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Incorporating forage grasses in riparian buffers for bioremediation of atrazine, isoxaflutole and nitrate in Missouri

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Abstract

Multi-species tree-shrub-grass riparian buffer systems have been recognized as one of the most cost-effective bioremediation approaches to alleviate nonpoint source agricultural pollution in heavily fertilized systems. However, highly concentrated herbicides in surface and subsurface water and shade cast by trees along the stream bank usually compromise the effectiveness of these systems. Greenhouse trials and field lysimeter studies were conducted to evaluate the tolerance of orchard grass (*Dactylis glomerata*), smooth bromegrass (*Bromus inermis*), tall fescue (*Festuca arundinacea*), timothy (*Phleum pratense*), and switchgrass (*Panicum virgatum*) ground covers to atrazine and Balance™ (isoxaflutole) plus their capacity to sequester and degrade these herbicides and their metabolites. Their ability to remove soil nitrate was also quantified. Concentrations of atrazine, Balance™ and their metabolites in the leachate, soil and plant samples were determined by solid phase extraction followed by high performance liquid or gas chromatographic analyses. Distribution of the herbicides and metabolites in the system was calculated using a mass balance approach. Herbicide bioremediation capacity of each lysimeter treatment was determined by the ratio of metabolites to parent herbicide plus metabolites. Bioremediation of nitrate was quantified by comparing nitrate reduction rates in grass treatments to the bare ground control. Based on this herbicide tolerance, bioremediation data and shade tolerance determined in a previous study, it was established that switch grass, tall fescue and smooth bromegrass are good candidates for incorporation into tree-shrub-grass riparian buffer systems designed for the bioremediation of atrazine, Balance™ and nitrate.

Introduction

Herbicides and nutrients derived from agricultural operations are the two most common classes of nonpoint source pollutants in the Midwestern region of the U.S. More than 60% of the nitrogen fertilizer and herbicides used in the U.S. are applied in the Midwest for corn and soybean production (U.S. Department of Agriculture, 2001).

Atrazine is the leading pre-emergence herbicide for broad-leaf weed control. About 24.6 million kg of atrazine are applied to the soil annually, more than any other herbicide (U.S. Department of Agriculture, 2001). In 2000, it was applied on more than 68% of all corn acreage (3.2×10^7 hectacres). Not surprisingly, atrazine and its metabolites were found in 24% of 579 wells monitored throughout the Midwest in 1993 (U.S. Department of Agriculture, 1994). The same report noted that atrazine in surface runoff ranged from 80 to 300 μg/L and could be detected during the 45 to 60 day period following field application. In 1995, atrazine concentrations from 250 to1000 μg/L were found in early season runoff and in topsoil along tested waterways (U.S. Department of

Agriculture, 1995). Atrazine concentrations as low as 0.1 μg/L in surface water have been linked to amphibian deformities (e.g., malformation, hermaphroditism) due to its endocrine disruption effect (Hayes et al. 2002). This low atrazine exposure concentration is far below the EPA Maximum Contaminant Level of 3 μg/L for drinking water.

Balance™ or isoxaflutole (IXF) is a herbicide manufactured by Bayer CropScience (Kansas City, Missouri) and was commercially introduced for the 1999 growing season in 16 key corn-producing states. It belongs to a new family of herbicides called isoxazoles. These herbicides inhibit 4-hydroxyphenylpyruvate dioxygenase (HPPD) in a wide range of C3 and C4 plants, thereby, blocking carotenoid biosynthesis (Pallett et al. 1998). This impairs chloroplast development. In field trials, Balance™ has proven effective against a wide spectrum of problem weeds in corn production (Lazo et al. 1997). It appears to perform well at relatively low dosages (about 11 to 64 g/ha of active ingredient) and offers season-long pre-emergence weed control (Lazo et al. 1997). The IXF has a very short soil half-life, and was rapidly transformed into biologically active diketonitrile (DKN) under field conditions (Lin 2002; Lin et al. 2003). Diketonitrile is much more polar and stable than the parent in the soil environment. Degradation of DKN produces a nonbiologically active benzoic acid derivative (BA) that is a highly stable and water-soluble metabolite (personal communication Rhône-Poulenc Agro.). Thus, DKN and BA are expected to appear as a nonpoint source pollutant in the near future.

Among several management practices, a tree-shrub-grass riparian buffer strip is recognized as one of the most cost-effective approaches to alleviate nonpoint sources of agricultural pollutants transported from adjacent crop lands (Schultz et al. 1995). In a watershed study conducted in central Texas, Hoffman et al. (1995) observed a 44-50% reduction in atrazine levels when a 9 m filter strip was used. Pinay et al. (1993) reported that a 30 m riparian buffer strip was sufficient to remove all the nitrates originating in ground water.

There are several physical, chemical, and biological mechanisms involved in the process of bioremediation within the riparian buffer zone. Pesticides and nutrients can be intercepted by the roots and residue of the vegetation via physical adsorption and filtration (Pestemer et al. 1984). Bacteria growing in the root zone may have the capacity to metabolize herbicides and nutrients through various biochemical mechanisms including enzymatic detoxification, nitrification and denitrification (Mandelbaum et al. 1993). Direct plant uptake may also help to eliminate the herbicides and nutrients from the subsurface flow (Burken and Schnoor 1997). Furthermore, the improvement of soil characteristics by vegetation (e.g., increases in organic matter content, improved porosity) may enhance the rhizosphere's capacity for adsorption and chemical hydrolysis of pollutants (Mandelbaum et al. 1993; Martin-Neto et al. 1994).

In order to establish a successful tree based vegetative buffer zone for bioremediation, several criteria must be met in terms of species selection. The selected ground cover must be tolerant to herbicides present in the surface run-off and subsurface water. They must also be able to grow satisfactorily in the shade cast by the trees along the stream bank. In addition, the ground cover must possess the desired bioremediation capacity to adsorb and hold or further degrade the agricultural chemicals. Information derived from a shade screening trial has helped to identify ground cover components for riparian buffer systems (Lin et al. 1998). However, the herbicide tolerance and bioremediation capacity of the shade-tolerant species is not known. Both greenhouse trials and field lysimeter studies were conducted to evaluate the tolerance of selected ground covers to atrazine and Balance™. Additionally, their capacity to sequester and degrade these herbicides and their metabolites and to remove soil nitrate was quantified. Incorporation of specific ground covers in tree-shrub-grass riparian buffers designed for the bioremediation of atrazine, Balance™ and nitrate is described.

Material and methods

Evaluation of herbicide tolerance

Four cool season C3 grasses observed to have shade-tolerance in previous screening trials and one warm-season C4 grass were selected for this study. They are 'Benchmark' orchardgrass (*Dactylis glomerata*), smooth bromegrass (*Bromus inermis*), 'KY31' tall fescue (*Festuca arundinacea*), timothy (*Phleum pratense*), and switchgrass (*Panicum virgatum*). Ten seedlings of each species were grown in 15 cm pots in a greenhouse located on the University of Missouri campus. Herbicide treatments consisted of atrazine or Balance™ containing three concentration levels: 0,

500, and 1000 μg/L for atrazine and 0, 100, and 250 μg/L for Balance™. The applied herbicide concentrations are representative of those expected in surface runoff from cornfields in northern Missouri (U.S. Department of Agriculture, 1995). Atrazine treatments began three months after seedling establishment. Herbicide solutions were applied in 200 mL volumes every other day until levels reached 0, 500, and 1000 μg/kg dry soil. Balance™ treatments began six months after seedling establishment. The application procedure was the same as for atrazine. Final soil concentrations were 0, 100, and 250 μg/kg. The treatments were arranged as a complete randomized design with six replications. Grasses were harvested about eight weeks after herbicide application. This was approximately four weeks after the first symptoms of herbicide damage were observed. Damage from atrazine exposure appeared as necrotic areas on leaf tips. Injury from Balance™ application appeared as a bleaching of the entire leaf blade. Following harvesting, total above ground dry weight was determined by placing tissues in an oven at 70ºC until the dry weight reached a constant value.

Evaluation of bioremediation capacity

Thirty-six 1 m wide and 0.5 m deep lysimeters with six different ground covers (bare ground, orchardgrass, smooth bromegrass, tall fescue, timothy, and switchgrass) were established in 1998 at the University of Missouri Horticulture and Agroforestry Research Center, New Franklin, Missouri (longitude 92° 46' W; latitude 39º 1' N). These lysimeters were arranged as a complete randomized design with three replications of each ground cover. Each lysimeter was filled with a sandy loam soil with an average pH of 7.0, organic matter content of 0.72%, and cation exchange capacity of 3.0 meq/100 g. The interior surfaces of the lysimeters are fluorinated and a 5 cm PVC drain line is connected from each to a central collection facility. At the collection facility, leachate was collected into a 13 L high-density polypropylene tank. Lysimeters were seeded by hand in August 1997 and re-seeded in February 1998 in order to achieve uniform vegetation coverage. In September 1998, herbicides were applied by irrigating each lysimeter with 3 L solutions containing atrazine (500 μg/L) or Balance™ (80 μg/L) along with nitrate (50 mg/L). These concentrations are representative of those expected in the surface runoff under corn production conditions in northern Missouri (USDA 1995). The leachate from each lysimeter was collected after every major rainfall event for 25 days following herbicide and nitrate application. Soil and plant samples were collected at the end of the 25-day period.

Chemical analysis of atrazine and its dealkylated metabolites (deethylatrazine and deisopropylatrazine) and hydroxylated metabolites (hydroxyatrazine, deethylhydroxyatrazine, and deisopropylhydroxyatrazine) in the leachate and soil was accomplished using solid phase extraction (SPE) followed by high performance liquid chromatography (HPLC). The HPLC instruments used for the analyses were coupled with UV or tandem mass spectrometry (HPLC-MS/MS) detectors as described by Lerch et al. (Lerch et al. 1995; Lerch et al. 1999). Isolation of atrazine and its dealkylated metabolites from plant tissues involved methanol extraction, partitioning between water and chloroform phases, and SPE cleanup procedures (Lin et al. 2000a). Procedures for the extraction of hydroxylated atrazine from plant material were based upon modifications of the soil extraction method. The analyses of atrazine and its metabolites in plant extracts were performed by both HPLC and gas chromatography – tandem mass spectrometry as described by Lin et al. (Lin et al. 2000a). The extraction and analyses of Balance™ (isoxaflutole) and its degradation products (DKN and BA) in leachate, plant tissues and soil were performed by HPLC-MS/MS (Lin et al. 2000b). Nitrate in the soil extract was analyzed with a Lachat QuikChem automated flow-injection ion analyzer by cadmium reduction (Lachat QuikChem Method 12-107-04-1-B). Soil microbial biomass carbon was determined by a modified chloroform fumigation and direct extraction method (Jordan and Beare 1991). The distribution of the herbicides and metabolites in the system was calculated using a mass balance approach. Herbicide bioremediation capacity of each lysimeter treatment was determined by the ratio of metabolites to total herbicide, i.e., parent herbicide plus metabolites. Bioremediation of nitrate was quantified by comparing nitrate reduction in grass treatments to the bare ground controls.

Results and discussion

Tolerance to shade and herbicides

Evaluation of the results from a previous shade screen study (Lin et al. 1998) suggested that the C3 species

Table 1. Effects of shade and herbicide stress on the above ground dry weight (DW) of ground cover forages (Missouri, USA).

	Effects of Shade on DW (g)[1]			Effects of Atrazine on DW(g)			Effects of Balance™ on DW(%)		
Species	Full Sun	50% Shade	80% Shade	0 μg/L	500 μg/L	1000 μg/L	0 μg/L	100 μg/L	250 μg/L
Orchardgrass (C3)	13.8a[2]	11.7a	6.4b	16.0a	13.9a	11.5b	58.4a	51.0a	61.5a
Tall fescue (C3)	13.3a	16.2a	8.0b	16.8a	15.1a	13.5a	82.0a	75.0a	68.4a
Timothy (C3)	10.2a	9.0a	5.5b	–[3]	–	–	–	–	–
Smooth bromegrass (C3)	9.6b	12.0a	9.5b	15.7a	15.4a	11.1b	40.9a	30.5b	23.2b
Switchgrass (C4)	79.5a	57.6b	26.4c	7.5a	7.2a	6.7a	27.1a	34.8a	18.3b

[1]Information derived from a shade screening trial (Lin et al., 1998); [2]Means followed by the same letter within the same row do not differ significantly from each other at 5% level of probability using the LSD test; [3]No data because of adverse response to high temperature in the greenhouse.

used here are more tolerant to shade than C4 switchgrass (Table 1). Under 50% shade, the C3 cool season grasses preformed equal to or better than under full sun. However, smooth bromegrass is the only species that exhibited tolerance to heavy shade (80% shade). The results of herbicide tolerance work here showed that the C3 grasses are more sensitive to atrazine than C4 switchgrass (Table 1). In contrast, switchgrass is more sensitive to Balance™ than orchardgrass and tall fescue at a 250 μg/L application level. In a separate greenhouse study using the same species, the inhibitory effects of these two herbicides were significantly enhanced by shade (Lin 2002).

Evaluation of atrazine bioremediation capacity

Interpretation of the mass balance calculations indicated that most applied herbicide (atrazine or Balance™) was retained by the soil column. In all cases, less than 3% was found in the above ground grass tissue and less than 15% was lost in the leachate 25 days after application.

Hydroxylated atrazine degradation products are the major degradation products detected in the soil. Total hydroxylated atrazine products account for 34.0 to 47.4% of atrazine measured in the soil (Figure 1). Dealkylated atrazine products account for 21.6 to 33.3% of atrazine in the soil. Among the lysimeter treatments, higher levels of atrazine degradation products were detected in the grass treatments than in the bare-ground controls (Figure 1). Atrazine degradation was significantly enhanced by 20 to 45% by the presence of the forages. Lysimeters with switchgrass exhibited the best capacity to degrade atrazine in the soil. Approximately 80.7% of atrazine was degraded into less toxic forms. Smooth bromegrass, timothy, orchardgrass and tall fescue also showed promising atrazine degradation capacity (66.5 to 74.7%) as compared to the control (55.5%). All grass-treated lysimeters have a significantly greater capacity to dealkylate atrazine (31.4-34.0%) when compared to bare ground controls (21.6%). However, atrazine dealkylation capacity was similar among the different C3 grass species. The highest capacity for atrazine hydroxylation was found in the C4 switchgrass lysimeters, 47.4% of total soil herbicide. This is about 40% greater than the hydrolysis capacity of the control lysimeters.

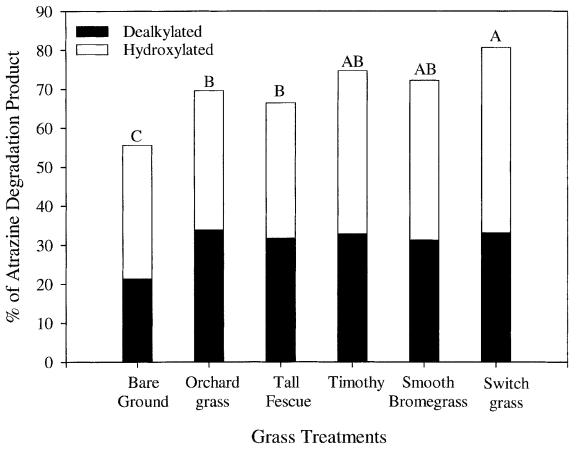

Figure 1. Percentage of atrazine degradation products in lysimeter soils (Missouri, USA). Means followed by the same letter do not differ significantly from each other at 10% level of probability using the LSD test.

Enhanced atrazine degradation by forage plants is strongly correlated with the increasing microbial population in the rhizosphere (Figure 2). As expected, increased microbial population was correlated with the presence of forages (data not shown). This correlation is associated with the added organic matter released from the plants or their residues (Reddy et al. 1980). In addition, oxidative and hydrolytic compounds in root exudates could directly hydrolyze

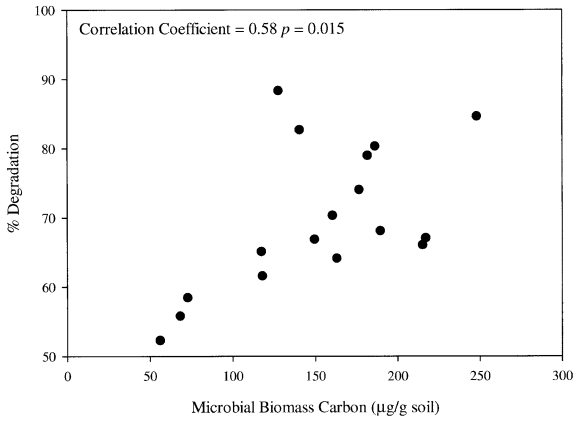

Figure 2. Correlation between degradation of atrazine (%) and microbial biomass carbon (µg/g soil) in lysimeter soils (Missouri, USA).

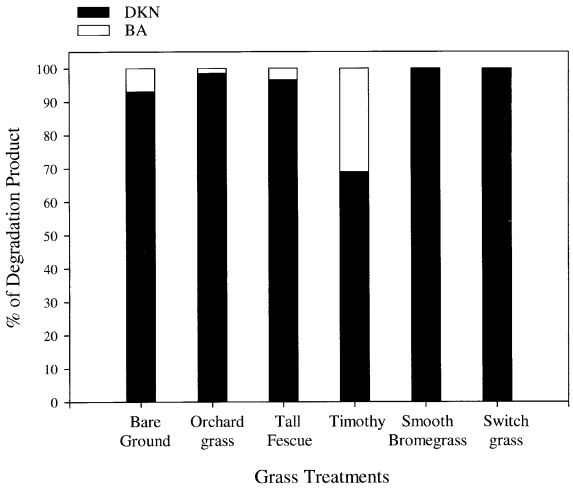

Figure 3. Percentage of Balance™ degradation products in lysimeter soils (Missouri, USA).

atrazine or stimulate the activity of a microbial degrader (Burken and Schnoor 1996). For instance, benzoxazinone, is a biologically derived hydrolytic catalyst reported to be abundant in the roots of many C4 species (Gronwald 1994). Biochemical agents such as this could facilitate the hydroxylation of atrazine and its metabolites and may account for the high levels of hydroxylation measured in the switchgrass treatment.

Several advantages result from the hydroxylation of atrazine and its metabolites in the soil. All hydroxylated degradation products have less toxicity than the parent atrazine and its dealkylated atrazine metabolites (Jones and Winchell 1984). Moreover, due to strong soil adsorption of the hydroxylated metabolites under natural conditions (Moreau-Kervevan and Mouvet 1998), the use of switchgrass in riparian buffer systems could promote the immobilization of atrazine.

Evaluation of Balance™ bioremediation capacity

As noted above, most of the applied Balance™ was retained by the soil. Diketonitrile was the major form of the herbicide remaining after 25 days with a small percentage of BA also present (Figure 3). No parent IXF was detected in any treatment. Isoxaflutole in aqueous solution is very sensitive to photolysis and/or hydrolysis, especially under conditions of high pH, high solar radiation and high temperature (Beltran et al. 2000; Lin 2002). Hydrolysis of IXF is accelerated in the presence of soil minerals (Taylor-Lovell et al. 2000). The half-life of IXF in the lysimeters was estimated to be from 9 to 14 hours. Soil water was near saturation and soil pH was 7.2. Additionally, during the 25-day period of the study daily high temperatures were often near 30 ºC. Lysimeter soil conditions were, therefore, likely favorable for hydrolysis of IXF.

Other than timothy, grass treatments did not significantly promote the degradation of the biologically active metabolite DKN to the nonbiologically active metabolite BA ($p > 0.1$) (Figure 3). The higher BA concentrations in the timothy treatments could be accounted for by the lower plant uptake rates or higher soil moistures than in the other forage treatments. The poor growth of the timothy in Missouri, due to the heat stress during the summer, results in less BA taken up by plants. In addition, lower evapotranspiration rates resulting from the poor growth provided higher soil moisture to favor the hydrolysis of DKN (Beltran et al. 2000). The higher soil moisture due to lower evapotranspiration might also account for the relatively high BA accumulation in the bare ground treatment.

The poor correlation between microbial population and DKN degradation (Figure 4) suggests that DKN hydrolysis is an abiotic reaction in this work. In contrast, Mougin et al. (2000) found that two extracellular fungal oxidases (lignin peroxidase and manganese-dependent peroxidase) could cleave DKN and produce BA. They demonstrated that *in vivo* degradation of DKN to BA by strains of two fungi, *Phanerochaete chrysosporium* and *Trametes versicolor*, growing in liquid culture was from 15.1 to 24.6% after 15

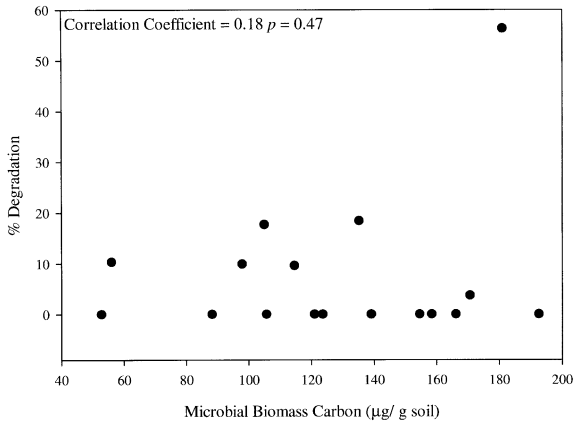

Figure 4. Correlation between degradation of diketonitrile to benzoic acid and microbial biomass carbon in lysimeter soils (Missouri, USA).

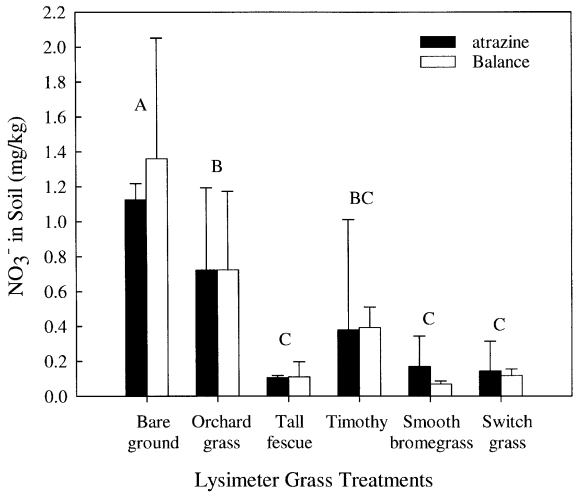

Figure 5. Nitrate concentration in lysimeter soils (Missouri, USA). Means followed by the same letter do not differ significantly from each other at 10% level of probability using the LSD test. The interaction between forage species and herbicide treatments on nitrate levels was not significant ($p = 0.93$). The soil nitrate levels between atrazine and Balance™ treatments were not significantly different ($p = 0.769$).

days. It is unknown whether suitable microorganisms were present in the lysimeters; however, if they were present, their impact was apparently small.

Evaluation of nitrate bioremediation capacity

No significant differences between herbicide treatments were observed in regard to nitrate removal from lysimeter soil (Figure 5). Relative to the nitrate level in the bare ground controls, tall fescue, switchgrass, smooth bromegrass, timothy and orchardgrass removed 90.5, 87.3, 84.9, 66.2, and 35.7% of soil nitrate in atrazine treated lysimeters, and 91.9, 91.4, 94.9, 71.1, and 46.8% in Balance™ treated lysimeters, respectively. The reduction of total nitrate in the soil by forages can be attributed to enhanced microbial denitrification or plant uptake (Reddy et al. 1980). In a separate analysis (Lin, 2002), the denitrification capacity was found to be greatest in soil collected from switchgrass, tall fescue and smooth bromegrass lysimeters. In addition, grass dry matter yield and microbial population were significantly correlated with the nitrate reduction rates.

Incorporating ground covers in a riparian buffer

Based upon the herbicide tolerance and bioremediation capacity of the forage grasses described above as well as the shade tolerance of these grasses (Lin et al. 1998), it is possible to begin the construction of a specific tree-shrub-grass riparian buffer model. This model will provide a robust and self-sustaining system for the natural bioremediation of agronomically derived pesticides and nutrients. Such a model would incorporate the basic features of riparian forest buffer systems (Schultz et al. 1995) and provide useful information regarding the selection of appropriate ground covers.

Identification of biotic and abiotic stresses in the microenvironment of plants is crucial to the selection of species to be used in a bioremediation system. This includes knowledge of temporal and spatial characteristics of each stress as well as mechanisms by which a stress may be reduced. In regard to bioremediation by tree-shrub-grass riparian systems, an understanding of the removal mechanism of specific herbicides and nutrients coupled with a measure of the herbicide and shade tolerance of plants used in the system is critical for success. Additionally, the flow of water through the system will determine where the highest herbicide stress is concentrated. For example, in a riparian buffer zone below the edge of a cornfield, herbicide levels will be greatest at the interface between the field and the buffer zone (U.S. Department of Agriculture, 1994). Ground covers may be eliminated by accumulated herbicides near this interface and the potential for channelization from surface flows will increase. Channelized flow accelerates gully erosion and alters biological and physical remediation mechanisms. Closer to the stream bank, herbicide stress is expected to be reduced with shade

stress becoming a major factor in limiting the establishment of ground covers.

Evaluation of the bioremediation data measured for switchgrass, orchard grass, tall fescue, timothy and smooth bromegrass suggests that the removal of Balance™ relies mainly on physical trapping by the buffer (Lin et al. 2003). In contrast, biological degradation plays an import role in the removal of atrazine. The following discussion describes how ground covers might be selected for a tree-shrub-grass riparian buffer in order to successfully reduce the levels of atrazine, Balance™ and nitrate in surface and/or subsurface runoff from agricultural fields.

In general, ground covers are included throughout the entire riparian buffer zone. As noted above, ground covers must be selected based upon an analysis of the micro-environment in which they will grow. Switchgrass provides an ideal first line defense along the cornfield where atrazine concentration is expected to be highest ($>$ 1000 μg/L). It will not only tolerate this level of atrazine, but its strong capacity to dealkylate and hydrolyze atrazine will lead to the rapid degradation and immobilization of the herbicide at the leading edge of the riparian buffer zone. Nitrate levels will also be significantly reduced by this forage grass. It has also been observed that the stiffness of stem tissues generates a more uniform sheet flow and, therefore, can help to prevent channelized flow (Lee et al. 1997). Trapping of sediments by stem tissues also reduces the transport of nitrate and phosphate (Lee et al. 1997). Well-established switchgrass plants can tolerate up to 100 μg/L of Balance™, but the inhibitory effect of Balance™ on resprouted seedlings is not known. In the Midwestern region of the U.S., switchgrass is not fully established until late May or early June. Highest atrazine and Balance™ concentrations in the surface and subsurface flow are expected to occur from late April to early May (U.S. Department of Agriculture, 1994). Thus, a secondary defense line is required to intercept, retain and/or degrade the herbicides before the switchgrass ground cover is fully established.

Tall fescue is suitable as a secondary ground cover. It is a cool season forage that is established very early in the growing season. Plants have excellent tolerance to Balance™ at 250 μg/L and may even tolerate levels as high as 2000 μg/L (Lin 2002). It is also expected to be tolerant of the diluted atrazine levels in its planted location below switchgrass. A high annual evapotranspiration rate of tall fescue plants relative to the other forages studied (data not shown) indicate that fescue canopies will rapidly remove soil moisture and facilitate the physical trapping of Balance™ in the soil. Tall fescue is also expected to be tolerant of the moderate shade projected by tree crowns closer to the stream bank (Lin et al. 1998). It also shows a strong capacity to remove nitrate and a moderate capacity to degrade atrazine.

Close to the stream bank, shade stress becomes more significant. In this area of the buffer zone, smooth bromegrass could be planted. It has been shown to perform well even under 80% shade (Lin et al. 1998). Despite the observation that smooth bromegrass is more sensitive to atrazine and Balance™ than the other C3 species, it is expected to survive atrazine and Balance™ concentrations below 500 and 100 μg/L, respectively. It also exhibits a high bioremediation capacity to remove nitrate and degrade atrazine in the soil.

A key element of tree-shrub-grass riparian buffer zones will be the herbicide tolerance of the woody plant species. Little information is available in regard to woody plant tolerance of either atrazine or Balance™. Fast growing hybrid poplar trees (*Populus deltoides x nigra* DN34) display some tolerance to atrazine and have the capacity to take up and significantly degrade the herbicide (Burken and Schnoor 1997). This species, therefore, may fit the requirements of the riparian buffer; however, more information is obviously required on the woody plant component before a complete model can be established.

Conclusion

The bioremediation capacities of switchgrass, tall fescue and smooth bromegrass make these forages ideal candidates for use in tree-shrub-grass riparian buffers where the bioremediation of atrazine, Balance™ and nitrate is desired. A scheme for their incorporation into a riparian buffer zone is proposed. However, further information is required to better understand the performance of these grasses in the field and to identify other suitable ground covers. For example, the availability of an early resprouting C4 grass with better Balance™ tolerance will allow for atrazine trapping and degradation during the early corn growing season. It will also be critical to know the bioremediation capacity during the resprouting phase as well as the inhibitory effects of herbicides, especially Balance™, on resprouted seedlings. Addi-

tionally, selection for morphological and physiological features such as stem stiffness and high transpiration rates is important. These traits facilitate the generation of a uniform sheet flow pattern and improved soil infiltration that result in a more effective removal of herbicides from the surface and subsurface flows. More data on the bioremediation capacity of the woody plant components of riparian buffer systems is also needed.

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