2004

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Abstract

Reed canarygrass (*Phalaris arundinacea* L.) is a dominant perennial grass species in many sedge meadows and wet prairies. Efforts to control and eradicate this species with herbicides have had limited short-term success. A system of correlative inhibition (apical dominance) may operate in reed canarygrass rhizomes, resulting in a persistent rhizome bud bank that must be depleted in order to restore function and diversity to reed canarygrass stands. Pretreatments that overcome correlative inhibition may predispose reed canarygrass rhizomes to more effective herbicidal control. I conducted a feasibility study to test the efficacy of pretreatment tillage and plant growth regulator (PGR) application for enhancing herbicidal effects of sethoxydim (Vantage) on reed canarygrass. Three treatments were tested: 1) Vantage application only (control), 2) tillage followed by Vantage application, and 3) PGR application followed by Vantage application. Species density, diversity, and non-reed canarygrass stem density were higher in tilled plots than PGR plots or Vantage only plots, although this outcome may have been an indirect effect of tillage removing litter. Plant growth regulator pretreatments led to higher species diversity than plots treated with Vantage alone, possibly due to increased lateral growth of desired species. All treatments suppressed reed canarygrass stem density to the same degree in the year they were administered. Treatment lags may exist while reed canarygrass bud banks become depleted, and the effects of pretreatments may not be immediately evident. This is an ongoing study, and collecting additional response data in upcoming growing seasons will clarify reed canarygrass responses to tillage and PGR application.

Keywords: *Phalaris arundinacea*, apical dominance, correlative inhibition, rhizome, plant growth regulator, tillage

Introduction

Reed canarygrass (*Phalaris arundinacea* L.) is a dominant perennial grass species in many sedge meadows and wet prairies (Apfelbaum and Sams 1987, Maurer and others 2003). Efforts to control and eradicate this species with herbicides have had limited success. Herbicide applications generate short-term topkill of reed canarygrass, but resurgence from rhizomes can occur when applications are discontinued, often with post-treatment stem densities surpassing pretreatment levels (Kilbride and Paveglio 1999). Holt (1954) noted an absence of internodal elongation in lateral rhizome buds and Reyes (2004) determined that 47 to 76% of rhizome buds in a reed canarygrass stand were metabolically dormant. Postemergence herbicides are not translocated to dormant tissues, and treated stands are able to resprout from their rhizomes, a phenomenon known as resurgence. Thus, herbicide applications alone are not likely to control reed canarygrass unless applied repeatedly over consecutive growing seasons. Experimentally documented occurrences of rhizome bud dormancy and resurgence might be explained by the existence of a system of correlative inhibition in reed canarygrass rhizomes. Disrupting this system may make reed canarygrass more susceptible to herbicide treatments.

Correlative Inhibition and Perennial Grass Rhizomes

Correlative inhibition (apical dominance) is the effect whereby terminal apices of rhizomes inhibit lateral bud growth. Although the exact mechanisms underlying correlative inhibition are not completely understood, there is evidence that the effect is caused by interactions among nutritional factors (principally nitrogen and water, but also carbohydrate assimilate supply) (reviewed by McIntyre 2001), climatological and ontogenic effects (Moore 1989), and phytohormones (reviewed by Weyers and Paterson 2001). Rhizome correlative inhibition is a well-documented phenomenon in problematic perennial grasses such as quackgrass (*Elytrigia repens* Nevski.), Johnsongrass (*Sorghum halpense* (L.) Pers.), and Bermudagrass (*Cynodon dactylon* (L.)

Pers.) (Johnson and Buchholtz 1962, McIntyre 1969, McIntyre 1971, Banks and Tripp 1983, Hicks and Jordan 1984, Robertson and others 1989, Taylor and others 1995).

At the plant level, correlative inhibition results in both actively growing and dormant (metabolically inactive) rhizome buds. Consequently, rhizomatous perennial grass stands possess a dormant bud bank from which to recover from disturbances (such as herbicide applications). Foliar-applied systemic herbicides (such as glyphosate and sethoxydim) are applied to reed canarygrass topgrowth and, following uptake, are translocated throughout the plant within the carbohydrate assimilate stream (Robertson and others 1989). However, these herbicides are not translocated to dormant lateral buds along the rhizome because dormant buds lack completely developed vascular connections with the rest of the rhizome and have no access to the assimilate stream. Robertson and others (1989) observed a mass of undifferentiated parenchyma cells at the intersection of dormant lateral buds and the main rhizome axis in quackgrass. Studies involving radiolabeled herbicides demonstrate that both glyphosate and sethoxydim translocate to and accumulate within distal portions of rhizomes (i.e., terminal apices), rather than being uniformly distributed throughout the rhizome (Claus and Behrens 1976, Harker and Dekker 1988). Systemic herbicide applications are effective at killing the rhizome apex (and possibly some distal lateral buds, depending on the time of year and degree of apical dominance in place during application), yet dormant lateral buds are unaffected and can resprout after the herbicide degrades. This recovery is called resurgence (Strand 1993). In practical terms, resurgence means that herbicides will need to be reapplied to reed canarygrass stands over multiple growing seasons to deplete its rhizome bud band in addition to its seed bank.

Overcoming Correlative Inhibition by Activating Dormant Rhizome Buds

Activating dormant rhizome buds prior to herbicide application may make them more susceptible to herbicidal effects and enhance treatment effectiveness (Harker and Vanden Born 1997). Tillage and pretreatments with plant growth regulators (PGRs) are two ways to activate dormant buds.

Tillage overcomes correlative inhibition by decapitating rhizomes and slicing them into isolated multi-node fragments (Leakey and others 1975). Lateral buds are no longer inhibited and initiate growth, and follow-up herbicide applications affect a greater number of buds. Paveglio and Kilbride (2000) monitored changes in species density and diversity over three years in reed canarygrass stands treated with a combination of tillage and glyphosate application. Diversity more than doubled and species density nearly quadrupled following a single tillage-herbicide regime, and the effects lasted for more growing seasons then plots treated with herbicide alone. Similarly, Harker and Vanden Born (1997) reported that tillage reduced rhizome viability and enhanced herbicidal effects of sethoxydim on quackgrass. In both of these studies, tillage reduced rhizome resurgence capacity.

Plant growth regulators are synthetic phytohormone analogs that overcome correlative inhibition by activating or inhibiting signal transduction pathways, altering nutrient allocation patterns, or enhancing plant tissue sensitivity to the effects of endogenous (naturally occurring) phytohormones. Plant growth regulators are used in various capacities in horticulture and agriculture, and several are commercially available (Plant Growth Regulation Society of America 1990). Plant growth regulators are registered, labeled, and regulated in the same manner as pesticides (Wixted and others 1998). Harker and Taylor (1994) tested chlormequat chloride, 2-chloroethyl trimethyl ammonium chloride, (CCC, Cycocel, Olympic Horticultural Products Company, Mainland, PA) and ethephon, 2-chloroethylphosphonic acid, (Proxy, Bayer Environmental Science, Montvale, NJ) for enhancing sethoxydim effectiveness in quackgrass stands. Both of theses PGRs are known inhibitors of apical growth. Pretreatment applications of a 2:1 mixture of CCC and ethephon prior to sethoxydim application reduced quackgrass dry mass 60% greater than sethoxydim application alone. This mixture is also used to increase yield in grain crops by promoting lateral growth and secondary tillering (Ma and Smith 1991).

Methods

Study Objectives

Although tillage and PGR pretreatments have been shown to enhance herbicidal effects in quackgrass, their utility for reed canarygrass abatement is virtually unexplored (but see Kilbride and Paveglio 1999, Paveglio and Kilbride 2000). I designed a feasibility study to test the efficacy of tillage and PGR pretreatments for enhancing herbicidal effects of sethoxydim on reed canarygrass. This is an ongoing study, and only first year results are reported here.

Study Site

The effects of tillage and PGR pretreatments on reed canarygrass were tested in a sedge meadow at the Savanna Oak Foundation's Pleasant Valley Conservancy, a 140-acre (57-ha) nature preserve and land trust located in the unglaciated Driftless Area of southwestern Wisconsin (43 00'N, 89 30'W; T7N R6E Sec. 5). Pleasant Valley Creek (a tributary of Blue Mounds Creek) flows through the sedge meadow at its southern end and there is additional hydrologic input from several natural springs located throughout the meadow. Adjacent land use is rural and undeveloped with agricultural activity limited to small hay fields and pastures.

Treatments

The effects of pretreatments on herbicide efficacy were tested in a randomized complete block design in 2004. Each block

consisted of one main plot (195 m^2) and three subplots (52 m^2). Three treatments were administered: 1) Vantage application only (control), 2) tillage followed by Vantage application (20-day treatment interval), and 3) 2:1 Cycocel/Proxy application followed by Vantage application (4-day treatment interval). The selective herbicide Vantage (sethoxydim, Micro Flo Company, Memphis, TN) was used in order to prevent collateral damage to non-target species and enable native species reestablishment, and because sethoxydim accumulates in rhizomes to a greater extent than glyphosate (Harker and Dekker 1988). A non-treated control was not used because the purpose of this study was to determine if combinations of treatments are more effective alternatives to exclusive use of herbicides. Treatment 1 (Vantage applications only) was used as a baseline from which to measure any additional effects of pretreatment tillage and PGR application on reed canarygrass control and native species reestablishment when carried out in conjunction with Vantage application. Vantage was applied at a rate of 3.75 pints/acre as a broadcast spray from a small capacity tank with a cone nozzle. A nonionic surfactant was added to Vantage tank mixtures at a rate of 0.03 pints/acre. A 2:1 (v/v a.i.) mixture of Proxy and Cycocel was applied at a rate of 1.25 pints/acre (Proxy at a rate of 0.25 pints/acre and Cycocel at a rate of 1.0 pints/acre). It was not necessary to add a surfactant to this mixture because Proxy and Cycocel formulations already contain the necessary adjuvants. Reyes (2004) reported that 90% of reed canarygrass rhizomes occurred within 10 cm (4 inches) of the soil surface. For that reason, plots were tilled to a depth of 10 cm with a 6-hp rototiller (TroyBilt, MTD International, Cleveland, OH). This device was used to simulate tillage with a multivator (a class of tillage implement with three sets of rotary tines powered by a tractor PTO). Subplots were prepared for tillage by mowing vegetation with a brush trimmer (STIHL USA, Virginia Beach, VA) equipped with plastic flails, and removing clippings from treatment plots. Plots were tilled on June 1, treated with PGR on June 15, and sprayed with Vantage on June 20. These dates correspond closely to reed canarygrass peak productivity (Klopatek and Stearns 1978).

Response Variables and Data Analysis

Stem density was estimated on August 13 in four randomly located 0.25-m^2 quadrats per treatment subplot (for a total of 36 quadrat samples among all treatments and replications). Quadrat shape and size were appropriate for this type of vegetation (Brummer and others 1994). All species present within each quadrat were sampled. Nomenclature follows the USDA PLANTS database. Stem density was used as an indicator of treatment effectiveness and as an indicator of abundance for diversity estimates. Total stem density was partitioned into two components for analysis: reed canarygrass stem density and non-reed canarygrass stem density. These two responses facilitated separate analysis of treatment effects on reed canarygrass and on desired endpoint species. Species presence was also recorded within each treatment subplot. Rhizomes were not sampled because rhizome sampling would disturb the soil and alter treatment conditions, barring objective analysis in forthcoming growing seasons. Species density was determined for each subplot as the number of taxonomically distinct species/0.25m^2. Species diversity in each subplot was estimated with the Shannon function, $H' = \Sigma\, p_i (\ln p_i)$, where p corresponds to the proportional abundance of the *i*th species. For clarity, H' estimates were converted into the same scale as species density with MacArthur's N_1 (where $N_1 = e^{H'}$) (MacArthur 1965). Percent litter was estimated within each quadrat as the percent of the quadrat area covered by litter. Percent litter measurements were taken from the top of the vegetation canopy directly above each quadrat sample to represent light penetration at the soil/litter surface during mid-day, when light is most intense. Data from each response were tested from normality (χ^2 goodness-of-fit test) and homoskedasticity (Bartlett's test) with the program TOXSTAT, v. 3.1 (D. D. Gulley, A. M. Boelter, and H. L. Bergman, University of Wyoming, Laramie, WY). Treatment effects were tested with a parametric analysis of variance (ANOVA) for a randomized complete block design. Subplots were the experimental units in the model and subplot means for all response variables were used in data analysis. Blocks and treatments were fixed factors and reed canarygrass stem density, non-reed canarygrass stem density, percent litter, species density, and the Shannon function were included as dependent variables in the model. Treatment means were separated with Tukey's protected W procedure. F ratios and treatment contrasts were tested for significance at the $\alpha = 0.05$ probability of type I error. Mean species richness (defined as the mean number of species per replicate of each treatment) and cumulative species richness (defined as the total number of species in all replications of each treatment) were also estimated, although statistical comparisons were not made on these responses because they were (by their definition) not properly replicated (Hurlbert 1984).

Results

A total of 58 species were present or sampled among all treatment and replications (Table 1). Of these, 52 species occurred in the tillage-Vantage® plots, 32 in PGR-Vantage® plots, and 23 in plots that were treated with Vantage® alone. Of the three treatments tested, tillage had the greatest impact on non-reed canarygrass stem density, species density, species diversity, and percent litter in 2004 (Table 2). Non-reed canarygrass stem density was 270% greater in tilled plots then plots treated with only Vantage®. Species density in tilled plots was 120% greater and diversity 87% greater than in plots treated with Vantage® alone. Percent litter was lowest in tilled plots and statistically similar in the other two treatments. In terms of species density and abundance, tillage-Vantage® treatments outperformed PGR-Vantage® treatments (Table 3). Non-reed canarygrass stem density was 99% greater in tillage-Vantage® plots than plots treated with PGR mixtures prior to Vantage® application. Species density was 52% greater and species diversity was 27% greater in tillage-Vantage® plots than PGR-Vantage® plots. Plant growth regu-

Table 1. Summary of species sampled (S) and present (P) within treatment plots in 2004.

Species	Treatment: Tillage & Vantage®	PGR & Vantage®	Vantage® only
Acer negundo (L.) (seedling)	P		P
Amaranthus spp.	P		
Angelica atropurpurea L.	S	P	S
Asclepias incarnata L.	S	P	
Aster prenanthoides Muhl.	S	S	S
Aster puniceus L.		S	S
Bidens cernua L.	S		P
Caltha palustris L.	P	S	
Carex lacustris Willd.	S		P
Carex stricta Lam.	S	S	
Carex tricocarpa Muhl.	S	S	S
Chenopodium album L.	P		
Cirsium muticum Michx.	P		
Cyperus spp.	P		
Cyperus bipartitus Torr.	P		
Eleocharis acicularis L. Roemer & Schultes.	S		
Erectites hieraciifolia (L.) Raf.	P		
Eupatorium maculatum L.	S	S	S
Eupatorium perfoliatum L.	S	P	P
Galium boreale L.	S	S	
Helenium autumnale L.	P	S	S
Impatiens capensis Meerb.	S	S	S
Iris virginica L.	S	S	
Juncus spp.	P		
Leersia oryzoides (L.) Swartz.	S	S	
Lobelia kalmii (L.)	P		
Lycopus americanus Muhl.	S	S	S
Onoclea sensiblis L.		P	
Oxalis stricta L.	S	S	
Parthenocissus quinquefolia (L.) Planchon.	S	S	S
Pedicularis lanceolata Michx.	P		
Phalaris arundinacea L. (live stem)	S	S	S
Poa pratensis L.	P	S	
Polygonum lapathifolium L.	P		
Polygonum hydropiper L.	P		P
Potentilla norvegica L.	P		
Pycnanthemum virginianum (L.) Durand & B.D. Jackson	S	P	
Ranunculus hispidus var. *nitidus* (Elliott) T. Duncan	S		
Ribes oxyacanthoides L.	S		P
Rubus occidentalis L.	S	S	P
Rudbeckia laciniata L.	S		
Rumex crispus L.	P	P	
Sagittaria latifolia Willd.	S	S	P
Salix spp. (seedling)	P		
Scirpus cyperinus (L.) Kunth.	S		
Sicyos angulatus L.		P	
Solanum dulcamara L.	S	P	
Solidago gigantea Aiton.		S	
Stellaria media (L.) Villars.	P		
Symplocarpus foetidus (L.) Nutt.	P		
Taraxacum officinale L.	P		
Urtica dioica L.	S	S	S
Viola sororia L.	S	S	S
Vitis riparia Michx.	P		
unknown1	P	S	S
unknown2	P		
unknown3		P	S
unknown4		S	P

lator pretreatments followed by Vantage® application had a larger influence than Vantage® application alone for species diversity only, which was 47% greater in PGR-Vantage® plots than Vantage® only plots. Despite improvements in species recruitment and abundance with tillage and PGR pretreatments, reed canarygrass stem density was statistically indistinguishable among treatments in 2004 (Table 3).

Discussion

Tillage followed by Vantage® application had a larger influence on species density and abundance than PGR pretreatments followed by Vantage® application or by Vantage® application alone. Tillage also decreased the percentage of soil surface covered by litter. Nevertheless, all treatments yielded similar reed canarygrass stem densities in 2004. Reed canarygrass stem densities in unmanaged stands can range from 55–100 stems/0.25m^2 (Evans and Ely 1941, Ho 1979, Kilbride and Paveglio 1999). Although an untreated contemporaneous control was not incorporated into the design of this experiment, comparing reed canarygrass stem densities observed in this study (Table 2) with those published in the literature demonstrate that all treatments had a suppressive effect in the same year as they were administered, even though this effect was similar among treatments. The theoretical purpose of pretreatments is to increase the effectiveness of herbicide applications by predisposing dormant lateral buds to herbicidal effects, thus depleting the dormant bud bank over time. If pretreatments are effective at activating dormant buds, more buds should be killed when the pretreatment is coupled to herbicide application than when herbicides are used alone. However, Reyes (2004) reported a viable bud density of 1,100–1,900 buds/m^2 in reed canarygrass stands, and pretreatment effects may not be reflected in stem density until the bud bank begins to become depleted (i.e., there may be a treatment lag before differences become apparent). Treatment lags for rhizome responses to split application herbicide regimes (an alternative method of activating dormant buds) have been suspected to occur in field experiments with quackgrass (Harker and Vanden Born 1997) yet have not been examined and documented in detail. If a lag in reed canarygrass stem density suppression exists, responses may not be detected by sampling until the second or third growing season. Thus, multiple year observations need to be made and more data collected to determine if pretreatments are effective ways of depleting the reed canarygrass bud bank. I plan to collect additional data during the 2005 growing season to determine if 2004 pretreatments had any additional effect on reed canarygrass stem density suppression with Vantage®, and to monitor reestablishment of desired vegetation.

It is worth mentioning that the stimulating effect of tillage on species density and abundance may have been indirect. In addition to stirring up the seed bank, tillage decreased the percentage of soil surface covered by litter (Table 2). Litter is known to have an inhibitory effect on seed germination and litter accumulation can alter species composition over time (Neill 1990). Unmanaged reed canarygrass stands can accu-

mulate a large amount of undecomposed litter. Howe (1995) observed that unburned plots accumulated 10–40 cm (4–16 inches) of litter in four growing seasons. Tillage mixed this layer into the soil. Removal of the litter layer exposed the seed bank to light, which could have facilitated germination of both desired species and reed canarygrass. Follow up treatment with the selective herbicide Vantage® was then able to set back reed canarygrass seedlings and resprouts long enough for desired species to become established. Reed canarygrass is one of the first species to emerge in the spring, enabling it to shade out native species that emerge later in the growing season, and many native species reach their maximum rate of biomass production more than one month after reed canarygrass (Klopatek and Stearns 1978). Thus, removing litter and suppressing reed canarygrass during the late spring growth period may have influenced species density and diversity to a greater degree than any direct effect of tillage on reed canarygrass. Coupling controlled burning to Vantage® application will also remove litter and set back reed canarygrass growth, but lethal temperatures do not affect reed canarygrass rhizomes (Reyes 2004) and resurgence can occur. Plant growth regulator pretreatments did not reduce litter, but may have encouraged lateral growth of desired perennial species, increasing the stem density component of diversity estimates in PGR-Vantage® plots. This may explain observed differences in diversity between PGR-Vantage® plots and Vantage® only plots. As with tillage, PGR pretreatments may have a lag time before reed canarygrass suppression is discernable.

Drawbacks to Tillage and PGR Pretreatments

Assuming tillage-Vantage® regimes will eventually reduce reed canarygrass stem density, long-term use of tillage may have detrimental effects in natural areas. Repeated tillage can homogenize soil structure and microtopographic heterogeneity, both of which correlate with species richness (Vivian-Smith 1997, Werner and Zedler 2002). Tillage has also been shown to disrupt VAM colonization of wetland plants, reducing phosphorus uptake and altering competition trajectories (Evans and Miller 1990). Furthermore, tillage equipment can cause soil compaction (Soulé and Piper 1992). In terms of treatment expense, both tillage-herbicide and PGR-herbicide regimes are more expensive than herbicide application alone. Vantage® application (with surfactant) costs about $40/acre. The PGR mixture used in this study (and at these rates) costs roughly $225/acre. These figures account for chemical costs only, and do not include additional costs of labor and equipment. The cost of tillage varies, depending on whether equipment is owned or has to be rented, and also on whether the work is outsourced. However, if effective, these increases in initial costs may be counterbalanced by reductions in long-term financial costs associated with herbicide applications over multiple years. Furthermore, speeding up reed canarygrass abatements may have the added benefits of lessening long-term herbicide usage and delaying the possible onset of herbicide resistance in reed canarygrass.

Table 2. Summary of treatment effects in 2004 (mean +/- 1SE; n = 3).

Response Treatment	RCG†	Non-RCG‡	% litter	H' [$e^{H'}$]	D§	Mean S#	S£
Tillage & Vantage®	22.7 (2.3)	70.6 (2.7)	7.0 (1.1)	1.998 [7.38] (0.4)	8.25 (0.5)	30	52
PGR & Vantage®	35.7 (3.5)	35.4 (1.6)	48.3 (2.8)	1.570 [4.81] (0.4)	5.42 (0.9)	18	32
Vantage® Only	30.7 (2.6)	19.3 (1.5)	73.75 (1.7)	1.069 [2.91] (0.4)	3.75 (0.6)	13	23

† Mean reed canarygrass stem density/0.25m^2.
‡ Mean non-reed canarygrass stem density/0.25m^2.
§ Species density (mean number of species/0.25m^2).
# Mean species richness (mean number of species in each replication of each treatment).
£ Cumulative species richness (total number of species in all replications of each treatment).

Table 3. Summary of ANOVA and linear comparisons among treatments in 2004 (n = 3).

Response variable:	$F_{(2,4)}$	P-value	significant comparisons*
RCG stem density	1.108	P > 0.250	n.s.
Non-RCG stem density	12.457	P < 0.020*	(Till x Vantage only); (Till x PGR)
Percent litter	13.149	P < 0.020*	(Till x Vantage only); (Till x PGR)
Shannon function (H')	121.825	P < 0.001*	all comparisons were significant
Species density	15.731	P < 0.020*	(Till x Vantage only); (Till x PGR)

* Main effects and linear comparisons were significant at the $\alpha = 0.05$ probability of type I error

Conclusions and Management Implications

Tillage-herbicide and PGR-herbicide regimes enhanced species density and diversity compared to Vantage® application only, though in the case of tillage, these effects may have been indirect. Nevertheless, neither tillage nor PGR application added to reed canarygrass stem density suppression in the same year treatments were administered. Although the effects of tillage and PGR pretreatments on correlative inhibition and stem density suppression of reed canarygrass cannot yet be properly addressed without further observations, this research is ongoing, and treatment lags may mask effect sizes for a few growing seasons before becoming discernable. Both tillage and PGR pretreatments add to the expense of reed canarygrass abatement, and these costs will be justified only if the pretreatments are found to be more effective than herbicide application alone.

Acknowledgments

The Savanna Oak Foundation, Inc. and Michler & Brown, LLC provided funding for this research. I thank Tom Brock, Kathy Brock, and Dale Secher for their input; Chris Reyes for sharing data; Jim Ludloph for use of his rototiller; and Paul Michler for assistance with species identification.

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