Selection of Plants for Optimization of Vegetative Filter Strips Treating Runoff from Turfgrass

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Runoff from turf environments, such as golf courses, is of increasing concern due to the associated chemical contamination of lakes, reservoirs, rivers, and ground water. Pesticide runoff due to fungicides, herbicides, and insecticides used to maintain golf courses in acceptable playing condition is a particular concern. One possible approach to mitigate such contamination is through the implementation of effective vegetative filter strips (VFS) on golf courses and other recreational turf environments. The objective of the current study was to screen ten aesthetically acceptable plant species for their ability to remove four commonly-used and degradable pesticides: chlorpyrifos (CP), chlorothalonil (CT), pendimethalin (PE), and propiconazole (PR) from soil in a greenhouse setting, thus providing invaluable information as to the species composition that would be most efficacious for use in VFS surrounding turf environments. Our results revealed that blue flag iris (*Iris versicolor*) (76% CP, 94% CT, 48% PE, and 33% PR were lost from soil after 3 mo of plant growth), eastern gama grass (*Tripsacum dactyloides*) (47% CP, 95% CT, 17% PE, and 22% PR were lost from soil after 3 mo of plant growth), and big blue stem (*Andropogon gerardii*) (52% CP, 91% CT, 19% PE, and 30% PR were lost from soil after 3 mo of plant growth) were excellent candidates for the optimization of VFS as buffer zones abutting turf environments. Blue flag iris was most effective at removing selected pesticides from soil and had the highest aesthetic value of the plants tested.

Urban and residential environments represent an increasing component of the United States landscape. Approximately 83% of an estimated 84 million households in the United States are "urban" and 79% of those households have private lawns (Whitmore et al., 1993). There are more than 16,000 golf courses in the U.S. and their numbers continue to grow (Clark and Kenna, 2000). Substantial turfgrass areas are also associated with parks, athletic fields, gardens, cemeteries, public institutions, commercial properties, roadways, and sod farms. It is estimated that at least 188,178 km^2 of maintained turfgrass exist in the United States, an area that exceeds the total planted area for cotton, sorghum, barley, and oats (Joyce, 1998).

There are numerous pests capable of damaging turf (diseases, insects, nematodes, weeds), and fungicide, insecticides, nematicides, and herbicides are applied to promote turf health (Clark and Kenna, 2000). Increased use of chemicals, particularly pesticides, to manage such environments has resulted in nonpoint source contaminant runoff into waterways, leading to increased public health and environmental concerns (Clark and Kenna, 2000). Studies from golf course greens have shown that 5 to 10% of the total pesticides applied are lost in runoff (Haith and Rossi, 2003).

Currently, runoff from most urban and residential lawns goes directly into surrounding streams, or is channeled into storm drains. Pesticides are commonly found contaminating our reservoirs (Thurman et al., 1996), lakes (Senseman et al., 1997; Thurman et al., 2000), and rivers (Thurman et al., 1996; Senseman et al., 1997; Clark and Goolsby, 2000). Because of the extent of surface water contamination by pesticides, the United States Department of Agriculture (USDA) and Natural Resources Conservation Service (NRCS) have recommended the use of vegetative filter strips (VFS) as a best management practice for treating nonpoint-source pollution (Krutz et al., 2005). Thus, the use of VFS to protect and sustain urban water supplies, while allowing turf environments to be maintained at the level necessary for society to benefit from their recreational and aesthetic qualities, appears credible.

Most studies on VFS have been conducted on agricultural plots and were designed to reduce nutrient and sediment loads (Patty et al., 1997; Abu-Zreigh et al., 2003), with few conducted to evaluate pesticide losses (Baird et al., 2000; Belden and Coats, 2004; Krutz et al., 2005).VFS are effective in reducing the loss of pesticides from

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agroecosystems by decreasing the runoff capacity (thus facilitating deposition of sediment), enhancing infiltration, sorbing dissolved phase pesticides to plant and soil surfaces, and acting as a pesticide sink where irreversible sorption, microbial degradation, and plant uptake are enhanced (Paterson and Schnoor, 1992; Benoit et al., 1999; Mersie et al., 1999; Seybold et al., 2001; Staddon et al., 2001; Rankins et al., 2002; Blanche et al., 2003; Krutz et al., 2003, 2004, 2005). The reduction of pesticide loss to the surrounding environment can occur through several mechanisms including photodegradation, hydrolysis, abiotic and biotic degradation, etc. The actual mechanism that causes this reduction will vary from pesticide to pesticide depending on their physical and chemical properties (Sigler et al., 2000).

The pesticides selected for use in the current study have a wide range of physical and chemical properties and have different mechanisms for retention and losses in the environment. Chloropyrifos has a half-life of 50 d at a pH of 8 and is generally degraded by photodegradation and hydrolysis. It is not directly degraded by microorganisms but they likely play a significant role in its mineralization as both the 3,5,6-trichloro-2-pyridinol and 3,5,6-trichloro-2-methoxypyridine metabolites are subject to microbial degradation. The dominant mechanism for the environmental loss of chlorothalonil loss is through photodegradation, hydrolysis reactions, and abiotic and biotic degradation, and its half-life is 30 to 90 d (Sigler et al., 2000). Pendimethalin absorbs strongly to organic matter and clay minerals, and is not mobile in soils. Its field half-life is 90 d (Wauchope et al., 1992) and is normally lost through photodegradation, volatilization, and biodegradation (WHO, 1993; Miller et al., 1996). Propiconazole has a half-life of 200 d at 10°C, and decreases with increasing temperatures and with drier soils (Bromilow et al., 1999). It interacts strongly with soil organic matter and is degraded biologically in the soil.

A number of studies reported higher dissipation rates of pesticides in VFS compared to unvegetated plots (Benoit et al., 1999; Mersie et al., 1999; Staddon et al., 2001; Shankle et al., 2001). VFS may need to be established for more than a single growing season, however, before reduced losses of pesticides from them become apparent (Mersie et al., 1999). Phytoremediation studies have indicated that plant species differ in their ability to enhance microbial populations in their rhizospheres and this aspect impacts the overall ability of the microbial populations to degrade pollutants. Thus, part of what makes an effective VFS involves phytoremediation processes and the screening of plant species for their ability to retain and/or degrade the pollutants of interest.

The objective of the current research is to screen ten aesthetically acceptable plant species for their ability to enhance the removal of four pesticides (chlorpyrifos, pendimethalin, chlorothalonil, and propiconazole) commonly used to maintain turfgrass from soil. The four pesticides are known to be degradable in plant/soil systems and are often detected in surface waters. The greenhouse studies we report here focused on identifying plants with the potential to enhance pesticide removal from soil for subsequent use in VFS in a field study. Although not part of this research, the field study will include observations on the mechanisms of pesticide removal. The novelty of this research is the concept of screening plant species for their abilities to remove specific pollutants from runoff water entering VFS. Preliminary screenings such as these should be conducted for all land uses and suites of contaminants that one may expect to enter VFS.

Materials and Methods

Pesticide Selection

Four pesticides were used to amend the experimental soil: Dursban Pro (chlorpyrifos, O,O-diethyl-O-(3,5,6-trichloro-2-pyridnyl phosphorothioate, a non-systemic insecticide); Bravo Ultrex (chlorothalonil, 2,4,5,6-tetrachloroisopthalonitrile, non-systemic fungicide); Prowl H20 (pendimethalin, *N*-(1-ethyl- propyl)-2,6-dinitro-3,4-xylidine, non-systemic herbicide); and Banner Maxx (propiconazole, 1-[[2-(2,4-dichlorphenyl)-4-Pr-1,3-dioxolan-2-yl] methyl]-1H-1,2,4-triazole, systemic fungicide). Pesticides were chosen because they: (i) are widely used and commonly detected in surface waters of the northeastern US; (ii) fall into three categories (insecticides, herbicides, and fungicides); and (iii) have a range of physical and chemical properties that will likely result in different mechanisms of bio- and phyto-remediation.

Experimental Design

A greenhouse study was initiated in February 2006 in the French Hall Greenhouses at the University of Massachusetts-Amherst. The soil used for the study was a silt loam collected from the University of Massachusetts Turfgrass Research Center (South Deerfield, MA). The soil was screened through a number 6 (3.35 mm) sieve and amended with the four pesticides at 5% of their respective application rates (Table 1), assuming that all of the pesticides in runoff would fall on the first foot of the VFS from a turfgrass area that is 6.1 m long and 0.9 m wide. While this overestimates the amount of pesticides likely being lost (most pesticide runoff lost is less than 5% of the application rate), it provided sufficient residues for screening plant species for their ability to remove pesticides from soil at amounts exceeding their detection limits. Pesticide formulations were mixed with acetone to obtain the desired solution concentration for each pesticide. The solution was then uniformly sprayed onto the soil to obtain the final soil pesticide concentration (Table 1).

Plant pots (19 L capacity) were lined with plastic garbage bags to prevent soil from escaping through the drainage holes at the bottom. The bags were punctured with pin-hole sized holes to allow adequate drainage and 2.28 kg of contaminated soil was added to each pot. After soils were amended with pesticides, zero (0)-time subsamples (n = 48) were collected from each pot for comparison against the pesticide concentrations in the soil after 3 and 7 mo of plant growth. Four random subsamples (20 g each) were taken with a hand spade (the soil was loose and dry) before placing the soil in the pot. Zero-time subsamples were stored at –20°C until analyzed. Following the sub sampling, plant treatments were introduced. The selected plant species were: Prairie Cord Grass (*Spartina pectinata*); Big Blue Stem (*Andropogon gerardii*); Woolgrass (*Scirpus cyperinus*); Eastern gama grass (*Tripsacum dactyloides*); Perennial Rye (*Lolium perenne*); Tall Fescue (*Festuca arundinacea*); Blue Flag Iris (*Iris versicolor*); Black Willow (*Salix nigra*); Tufted Sedge (*Carex

Table 1. Pesticides, application rates, and amounts used.

Pesticide class	Pesticide (trade name)	Type	Maximum application rate (MAR) (% a.i.)†	Active ingredient lost from 5.58 m^2 at 5% loss of MAR	Zero-time pesticide concentration in soil Average(± SD)
			kg ha^{-1}	g	mg kg^{-1}
Insecticide	Chlorpyrifos (Dursban Pro)	Non-systemic	1.12 (23.5%)	0.03	0.18 (± 0.02)
Herbicide	Pendimethalin (Prowl H2O)	Non-systemic	10.98 (37.4%)	0.11	1.07 (± 0.09)
Fungicides	Chlorothalonil (Bravo Ultrex)	Non-systemic	22.4 (82.5%)	0.52	2.77 (± 0.32)
	Propiconazole (Banner Maxx)	Systemic	12.32 (14.3%)	0.05	0.21 (± 0.02)

†% a.i. = percent active ingredient.

stricta); and Rice Cutgrass (*Leersia oryzoides*). All plant treatments were compared to unvegetated controls. Many of these plants have been shown to be effective in previous VFS studies discussed above or have some other qualities that make them good candidates (e.g., large root biomass, salt tolerance, stiff (non-pliable) stems, high transpiration rates, tolerance to drought, tolerance to flooding). Prairie Cord Grass, a salt-tolerant plant, was chosen because some pesticides cause salt toxicity in plants. Prairie Cord Grass and many other grass species also establish dense turf, a quality closely linked to VFS effectiveness (Abu-Zreigh et al., 2003). Another plant quality that increases the effectiveness of VFS is their ability to increase the soil infiltration of runoff water (Asmussen et al., 1977; Rhode et al., 1980; Hall et al., 1983; Kloppel et al., 1997; Patty et al., 1997; Tingle et al., 1998; Rankins et al., 2001; Seybold et al., 2001). Most of the plants evaluated in the current study have high transpiration rates and would deplete soil moisture, creating additional space for incoming water and increasing the soil infiltration rate of VFS. Finally, the overall aesthetics of the plants was an important consideration because the VFS will often be viewed by the public. It was for this reason that Blue Flag Iris was selected.

All plant treatments were replicated four times. Replicates were arranged in blocks in the greenhouse along the existing temperature gradient (one side of the greenhouse was consistently 1–2°C warmer than the other at any given time). Over the course of the experiment, the minimum temperature varied from 15 to 18°C and the maximum temperature varied from 32 to 37°C. Within a block, all treatments were randomized. The block was designed to overcome the variation in temperature across the greenhouse. Statistical analysis, however, revealed that the block design was not necessary in that the temperature variation across the greenhouse did not impact the results significantly. Once plants were established, they were allowed to grow for 10 mo. Soil samples were taken at 3 and 7 mo and stored at −20°C until analysis. Triplicate soil samples (20 g each) were taken using a soil probe at random locations and then composited to ensure samples were representative.

Root Biomass

Root biomass was determined at the end of the experiment (10 mo of plant growth) by first cutting the shoot biomass at the soil surface. The root biomass was separated from the soil by sieving and shaking away soil from the root mass. Root mass was washed with deionized water and dried in an oven at 105°C. Dry weights were recorded and used as the root biomass.

Pesticide Analysis

Soil samples were thawed, thoroughly mixed, and 25-g subsamples fortified with 1.0 mL of a 10 mg L^{-1} propachlor surrogate standard solution in acetone. Pesticide-free soil (25 g) was fortified with 1.0 mL of a spiking solution (10 mg L^{-1} of chlorpyrifos, chlorothalonil, pendimethalin, and propiconazole in acetone) and 1.0 mL of the propachlor surrogate standard solution to determine recovery.

Pesticides were extracted from soil by pressurized fluid extraction (PFE) using a Dionex ASE 300 Accelerated Solvent Extractor (Dionex Corp., Sunnyvale, CA) equipped with 33 mL stainless steel extraction cells and 60 mL collection vials. Soil samples were mixed with 30 g sand (Ottawa sand, 20–30 mesh, Fisher Scientific, Fair Lawn, NJ) and placed into extraction cells. Extraction conditions were as follows: hexane/acetone (60:40) solvent system; extraction temperature 100°C; pressure 1500 psi; 5 min pre-heating period; 10 min static extraction period; 1 cycle flush volume was 25%; 60 s purge time. The extract was transferred to a 100 mL graduated cylinder, the volume recorded, and a 15-mL aliquot transferred to a 50 mL centrifuge tube for liquid-liquid clean-up. Briefly, 15 mL of a 7.5% NaCl solution was added and the mixture vortexed for 1 min. The top layer (hexane) was transferred to a new 15 mL centrifuge tube. The aqueous layer was re-extracted with 2 mL fresh hexane and the hexane layers combined. The hexane extract was dried over 1 g anhydrous Na_2SO_4, transferred to a clean tube, and reduced to 1 mL under N_2. The extract was filtered through a 0.45 μm PTFE membrane filter into a 2 mL autosampler vial.

Pesticide analysis was performed on an Agilent Technologies 6890 gas chromatograph equipped with a nitrogen-phosphorous detector (GC/NPD) and 7683 automatic sampler (Agilent Technologies, Inc., Wilmington, DE). A 2 μL splitless injection was made onto a fused silica HP-35MS liquid phase capillary column (30 m × 0.25 mm × 0.25 μm) (Agilent Technologies). Helium carrier gas had a linear velocity of approximately 30 cm s^{-1}. Injector temperature was 250°C, and the detector was held at 300°C. The oven was temperature programmed from 100 to 300°C (held for 4.0 min) at 15°C min^{-1}. Extraction efficiencies were 93 to 99% efficient for chlorpyrifos, 99 to 100% efficient for chlorothalonil, 92 to 100% efficient for pendimethalin, and 88 to 99% efficient for propiconazole. The propachlor, which was used as a surrogate standard, was extracted with 90 to 100% extraction efficiency. This method was developed and tested in the Massachusetts Pesticide Analysis Laboratory (unpublished data, 2006).

Table 2. Average fraction of pesticides lost from various plant treatments after 3 and 7 mo of plant growth.†

	3 mo				7 mo			
Plants	CP	CT	PE	PR	CP	CT	PE	PR
Blue flag iris	0.76 a	0.94 ab	0.48 a	0.33 a	0.81 cd	0.997 a	0.72 ab	0.67 a
Black willow	0.67 ab	0.89 ab	0.21 ab	0.22 ab	0.92 ab	0.996 ab	0.74 a	0.59 ab
Prairie cord grass	0.58 abc	0.96 a	0.34 ab	0.24 ab	0.82 bcd	0.996ab	0.42 cd	0.42 b
Big blue stem	0.52 abc	0.91 ab	0.19 ab	0.30 a	0.88 abcd	0.992 c	0.60 abc	0.56 ab
Eastern gama grass	0.47 bc	0.95 a	0.17 ab	0.22 ab	0.80 d	0.995 abc	0.60 abc	0.54 ab
Tall fescue	0.47 bc	0.90 ab	0.24 ab	0.13 ab	0.87 abcd	0.993 bc	0.58 abc	0.43 b
Cutgrass	0.46 bc	0.88 ab	0.12 ab	0.07 ab	0.91 abc	0.995 abc	0.47 bcd	0.40 b
Tufted sedge	0.44 bc	0.90 ab	0.01 b	0.01 b	0.88 abcd	0.996 ab	0.53 abcd	0.45 ab
Perennial rye	0.43 bc	0.90 ab	0.19 ab	0.01 b	0.93 a	0.996 ab	0.48 bcd	0.50 ab
Woolgrass	0.39 c	0.91 ab	0.03 b	0.11 ab	0.88 abcd	0.996 ab	0.43 cd	0.40 b
Unvegetated	0.46 bc	0.86 b	0.08 b	0.12 ab	0.87 abcd	0.994 abc	0.31 d	0.46 ab
LSD	0.25	0.08	0.40	0.27	0.11	0.003	0.26	0.23

† CP = chlorpyrifos, CT = chlorothalonil, PE = pendimethalin, PR = propiconazole. Least significant differences (LSD) between means at the α = 0.05. Values with the same alphabetical letter within a column are not statistically different. The LSD at the α = 0.1 for CT after 3 mo of growth is 0.07. The LSD at the α = 0.1 for CT after 7 mo of growth is 0.0027.

Statistics

Measured pesticide concentrations (μg kg^{-1} dry wt. soil) were compared with the stored zero-time samples using a full ANOVA conducted with the general linear regression model of SAS (SAS Institute, 2005) to determine which plant species were most effective in removing pesticides from soil. Significance was assumed at $\alpha = 0.05$ unless otherwise stated. Significant differences amongst mean percent differences of plant treatments were determined using the least significant difference test. The general regression procedure in SAS was used to determine if root biomass was a significant predictor of pesticide loss. Before any statistical analysis, negative percent loss values were set to zero.

Results

Pesticide Loss

Chlorpyrifos loss ranged from 39 to 76% after 3 mo of plant growth (Table 2) from an average starting soil concentration of 0.18 mg kg^{-1} (Table 1). Blue flag iris showed significantly ($p < 0.05$) greater reduction than the unvegetated control. All other plant species were not significantly different from the unvegetated control (Table 2). Chlorpyrifos loss ranged from 80 to 93% after 7 mo of plant growth (Table 2). No treatment was significantly different from the unvegetated control. However, perennial rye had significantly ($p < 0.05$) greater loss than did prairie cord grass, blue flag iris, and eastern gama grass. Black willow had significantly ($p < 0.05$) greater loss than did eastern gama grass.

Chlorothalonil loss ranged from 86 to 96% after 3 mo of plant growth (Table 2) from an average starting soil concentration of 2.77 mg kg^{-1} (Table 1). Prairie cord grass and eastern gama grass significantly ($p < 0.05$) reduced chlorothalonil residues compared to the unvegetated control, and blue flag iris showed the same trend ($p < 0.10$) (Table 2). Chlorothalonil loss ranged from 99.2 to 99.7% after 7 mo of plant growth with blue flag iris ($p < 0.05$) and perennial rye ($p < 0.1$) showing trends of significantly greater loss than the unvegetated control (Table 2). The biologically significance of this is unclear since 99% of all the chlorothalonil was lost after 7 mo of plant growth and in the unvegetated control.

Pendimethalin loss ranged from 0.52 to 48% after 3 mo of plant growth (Table 2) from an average starting soil concentration of 1.06 mg kg^{-1} (Table 1). Blue flag iris had significantly ($p < 0.05$) higher loss than the unvegetated control, woolgrass, and tufted sedge (Table 2). Pendimethalin loss ranged from 31 to 74% after 7 mo of plant growth with black willow, blue flag iris, big blue stem, eastern gama grass, and tall fescue showing significantly greater losses ($p < 0.05$) than the unvegetated control (Table 2). Tufted sedge also showed the same trend ($p < 0.1$) compared to the unvegetated control (Table 2).

Propiconazole loss ranged from 0.52 to 33% after 3 mo of plant growth (Table 2) from an average starting soil concentration of 0.21 mg kg^{-1} (Table 1). Blue flag iris and big blue stem resulted in significantly ($p < 0.05$) more loss than tufted sedge and perennial rye grass, but losses were not significantly greater than the unvegetated control (12% loss) (Table 2). Propiconazole loss ranged from 40 to 67% after 7 mo of plant growth and no plant treatment was significantly different from the unvegetated control (Table 2). Blue flag iris, however, showed significantly greater ($p < 0.05$) loss than tall fescue, prairie cord grass, woolgrass, and perennial rye.

Plant Root Biomass after 10 Months of Growth

There were significant differences amongst the root biomass of plants after 10 mo of growth (Fig. 1). Blue flag iris had the most root biomass and had significantly ($p < 0.05$) more root biomass than black willow, prairie cord grass, tall fescue, woolgrass, perennial rye, and tufted sedge. Blue flag iris was also the plant that most frequently resulted in the highest loss of pesticides from soil. This finding suggests that root biomass may be a significant predictor of pesticide loss from soil.

Root biomass as a predictor of pesticide lost was tested for all pesticides using both the 3 and 7 mo sampling data. Root biomass was found to be a significant ($p < 0.05$) predictor of pesticide loss for chlorpyrifos ($r^2 = 0.19$), chlorothalonil ($r^2 = 0.19$), propiconazole ($r^2 = 0.27$) after 3 mo, and pendimethalin ($r^2 = 0.18$) and propiconazole ($r^2 = 0.09$) after 7 mo. While root biomass was a significant predictor of all pesticide losses studied, the low r^2 values, as indicated for propiconazole after 3 mo of plant growth, indicate that this is not a strong predictor and other characteristics of the plant are likely involved in pesticide loss (Fig. 2).

Discussion

Blue flag iris is a perennial characterized by dense rhizomes often found in wet habitats such as bog mats, floodplains, wet pastures, and swamps where it spreads vegetatively and forms dense colonies (Kron and Stewart, 1994). Few phytoremediation studies have utilized iris species and then usually only for its aesthetic value (Aarons, 2001). No studies have evaluated the ability of species of iris to remove contaminants. Nevertheless, it has been used successfully in conjunction with other plant species in constructed wetlands in Montana (Grove & Stein, 2005), Turkey (Zaimoglu, 2006), and Ireland (Clelland, 1998).

Plant species in the iris genus commonly contain irones, which are terpenoid compounds used by perfumers for their violet-like scent (Torii et al., 1980). These compounds contain structural moieties common to the pesticides used in this study (e.g., benzene rings, carboxylic acid groups, and carbon chains) (Bonfils et al., 1994). One phytoremediation mechanism involves the stimulation of the rhizobial microbial community by organic compounds secreted by the plant and the co-metabolism of pollutants (Leigh et al., 2006). Considering the success of blue flag iris in our study, it is likely that some degradation of the test pesticides is occurring in the rhizosphere of these plants.

Another possibility as to why blue flag iris performed well in enhancing pesticide loss from soil is its large root biomass. The pesticides used in this study all have relatively high K_{ow} values (3.72–5.18) and would be expected to sorb to root surfaces. If true, pesticides would remain in the VFS, reducing losses to surrounding environments such as water bodies, etc. Additionally, new growth would maintain a high level of sorption from year to year. Because blue flag iris has a very slow root turnover rate (Kron & Stewart, 1994), sorbed pesticides should remain in the VFS over time.

Eastern gama grass has been used successfully in VFS (Rankins et al., 2001; Krutz et al., 2005) and is thought to be effective because it is a tall erect plant. One of the factors that increases the effectiveness of a VFS is the inclusion of non-pliable plants, especially non-pliable grasses (Dabney et al., 1993). Rankins et al. (2001) found big blue stem, eastern gamagrass, switchgrass, and tall fescue all significantly reduced fluometuron concentration in runoff passed through a VFS. Big blue stem reduced herbicide loss by 55%, eastern gama grass by 76%, switchgrass by 49%, and tall fescue by 46% compared to the unvegetated control (Rankins et al., 2001). These results are consistent with that observed in the current study where pesticide loss was greater with big bluestem and eastern gama grass than with tall fescue. Our results also suggest that some of the same plant species that were effective in VFS associated with agricultural fields will also be effective in VFS surrounding turfed urban land uses such as golf courses. In addition to being effective in VFS, these plants have also shown tolerance to a wide variety of pollutants (Hetrick et al., 1993; Levy et al., 1999; Karthikeyan et al., 2004).

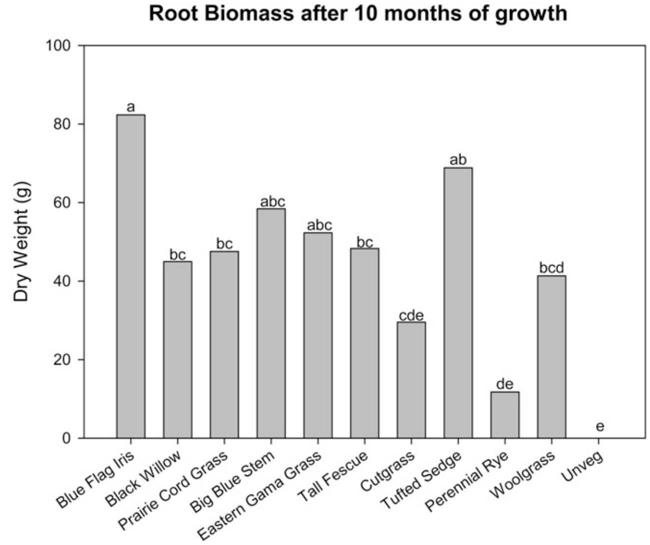

Fig. 1. Dry root biomass after 10 mo of plant growth. Bars with the same letters were not significantly ($p < 0.05$) different (least significant difference test).

Global pesticide use is increasing (Tilman et al., 2001) and the optimizations of best management practices to minimize the loss of pesticides into the environment are necessary. This study has identified plant species capable of enhancing the removal of pesticides from soils that are commonly applied to and lost from golf courses and other turf environments. Results from these types of studies can be used to make useful recommendations to golf course managers and superintendents on plant species selection for establishing VFS to reduce the loss of specific pesticides found in runoff.

Our findings reveal that blue flag iris is a useful general purpose plant for establishment in VFS that abuts turf environments. It effectively removes several turfgrass pesticides, is aesthetically pleasing, and should be well received by golfers, golf course superintendents, and home owners. Along with blue flag iris, we would recommend placing eastern gama grass in high chlorotha-

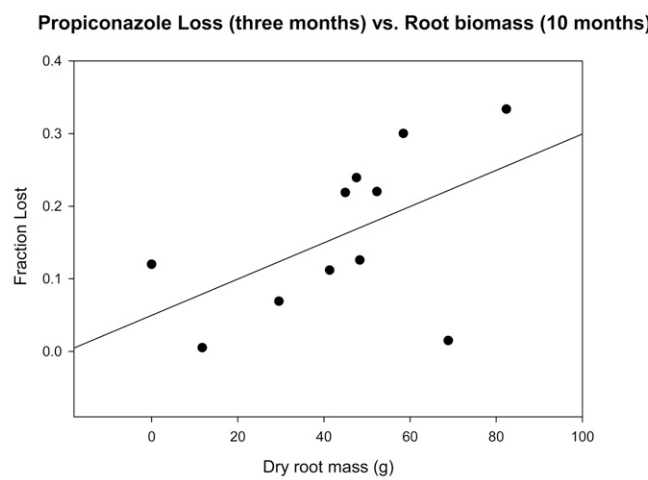

Fig. 2. Propiconazole loss after 3 mo of plant growth versus dry root biomass after 10 mo of growth. Dry root biomass was a significant ($p < 0.05$) predictor of propiconazole loss, $r^2 = 0.27$ (general linear regression).

lonil and/or pendimethalin situations, and big blue stem in high pendimethalin and/or propiconazole situations. In situations with high levels of chlorothalonil, incorporating prairie cord grass and perennial rye into VFS would likely reduce losses of this fungicide into surrounding environments. In areas with high pendimethalin use, black willow and tall fescue should also be considered. These results will be validated under field conditions to determine if the same trends of pesticide loss and removal from runoff water are observed. In addition, the actual mechanisms of pesticide removal will be examined in detail in the upcoming field study.

Growing Conditions of Recommended Plant Species

Blue flag iris generally grows best in moist or wet soils with full sun, but will tolerate moderately brackish water, partial shade and permanent inundation (Kron and Stewart, 1994). In our experience, these plants will also tolerate lower moisture conditions as all plants were maintained at field capacity for this study, but in between watering the moisture content of the soils dipped below field capacity. Eastern gama grass does best in well drained to somewhat poorly drained soils. It is not shade tolerant. Most released cultivars can withstand up to 5 d of flooding, but other ecotypes found in the Southeast have been reported to tolerate up to 23 d of inundation (USDA-NRCS, 2007). Big blue stem does best on moderately well drained to excessively well drained soils and is adapted to a range of conditions including shallow soil depth, low pH, and low fertility (USDA-NRCS, 2004). We expect that all three of these selected plant species will do well in VFS surrounding golf course greens and other turf environments.

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