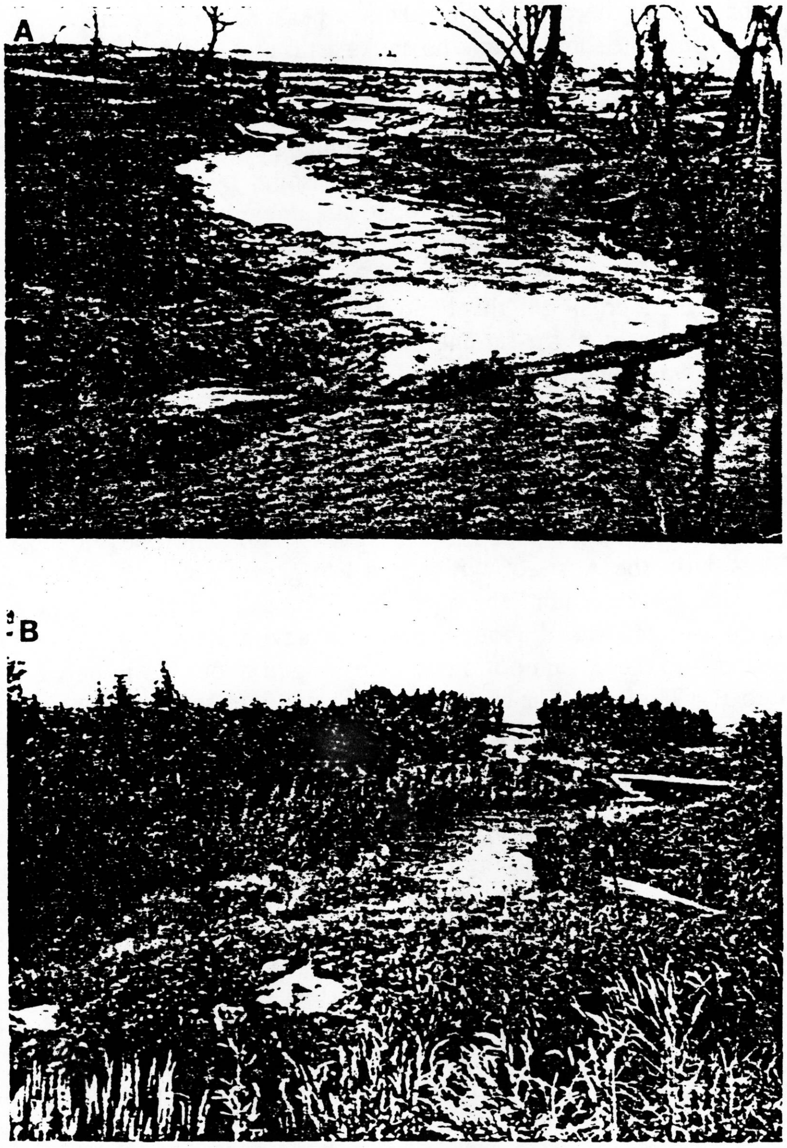

Fig. 5. Looking downstream to the southwest from the end of plot 12 (poplar hybrid) (A) before planting, March, 1990; (B) June, 1994.

west side of the creek with plot 4 on the southeast side of the creek. Photo A was taken in March 1990 and photo B was taken in June 1994. Notice the fence along the right side of the creek in photo A identifying the grazed and cultivated areas along the creek. The bridge is located just beyond the farm equipment standing near the center of the photo. Also notice the very steep, bare banks and the point bar on the southeast side of the creek. Without the cattle grazing the sandbar and the banks grass and herbaceous cover have been restored. No willow cuttings have been planted along this portion of the creek. Even after the floods of 1993 the streambank integrity was maintained. The trees on both sides of the creek are poplar hybrids which averaged 4 m in height at the end of the 1993 growing season.

Figure 6 shows the willow post streambank bioengineering for bank stabilization. Photo A was taken near the end of the growing season in 1991 looking north along the edge of plot 2. The floods of 1990 and 1991 caused excessive bank erosion in this bend. In photo A, notice that two rows of silver maple can be seen at the far end of the eroded segment of the bank. The photographer was standing in the middle of where these trees had been machine-planted in 1990. Spacing between the tree rows is 1.8 m. The smaller, lighter colored walnut seedlings can be seen to the left of the eroded bank. A total of about 4.5 m of streambank was eroded from this location during the first two years of the project.

Using modified methods of streambank stabilization developed in Illinois (SCS, 1990), the Austree® whips that had grown on the point bar shown in Fig. 4 were harvested in February, 1992. Whips of 2.5 cm diameter, or greater, were cut into lengths of about 1 m. Cuttings with diameters of 5–7.5 cm were pounded into the stream bottom at a spacing of about 0.5 m between cuttings (photo B). Three to four rows were pounded into the sediment at the toe of the collapsed bank. Smaller 0.5 m long whips were pushed into the vertical portion of the bank at about a 0.5 m spacing between cuttings. The first set of cuttings were installed in March of 1992 with another set installed in March of 1994 to extend the planting beyond the end of the slumped area.

The results of the planting exceeded expectations, especially considering the extensive flooding that occurred in 1993. Photo B shows the planting in June 1994. A visit to the site in late November, 1993, after the leaves had fallen from the trees, indicated that the posts were trapping sediment from the stream as well as sediment from further collapse of the bank. Only an additional 0.3 m of bank has been lost since the willow posts were installed. What had been a straight wall now has an angle approaching 45°. The slope of the bank should continue to become more gentle as the permanent woody as well as herbaceous vegetation become established. It has been very encouraging to observe how well this system withstood the intense flooding of 1993. Several large logs and two bridge planks were caught in the willow thicket. Although some of the stems were skinned and did not resprout, most survived and continued to grow. The placement of willow cuttings in the vertical bank and in the streambed seems to be a viable method of stabilizing streambanks, especially before the other buffer strip tree root systems become established to the point that they also stabilize the bank.

Notice the growth of the silver maple through the 1993 season (Fig. 5). Silver maple grows slower than the popular hybrids during the first several years but after the third growing season it begins to accelerate growth dra-

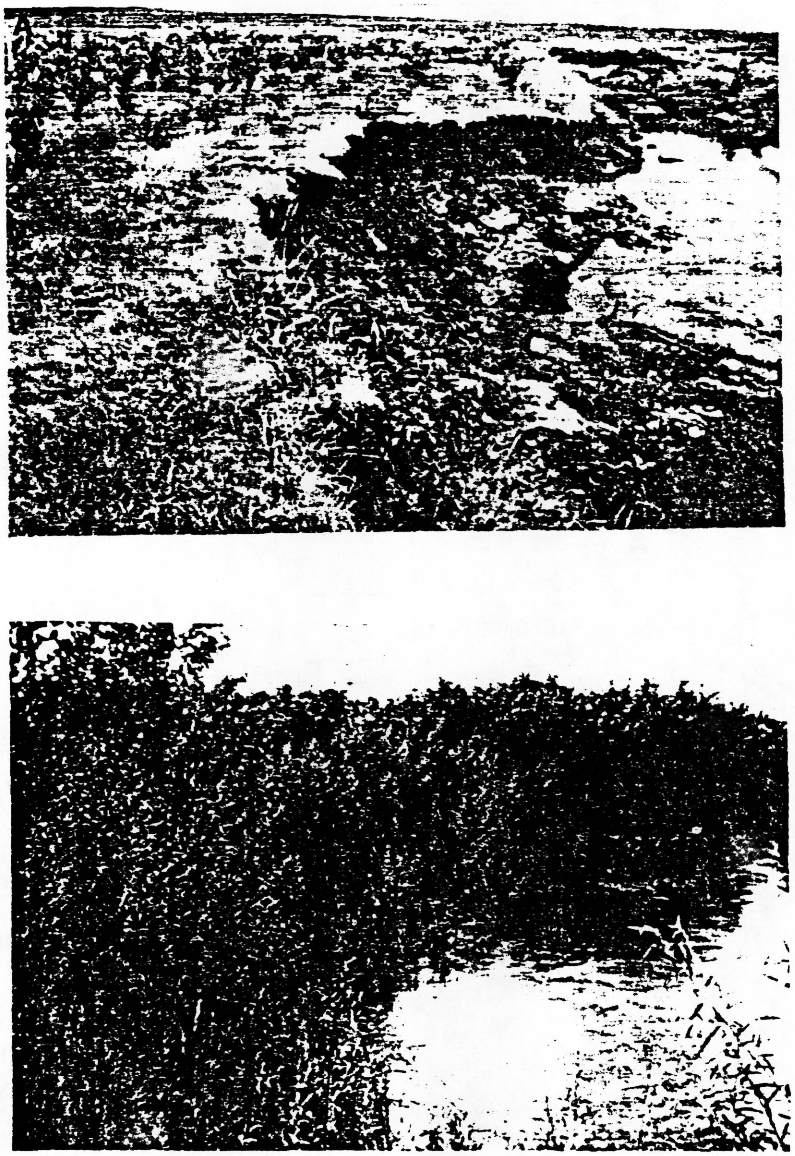

Fig. 6. Looking downstream toward the northwest along plot 2 (silver maple) (A) before soil bioengineering live stakes were installed, September, 1991; (B) June, 1994.

matically. At the end of the 1993 season the silver maple in the background averaged 3 m in height.

The impact of the developing MSRBS on water quality demonstrates its effectiveness at reducing NPS pollutants. Results for nitrate nitrogen (NO_3-N) and atrazine are shown in Figs 7 and 8. As can be seen the NO_3-N

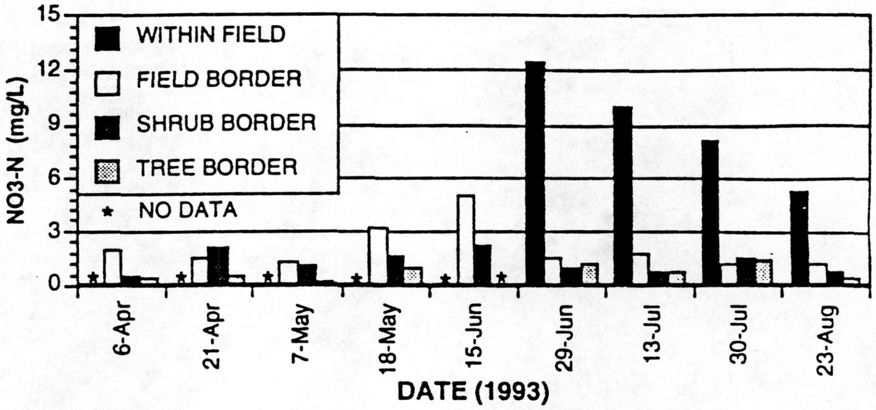

Fig. 7. Mean 1993 nitrate-nitrogen concentrations in the field and at the field-switchgrass, switchgrass-shrub, and tree-streambank borders in plots 1 and 3 of the MSRBS.

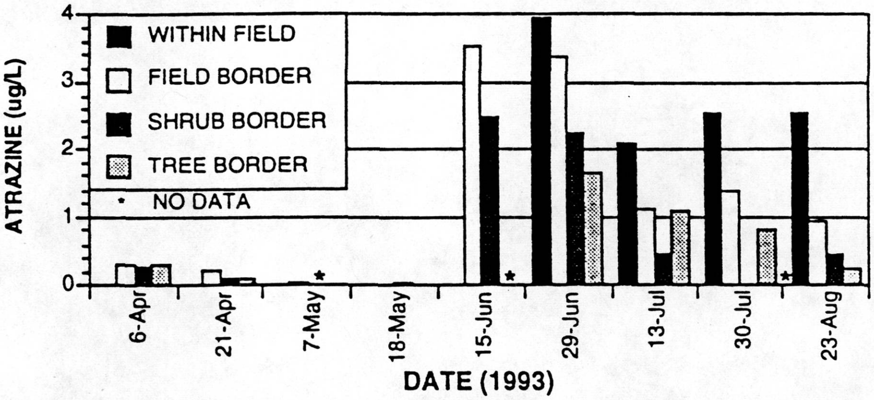

Fig. 8. Mean 1993 atrazine concentrations in the field and at the field-switchgrass, switchgrass-shrub, and tree-steambank borders in plots 1 and 3 of the MSRBS.

concentrations in the MSRBS never exceed 2 mg l^{-1} even though levels of NO_3-N exceed 12 mg l^{-1} in the field. The field measurements are not collected until the end of June almost two months after the fertilizer and herbicide are applied because lysimeters are not installed until after the last cultivation. Atrazine concentrations were high during the rainy months of June through August and exceeded the EPA Maximum Contaminant Level (3 mg l^{-1}) in the field and at the field border with the MSRBS after application in the beginning of May. In each of the measurement periods, atrazine concentrations decreased in the field and across the buffer strip. These data suggest that the buffer strip is effective in reducing NPS pollutants in the vadose zone. Similar data from minipiezometers located at 3 m below the MSRBS in each of the instrument nests confirms that these chemicals also are not moving below the buffer strip.

Preliminary data from the first 4 months of operation of the field drainage tile wetland demonstrate that the microbial degradation of NO_3-N is taking place. Measurements of > 15 mg l^{-1} are measured at the inflow while measurement at the outflow are less than 3 mg l^{-1}. Under stormflow conditions when residence times are reduced NO_3-N levels are not as effectively reduced. We expect the treatment capability of the wetland to increase in the coming years as organic matter accumulation of bottom sediments continues.

Riparian zone management is a very important topic at the present time. To manage the landscape for sustainable agriculture means that NPS pollution must be controlled and that water quality is maintained at a high level. Sustainable agriculture also means diversifying the opportunities for the farmer as well as diversifying the landscape. Riparian zone buffer strips provide an opportunity to accomplish these objectives. To date most riparian zone research has been conducted either in existing naturally vegetated riparian zones or using cool-season grass buffer strips. It would seem that a MSRBS offers numerous additional advantages over the traditional cool season grass buffer strips and could be designed to be more efficient at trapping sediment and reducing chemicals than some existing natural systems.

The USDA National Resource Conservation Service (NRCS) has recently published its new riparian forest buffer guidelines (SCS September, 1993) for the control of NPS pollutants from agricultural lands; the MSRBS fits the guidelines very well. The guidelines that the NRCS developed resulted from work that the USDA Forest Service [Welsch, 1991] conducted along forested riparian zones in the Eastern US. The Forest Service and NRCS riparian forest buffer models consist of three zones of management. Zone 1 is the tree (and/or shrub) strip immediately adjacent to the stream edge that is not managed except for the occasional removal of valuable tree species. Its minimal width is ~4.6 m. Zone 2 is a managed strip of trees or shrubs extending another 18.3 m (minimum width) upland, beyond zone 1. This zone is managed for nutrient removal to stimulate efficacy of nutrient uptake. Finally, Zone 3 is a managed strip of grasses and/or forbs with a minimum width of 6.1 m selected to slow surface runoff and convert it to sheet flow. This zone may be grazed or harvested to maintain its functional value. Both the NRCS and Forest Service models address the role, functioning, and design of existing streamside forests or planted forests to protect rivers, streams, and water bodies from NPS pollutants and to enhance the socio-economic and environmental benefits from these resources.

The MSRBS is designed to diversify the non-forested agricultural landscape of much of the Midwest and eastern Great Plains regions of the US. No zone 1 is described in this model because many of the streams along which it would be used were native prairie streams that did not have forested riparian zones. In addition, most farmers in this region are very concerned about course woody debris which might slow stream flow thus slowing drainage of their fields. The MSRBS could easily be modified to include a zone 1 along stream reaches where such a zone would be appropriate. The MSRBS and NRCS and Forest Service models are similar in that they depend on management of most of the trees and the grass strip to maximize nutrient uptake and sequestering.

There are still many unanswered questions about the functions of MSRBS or any buffer strip. Among the most important are quantification of changes in soil quality and nutrient and pesticide reduction over time. Changes in soil quality resulting from the presence of the permanent MSRBS buffer strip system will increase infiltration and lengthen residence time of water moving through the vadose zone. The fluxes and fates of nitrogen and other chemicals must be described if models for buffer strip widths are to be developed. Quantification of wildlife habitat values of this or other buffer strips also are needed. And, the socio-economic and environmental benefits and costs of these systems must be determined.

Acknowledgments

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References

Armour CL, Duff DA and Elmore W (1991) AFS position statement on the effects of livestock grazing on riparian and stream ecosystems. Fisheries 16: 7–11

Bishop RA and van der Valk AG (1982) Wetlands. In: Cooper TC (ed) Iowa's Natural Heritage, Iowa Acad Sci and Iowa Nat Heritage Foundation, Des Moines, IA

Brinson MM, Swift BL, Plantico RC and Barclay JS (1981) Riparian ecosystems; their ecosystems and status. FWS/OBS-81-17, Eastern Energy and Land Use Team, US Fish and Wildlife Service, Kearneyville, WV, 155 pp

Colletti JP, Schultz RC, Mize CW, Hall RB and Twarok CJ (1991) An Iowa demonstration of agroforestry: short-rotation woody crops. For Chron 67: 258–262

Cooper JR and Gilliam JW (1987) Phosphorus redistribution from cultivated fields into riparian areas. Soil Sci Soc Am J 51: 1600–1604

Cooper JR, Gilliam JW, Daniels RB and Robarge WP (1987) Riparian areas as filters for agricultural sediment. Soil Sci Soc Am J 51: 416–420

DeWitt TA (1984) Soil Survey of Story County, Iowa. USDA Soil Cons Serv, Washington, DC

Foster GR and Meyer LD (1977) Soil erosion and sedimentation by water – an overview. Proc National Symposium on Soil Erosion and Sedimentation by Water, Chicago, Il, Dec 12–13, 1977

Hayes JC, Barfield BJ and Barnhisel RI (1984) Performance of grass filters under laboratory and field conditions. Am Soc Agri Engin 79: 2530

Heede BH (1990) Vegetation strips control erosion in watersheds. USDA Forest Service Research Note RM-499, 5 pp

Hehnke M and Stone CP (1978) Value of riparian vegetation to avian populations along the Sacramento River system. In: Johnson RR and McCormick JF (eds) Strategies for Protection and Management or Floodplain Wetlands and other Riparian Ecosystems, pp 228–235. General Technical Report WO-12, US For Ser, Washington, DC

Hubert C (1992) Huge new system to clean nitrates from DM water. The Des Moines Register, Jan 26

Jacobs TC and Gilliam JW (1985) Riparian losses of nitrate from agricultural drainage waters. J Environ Qual 14: 472–478

Karr JR and Schlosser IJ (1978) Water resources and the land-water interface. Science 201: 229–234

Kelley RD (1990) Iowa's surface water quality. Iowa Groundwater Association Newsletter No 10, pp 9–10

Kemmis TJ, Hallberg GR and Lutenegger AJ (1981) Depositional Environments of the Des Moines Lobe, Iowa. Iowa Geological Survey Guidebook Series No 6, 132 pp

Kovacic DA, Osborne LL and Dickson BC (1991) Buffer strips and nonpoint pollution. Illinois Natural History Survey Reports, Feb 1991, No 304

Lowrance RR (1992) Groundwater nitrate and denitrification in a coastal plain riparian forest. J Environ Qual 21: 401–405

Lowrance R, Leonard R and Sheridan J (1985) Managing riparian ecosystems to control nonpoint pollution. J Soil Water Conserv 40: 87–91

Lowrance RR, Todd R, Fail Jr J., Hendrickson Jr O, Leonard R and Asmussen (1984a) Riparian forests as nutrient filters in agricultural watersheds. BioSci 34: 374–377

Lowrance RR, Todd RL and Asmussen LE (1984b) Nutrient cycling in an agricultural watershed: I. Phreatic movement. J Environ Qual 13: 22–27

Lowrance RR, Todd RL and Asmussen LE (1984c) Nutrient cycling in an agricultural watershed: II. Streamflow and artificial drainage. J Environ Qual 13: 27–32

Magette WL, Brinsfield RB, Palmer RE and Wood JD (1989) Nutrient and sediment removal by vegetated filter strips. Trans of ASAE 32: 663–667

Mahoney DL and Erman DC (1984) The role of streamside bufferstrips in the ecology of aquatic biota. In: Warner RE and Hendrix KM (eds) California Riparian Systems, pp 168–176. Univ of California Press, Berkeley

McColl RHS (1978) Chemical runoff from pasture: the influence of fertilizer and riparian zones. NZ J Marine and Freshwater Res 12: 371–380

Morgan RPC and Morgan DDV (1982) Predicting hillslope runoff and erosion in the United Kingdom: Preliminary trials with the CREAMS model. In: Sveltosanov V and Knisel WG (eds) European and United States Case Studies in Application of the CREAMS Model. International Institute for Applied Systems Analysis, Laxenburg, Austria

Osborne LL and Kovacic DA (1993) Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology 29: 243–258

Peterjohn WT and Correll DL (1984) Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65: 1466–1475

Phillips JD (1989) Nonpoint source pollution control effectiveness of riparian forests along a coastal plain river. J Hydrol 110: 221–237

Pionke HB and Chesters G (1973) Pesticides-sediment-water interactions. J Environ Qual 2: 29–45

Schlesinger RB (1979) Natural removal mechanisms for chemical pollutants in the environment. Bioscience 29: 95–101

Schlosser IJ and Karr JR (1981a) Water quality in agricultural watersheds: impact of riparian vegetation during base flow. Water Resources Bul 17: 233–240

Schlosser IJ and Karr JR (1981b) Riparian vegetation and channel morphology impact on spatial patterns of water quality in agricultural watersheds. Envir Mang 5: 233–243

Soil Conservation Service, September 1993. Riparian forest buffer: definition and technical note

Thompson ML and Scharf RL (1994) An improved zero-tension lysimeter to monitor colloid transport in soils. J Environ Qual 23: 378–383

Thompson GW and Hertel HG (1981) The forest resources of Iowa in 1980. Proc Iowa Acad Sci 88: 2–6

Waldron LJ and Dakessian S (1982) Effect of grass, legume, and tree roots on soil shearing resistance. Soil Sci Soc Am J 46: 894–899

Waldron LJ, Dakessian S and Nemson JA (1983) Shear resistance enhancement of 1.22 meter diameter soil cross sections by pine and alfalfa roots. Soil Sci Soc Am J 47: 9–14

Welsch J (1991) Riparian Forest Buffers: Function and Design for Protection and Enhancement of Water Resources, NA-PR-07-91. USDA Forest Service, Radnor, Pennsylvania