RESEARCH ARTICLE

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Effects of Tillage and Growth Regulator Pretreatments on Reed Canarygrass (*Phalaris arundinacea* L.) Control with Sethoxydim

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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 this species with herbicides have had limited short-term success, partly because reed canarygrass resurges from its rhizomes whenever applications are suspended. A system of apical dominance may operate in reed canarygrass rhizomes, resulting in a persistent rhizome bud bank that must be depleted in order to achieve effective, long-lasting control of this species. Pretreatments that overcome apical dominance may predispose reed canarygrass to more effective herbicidal control. I tested whether coupling pretreatment tillage or pretreatment plant growth regulator (PGR) application to herbicide application would result in greater reed canarygrass control compared to herbicide application alone. Three treatments were tested: (1) Sethoxydim (Vantage®) application only (standard method control), (2) Tillage followed by Vantage® application, and (3) Plant Growth Regulator application (2:1 (a.i.) Cycocel®/Proxy®) followed by Vantage® application. Tillage-Vantage® treatments had a larger effect on reed canarygrass suppression and native species abundance than the other two treatments, and these effects persisted into the subsequent growing season after treatments were discontinued. Coupling PGR pretreatments with herbicide application reduced reed canarygrass stem density 26% greater than herbicide application only. Tillage and PGR pretreatments have potential for enhancing the effects of Vantage® herbicide on reed canarygrass.

Index terms: apical dominance, *Phalaris arundinacea*, plant growth regulator, reed canarygrass, resurgence

INTRODUCTION

Reed canarygrass (*Phalaris arundinacea* L.) is a dominant perennial grass species in many sedge meadows and wet prairies, where it displaces native species and derails restoration efforts (Apfelbaum and Sams 1987; Galatowtisch et al. 2000; Maurer et al. 2003; Lavergne and Molofsky 2006). Control of this species is difficult and usually requires multiple-year efforts. Effective control and restoration strategies need to be developed for reed canarygrass-dominated communities.

Herbicide applications are the most common method for control, although a number of non-chemical techniques are available or under development (Apfelbaum and Sams 1987; Lavergne and Molofsky 2006). Herbicide applications offer short-term suppression of reed canarygrass, but their effects do not always persist, and reed canarygrass often returns to its pretreatment abundance when herbicide treatments are discontinued. This recovery is called weed resurgence (Strand 1993). The absence of herbicide carryover effects and resurgence in stem density are frequently reported for reed canarygrass (c.f., Kilbride and Paveglio 1999; Lesica and Martin 2004; Reinhardt and Galatowitsch 2004; Wilcox 2004; Annen et al. 2005; Hovick and Reinhartz 2005), leading most authors to conclude that herbicide applications alone are not likely to control reed canarygrass unless applied repeatedly over consecutive growing seasons. Reinhardt and Galatowitsch (2004) showed that land managers consider "resprouting" to be the foremost cause of control failure for reed canarygrass.

Resurgence is a well-documented phenomenon in other invasive perennial grasses such as quackgrass (*Elytrigia repens* (L.) Nevski.), johnsongrass (*Sorghum halpense* (L.) Pers.), and bermudagrass (*Cynodon dactylon* (L.) Pers.). Studies on these species suggest that resurgence may be an indirect result of rhizome apical dominance and its effect on herbicide distribution gradients within perennial grass rhizomes (Figure 1) (Johnson and Buchholtz 1962; McIntyre 1969; McIntyre 1971; Banks and Tripp 1983; Hicks and Jordan 1984; Robertson et al. 1989, Harker and O'Sullivan 1993; Taylor et al. 1995; Wall and Smith 2000).

Apical dominance (correlative inhibition) occurs when 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) (McIntyre 2001), climatological and ontogenic effects (Trewavas 1981), and plant hormones (Moore 1989; Cline 1991; Weyers and Patterson 2001).

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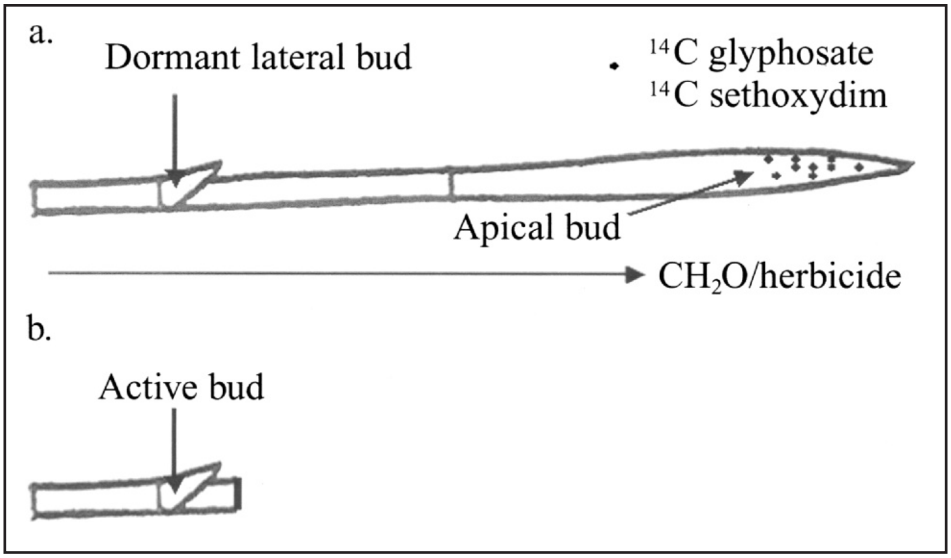

Figure 1. The effect of apical dominance on herbicide distribution in a perennial grass rhizome. a. Herbicides applied to topgrowth are translocated with carbohydrates (CH_2O) to the rhizome apex, but not to dormant lateral buds. Herbicide accumulates in the apex rather than being uniformly distributed throughout the rhizome. b. The apex is killed, making the previously dormant lateral buds active. Once the herbicide degrades, these buds can resprout and form new tillers, resulting in resurgence.

Apical dominance results in both actively growing and dormant (metabolically inactive) rhizome buds. Postemergence herbicides are not translocated to dormant tissues; thus, rhizomatous perennial grasses possess dormant buds that can initiate renewed growth after herbicide applications. When systemic herbicides (such as glyphosate and sethoxydim) are applied to reed canarygrass foliage, they are translocated throughout the plant with the carbohydrate assimilate stream. However, these herbicides are not translocated to dormant lateral buds because dormant buds lack completely developed vascular connections with the rest of the rhizome and have no access to the assimilate stream. Robertson et al. (1989) observed a mass of undifferentiated parenchyma cells at the intersection of dormant lateral buds and the main rhizome access in quackgrass. Holt (1954) described the innermost rhizome scale leaves of reed canarygrass as possessing undeveloped provascular bundles rather than functional vascular tissue capable of conducting assimilate into the lateral bud. Previous studies with radiolabeled herbicides demonstrated that both glyphosate and sethoxydim translocated to and accumulated 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) (Figure 1a). Thus, systemic herbicide applications are effective at killing the rhizome apex, yet dormant lateral buds are unaffected and can resurge when the herbicide degrades (Figure 1b). In practical terms, resurgence means that herbicides will need to be reapplied to reed canarygrass stands over multiple growing seasons in order to deplete its rhizome bud bank as well as its seed bank.

Although rhizome apical dominance has not been specifically confirmed in reed canarygrass, evidence that this type of system is operating in its rhizomes has been presented by Holt (1954), who noted an absence of internodal elongation in lateral rhizome buds of reed canarygrass, and by Reyes (2004), who determined that 47-76% of rhizome buds in a reed canarygrass stand were metabolically dormant. If resurgence in reed canarygrass is the result of a system of apical dominance in its rhizomes, disrupting this system may make reed canarygrass more susceptible to herbicide treatments.

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

Tillage overcomes apical dominance by decapitating rhizomes and slicing them into isolated multi-nodal fragments (Leakey et al. 1975). Lateral buds are no longer inhibited and initiate growth, and follow-up herbicide applications affect more buds. Harker and Vanden Born (1997) reported that tillage reduced rhizome viability and enhanced effects of sethoxydim on quackgrass. Similarly, Kilbride and Paveglio (1999) and Paveglio and Kilbride (2000) showed that tillage-glyphosate treatments suppressed reed canarygrass stem density more than herbicide application alone. They also reported that these effects were not limited to the growing season when treatments were applied; two years after treatments, reed canarygrass stem density remained at 30% of its untreated density. These studies also noted improvements in native species abundance and diversity in tillage-herbicide regimes compared to control strategies employing only herbicides. In each of these experiments, tillage reduced rhizome resurgence capacity.

Although tillage has been shown to enhance reed canarygrass control and improve native species density and diversity, this treatment may not be a practical option for all abatements. For instance, a site may be inaccessible or too wet for tillage equipment. Natural features (such as boulders, tree stumps, shrubs, and springs) also limit tillage. Long-term use of tillage can also have detrimental impacts on natural areas. Repeated tillage can homogenize soil structure and microtopography, both of which correlate with species richness in sedge meadows (Vivian-Smith 1994; Werner and Zedler 2002). Tillage also disrupts colonization of wetland plants by mycorrhizal fungi, reducing phosphorus uptake and altering competition trajectories (Evans and Miller 1990). Furthermore, tillage equipment can cause soil compaction (Soule and Piper 1992). For these reasons, it is important to continue to evaluate alternatives to tillage for disrupting apical dominance and enhancing reed canarygrass control.

Plant growth regulators are synthetic plant hormones that overcome apical dominance by activating or inhibiting molecular signals, altering nutrient allocation patterns, or enhancing plant tissue sensitivity to the effects of endogenous (naturally occurring) plant hormones. To overcome apical dominance in reed canarygrass, a PGR must be able to initiate development and bring about differentiation of provascular cells in dormant lateral buds, converting them into functional vascular tissue bundles. When this occurs, carbohydrates, nutrients, and herbicides can be transported into the lateral bud (Figure 2). PGRs are used in various capacities in horticulture and agriculture, and several are commercially available (Plant Growth Regulation Society of America 1990). Harker and Taylor (1994) tested chlormequat chloride ((2-chloroethyl) trimethyl ammonium chloride, or CCC) and ethephon (2-chloroethylphosphonic acid) for enhancing sethoxydim effectiveness in quackgrass stands. 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. Both of these PGRs are known inhibitors of apical growth (Moore 1989) and are used in agriculture to increase yield in grain crops by promoting lateral growth and secondary tillering (Ma and Smith 1991). McIntyre (1971) reported that lateral buds of quackgrass rhizomes were released from apical dominance after topical treatment with kinetin (6-furfurylaminopurine).

PGRs have been applied to reed canarygrass by previous researchers. Landgraff and Junttila (1979) tested ethephon for enhancing seed germination, and Hovin et al. (1973) used ethephon to improve propagation and establishment of this species from culm segments. Also, Heide (1994) suggested the use of alternating applications of cytokinin and gibberellin to suppress panicle induction in reed canarygrass and related species. None of these studies has addressed the potential of PGRs for enhanced control of reed canarygrass with herbicides.

Although tillage and PGR pretreatments have been shown to enhance herbicide effects in quackgrass, their utility for reed canarygrass abatement is virtually unexplored (but see Kilbride and Paveglio 1999; Paveglio and Kilbride 2000). The objective of this study was to determine if coupling pretreatment tillage or pretreatment plant growth regulator application to herbicide application would result in greater reed canarygrass control compared to herbicide application alone.

METHODS

Study site

The effects of tillage and PGR pretreatments on reed canarygrass were tested in a remnant sedge meadow community at the Savanna Oak Foundation's Pleasant Valley Conservancy, a 57-ha nature preserve and land trust located in southwestern Wisconsin (N43º 00' and W89º 30'). Pleasant Valley Creek flows through the sedge meadow at its southern end, and there is additional hydrologic input from several natural springs located throughout the meadow. At the beginning of the experiment, soil nitrate-N in research plots ranged from 3.3 to 4.2 mg/L (mean = 3.7 mg/L).

Treatments

The effects of pretreatments on herbicide performance were tested in a randomized block design with a standard method control in 2004 and 2005. Post-treatment monitoring was conducted in 2006 to assess resurgence capacity. Each block consisted of one main plot (195-m^2) and three subplots (52-m^2). Three treatments were administered: (1) Standard Method Control (Vantage® application only), (2) Tillage followed by Vantage® application (19-d treatment interval), and (3) 2:1 CCC/ethephon application followed by Vantage® application (5-d treatment interval). We chose to use the standard method control (Ott and Longnecker 2001) in this design in place of a non-treated control because our objective was to determine if coupling pretreatments to herbicide application had any additional effects over herbicide application alone. Vantage® only plots were the baseline treatment against which other treatments were compared. The selective herbicide Vantage® (13% a.i. sethoxydim, Micro Flo Company, Memphis, TN) was chosen to minimize collateral damage to non-target species (Calkins et al. 1996) and enable native species reestablishment. At the time of herbicide application, reed canarygrass was 10-15 cm tall in tillage plots and 60-75 cm tall in PGR and control plots. Treatments were randomly assigned to subplots and replicated three times.

Vantage was applied at a rate of 4.45 L/ha as a broadcast spray from a small capacity tank with a cone nozzle adjusted to provide a wide spray pattern. A nonionic surfactant/methylated soybean oil blend (Destiny®, AgriSolutions Chemical Company, St. Paul, MN) was added to Vantage® tank mixtures at a rate of approximately 3.75 mL/L (0.375% v/v) to enhance uptake. A water-conditioning agent (ReQuest®, Helena Chemical Company, Memphis, TN) was added to tank mixtures at a rate of approximately 2.5 mL/L (0.25% v/v) to stabilize tank mixture pH and sequester hard water cations, which can accelerate chemical degradation of sethoxydim (Beckett et al. 1992; Shoaf and Carlson 1992). A 2:1 (v/v a.i.) mixture of chlormequat chloride (Cycocel®, Olympic Horticultural Products Company, Mainland, PA) and ethephon (Proxy®, Bayer Environmental Science, Montvale, NJ) was applied at a rate of 1.5 L/ha (Proxy® at a rate of 0.30

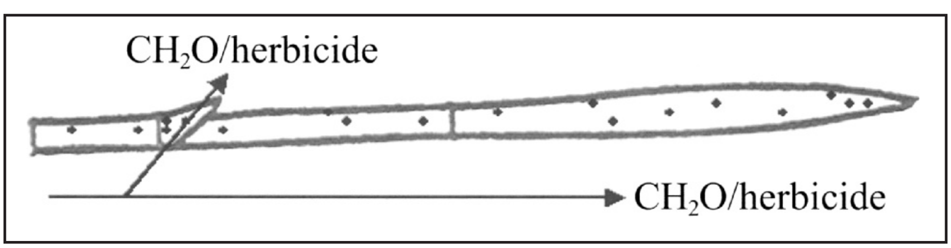

Figure 2. Theoretical effect of plant growth regulator (PGR) on herbicide distribution in a perennial grass rhizome. PGR application promotes vascular tissue development in dormant lateral buds, and herbicide applied to topgrowth is distributed uniformly within the rhizome.

L/ha and Cycocel® at a rate of 1.2 L/ha). It was not necessary to add a surfactant to this mixture because commercial formulations of Proxy® and Cycocel® already contain the necessary additives. ReQuest® conditioner was added to PGR tank mixtures at a rate of approximately 2.5 mL/L (0.25% v/v) and fertilizer (Miracle Gro®, Scotts Miracle-Gro Products, Inc.) was added at a rate of 10 g/plot. Fertilizers are believed to enhance uptake, translocation, and activity of PGRs applied to fruit and vegetable crops (Leo Brostowitz, Professional Crop Consultant, pers. comm.). Reyes (2004) reported that 90% of reed canarygrass rhizomes were located within the top 10 cm of soil. For that reason, plots were tilled by light rotovation to a depth of 10 cm with a 6-hp rototiller (TroyBilt®, MTD International, Cleveland, OH). Subplots were prepared for tillage by mowing existing vegetation with a brush trimmer equipped with plastic flails (STIHL USA, Virginia Beach, VA) and removing clippings from treatment plots. In 2004, subplots were tilled on June 3, sprayed with PGR on June 17, and sprayed with Vantage® on June 22. In 2005, subplots were tilled on June 1, sprayed 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). This is also the time of year when leaf growth predominates over shoot growth (Ho 1979), which is a condition suited to the use of foliar-applied herbicides and plant growth regulators. All treatments were applied to the same subplots in 2004 and 2005.

Response variables and data analysis

Treatment responses were measured on 13 August 2004 and 14 August 2005. A post-treatment survey was conducted on 14-15 June 2006 to measure subsequent resurgence during reed canarygrass peak productivity. Stem density was measured in four randomly located 0.25-m^2 square quadrats per treatment subplot. Quadrat shape and size were appropriate for this type of vegetation (Brummer et al. 1994). All species present within each quadrat were sampled. Nomenclature follows Gleason and Cronquist (1991). 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 density was determined for each subplot as the number of species/0.25 m^2. Species diversity in each subplot was estimated with the Shannon function, $H' = \Sigma\, p_i\,(\ln p_i)$, where p_i 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). Species presence was also recorded within each treatment subplot. Significance was set at $\alpha = 0.05$. When constructing standard errors for estimates of the Shannon function, variance estimates for *H'* were calculated following methods outlined in Magurran (1988).

RESULTS

2004-Initial series of treatments, first growing season

Fifty-seven species were present or sampled among all treatments and replications in 2004. Of these, 50 species occurred in tillage-Vantage® plots, 32 in PGR-Vantage® plots, and 23 in plots that were treated only with Vantage®. Of the three treatments tested, tillage had the greatest impact on non-reed canarygrass stem density, species density, and species diversity in 2004 (Table 1). Non-reed canarygrass stem density was 270% greater in tilled plots than in plots treated only with Vantage®. Species density in tilled plots was 118% greater and diversity 87% greater than in plots treated only with Vantage®. In terms of species abundance and diversity, tillage-Vantage® treatments outperformed PGR-Vantage® treatments (Table 1). Non-reed canarygrass stem density was 99% greater in tillage-Vantage® plots than plots treated with PGR mixtures prior to Vantage® application. Diversity was 27% greater in tillage-Vantage® plots than PGR-Vantage® plots. PGR pretreatments followed by Vantage® application had a larger influence than the standard method baseline for species diversity and non-reed canarygrass stem density, which were 47% and 84% greater in PGR-Vantage® plots than Vantage® only plots. Despite improvements in species recruitment and abundance with tillage and PGR pretreatments, all treatments suppressed reed canarygrass stem density equally in the first year of the experiment (Table 1).

2005-Second series of treatments, second growing season

Fifty-two species were present or sampled among all treatments and replications in 2005. Of these, 48 species occurred in tillage-Vantage® plots, 28 in PGR-Vantage® plots, and 20 in plots treated with Vantage® only. As in 2004, tillage had the greatest impact on all response variables in 2005 (Table 1). Following two rounds of treatments, reed canarygrass comprised 5.3%, 48.1%, and 33.2% of the total stem density in tillage-Vantage, PGR-Vantage, and Vantage only plots, respectively. Reed canarygrass stem density in tillage-Vantage® plots was 443% lower than the standard method baseline and 581% lower than PGR-Vantage® plots (Table 1). Tillage also had the greatest effect on species abundance. Non-reed canarygrass stem density was 65% higher and species density and diversity were 127% and 51% higher in tillage-Vantage® plots than Vantage® only control plots. Similarly, non-reed canarygrass stem density, species density, and species diversity were 145%, 102%, and 53% greater in tilled plots than plots where PGR application was the pretreatment, respectively. In 2005, non-reed canarygrass stem density was 49% greater in Vantage® only control plots than PGR-Vantage® plots. All other herbaceous species responses to PGR pretreatments were similar to the standard method baseline in 2005 (Table 1).

2006-Post-treatment survey, third growing season

Fifty-three species were present or sampled among all treatments and replications in 2006. Of these, 44 species occurred in

Table 1. Summary of treatment (2004-2005) and post-treatment (2006) effects (means +/- 1SE). Means with different letters were different at $\alpha = 0.05$.

Response	2004	2005	2006
RCG Stem Density/0.25 m^2			
Till + Vantage®	22.67 (2.3) a	5.17 (1.2) a	25.75 (2.5) a
PGR + Vantage®	35.67 (3.5) a	35.25 (2.6) b	67.08 (2.2) b
Vantage® only	30.67 (2.6) a	28.08 (1.2) b	84.58 (2.3) c
Non-RCG Stem Density/0.25 m^2			
Till + Vantage®	70.58 (2.7) a	93.17 (1.9) a	181.83 (4.4) a
PGR + Vantage®	35.42 (1.6) b	38.08 (1.3) b	72.83 (2.6) b
Vantage® only	19.25 (1.5) c	56.58 (2.7) c	77.17 (4.2) b
Species Density/0.25 m^2			
Till + Vantage®	8.25 (0.5) a	10.58 (0.9) a	12.00 (1.1) a
PGR + Vantage®	5.42 (0.9) b	5.25 (0.8) b	6.50 (0.8) b
Vantage® only	3.75 (0.6) b	4.58 (0.8) b	6.42 (1.0) b
Shannon's Entropy/0.25 m^2 [$e^{H'}$/m^2]			
Till + Vantage®	1.998 [7.38] (0.06) a	2.133 [8.44] (0.08) a	1.981 [7.25] (0.04) a
PGR + Vantage®	1.575 [4.83] (0.06) b	1.394 [4.03] (0.07) b	1.472 [4.36] (0.05) b
Vantage® only	1.069 [2.91] (0.08) c	1.411 [4.10] (0.06) b	1.273 [3.57] (0.05) b

tillage-Vantage® plots, 32 in PGR-Vantage® plots, and 26 in plots treated with Vantage® only. Resurgence occurred in all treatments in the growing season when treatments were discontinued (Table 1), but the magnitude of resurgence was different among treatments. In 2006, reed canarygrass comprised 12.4% of the total stem density in tilled plots, 50.2% in plots that received a PGR pretreatment, and 52.3% of the total stem density in plots that received only herbicide application. In the third growing season, both tillage and PGR pretreatments had greater carryover effect on reed canarygrass stem density than plots treated with Vantage® only (Table 1). Reed canarygrass stem density in till-Vantage® plots was 228% lower than plots treated with Vantage® only and was 26% lower in PGR-Vantage® plots than the standard method baseline. Plots where tillage was coupled to herbicide application also had greater carryover effects on non-reed canarygrass stem density and species diversity than plots treated with only herbicide. Non-reed canarygrass stem density and species diversity were 136% and 56% greater in tilled plots than control plots (Table 1). Carryover effects from tillage pretreatments were greater than those from PGR pretreatments, with 161% lower reed canarygrass stem density, 150% greater non-reed canarygrass stem density, and 35% greater species diversity in tilled plots compared to plots where a PGR pretreatment was used (Table 1). Species density was similar among all treatments in the post-treatment growing season (Table 1).

DISCUSSION

Coupling pretreatments to herbicide application reduced reed canarygrass resurgence capacity relative to treating with only herbicide. Although there were slight improvements in reed canarygrass stem density suppression following two rounds of herbicide application coupled to PGR pretreatments, carryover effects from tillage were considerably greater than those from PGR pretreatments. Tillage-Vantage® treatments had a larger effect on reed canarygrass suppression and native species abundance than the other two treatments, and these effects persisted into the subsequent growing season after treatments were discontinued. Furthermore, the majority of reed canarygrass culms that were sampled in tilled plots were immature (non-flowering) seedlings, whereas the PGR-Vantage® and standard method control plots contained mostly mature reed canarygrass (C.A. Annen, pers. observation). Throughout the experiment, tilled plots consistently had more than twice as many abundant endpoint species (defined as species with a mean stem density greater than 3.0 stems/0.25 m^2) compared to the other treatments (Table 2). Likewise, Kilbride and Paveglio (1999), Paveglio and Kilbride (2000), and Hovick and Reinhartz (2005) reported enhanced reed canarygrass control and native species abundance when tillage was coupled to herbicide application. They also reported that the effects of these treatments lingered into subsequent post-treatment growing seasons. Tillage is known to raise buried seeds to the soil surface and remove litter,

Table 2. Summary of abundant endpoint species by year and treatment. Species were considered abundant if their mean stem density was > 3.0 stems/0.25m^2.

Treatment	Species	2004	2005	2006
Till + Vantage®	*Aster prenanthoides* Muhl.	6.3	6.8	13.8
	Carex lacustris Willd.	3.3	5.3	0.0
	Carex stricta Lam.	6.2	7.6	0.0
	Carex trichocarpa Muhl.	7.9	22.5	4.5
	Eleocharis acicularis (L.) *Roemer & Schultes.*	5.2	0.0	0.0
	Eupatorium maculatum L.	22.9	12.7	16.8
	Eupatorium perfoliatum L.	0.0	3.1	3.7
	Sagittaria latifolia Willd.	5.9	0.0	0.0
	Lycopus americanus Muhl.	0.0	0.0	31.2
	Ranunculus hispidus Michx.	0.0	0.0	7.3
	Scirpus atrovirens Willd.	0.0	0.0	4.2
PGR + Vantage®	*Aster prenanthoides* Muhl.	4.9	14.8	30.6
	Carex stricta Lam	0.0	4.8	0.0
	Carex trichocarpa Muhl.	6.4	0.0	0.0
	Impatiens capensis Meerb.	11.6	10.3	21.3
	Lycopus americanus Muhl.	0.0	0.0	7.5
Vantage® only	*Aster prenanthoides* Muhl.	0.0	3.3	11.3
	Carex stricta Lam.	0.0	8.5	25.4
	Carex trichocarpa Muhl.	7.4	8.8	0.0
	Impatiens capensis Meerb.	6.1	23.3	24.3
	Lycopus americanus Muhl.	0.0	0.0	7.5

facilitating germination. In this experiment, tillage-Vantage® treatments resulted in greater native species abundance than either PGR-Vantage® treatments or solitary use of herbicide. Competition has been shown to augment tillage-sethoxydim treatments in quackgrass stands (Harker and O'Sullivan 1993). The increased abundance of native species may have interacted with treatments to further suppress reed canarygrass and lessen resurgence, although this study was not designed to specifically address this hypothesis.

In the present study, reed canarygrass stem density reached its minimum after two rounds of pretreatments (i.e., there was a two-year treatment lag before improvements in suppression were discernable). Similarly, Lemeiux et al. (1993) reported a two-year treatment lag for quackgrass suppression with tillage-herbicide regimes, and Ma and Smith (1991) reported time lags for spring barley (*Hordeum vulgare* L.) to respond to ethephon applications. Reyes (2004) reported a viable bud density of 1100-1900 buds/m^2 in reed canarygrass stands, and pretreatment effects of tillage and PGR applications on reed canarygrass stem density may not be apparent until its rhizome bud bank begins to become depleted. Therefore, future studies involving tillage and PGR pretreatments should be conducted over multiple growing seasons because lags may occur before treatment effects are discernable.

Pretreatment with a 2:1 mixture of CCC and ethephon failed to enhance suppression of reed canarygrass stem density in both treatment years of the experiment, but led to a 26% reduction in reed canarygrass resurgence capacity by the third growing season. Harker and Taylor (1994) reported that a 2:1 mixture of CCC and ethephon enhanced the effects of sethoxydim on quackgrass, but only in years when precipitation was greater than normal, a condition that is itself suspected to ease apical dominance in rhizomes (McIntyre 2001). These results suggest that environmental factors, rather than direct action of the PGR, may have been responsible for PGR-related effects in the Harker and Taylor (1994) study, and possibly in this one as well. At this point, it is unclear whether pretreatments with a 2:1 mixture of CCC and ethephon have practical utility for enhanced reed canarygrass control with Vantage® herbicide. Molecular studies are necessary to determine if the PGR mixture used in this experiment affects reed canarygrass rhizomes. Moreover, the cost for two rounds of Vantage® application coupled to PGR pretreatment totaled $215 [2006 U.S. dollars] per ha for chemicals alone (labor and equipment add more to the cost of this treatment); some practitioners may not feel that these expenses are justified by an additional 26% suppression in reed canarygrass stem density, especially when tillage pretreatments were more than twice as effective and considerably less expensive (the cost for two rounds of the tillage-Vantage® regime was approximately $57 per ha (not including labor)). Two rounds of Vantage® application (chemicals only) cost approximately $40 per ha (price includes herbicide additives but not labor) at the 4.45 L/ha spray rate.

Although ethephon/CCC applications are expensive and require multiple-year applications, this no-till approach to overcoming apical dominance merits further investigation. A growing body of literature suggests that ontogenic and metabolic sensitivity are prerequisites for a hormone or exogenous hormone analog (PGR) to elicit physiological and developmental effects in plants (see Trewavas 1981; Weyers and Patterson 2001 for reviews). Unfortunately, there are no data documenting the sensitivity of reed canarygrass rhizomes to CCC or ethephon in the literature. Molecular studies on reed canarygrass sensitivity to PGRs would be useful for narrowing treatment windows.

Several variations in application procedures (such as matching applications to canarygrass rhizome sensitivity) are possible and should be investigated in greater detail before the potential of 2:1 mixtures of CCC and ethephon for enhanced reed canarygrass control can be thoroughly evaluated. Ma and Smith (1991) reported significant interactions between time-of-application and PGR effectiveness in spring barley. Multiple applications within the same growing season may be required to overcome apical rhizome apical dominance and diminish resurgence capacity. Furthermore, a variety of additional plant growth regulators are commercially available and should also be tested.

Utility of PGRs may be further complicated by genotypic variability in reed canarygrass populations, and genotypic identity may play a role in sensitivity to this type of chemical treatment. Genetic variability is suspected to be high between and within reed canarygrass stands (Morrison and Molofsky 1998; Morrison and Molofsky 1999; Gifford et al. 2002). Ma and Smith (1991) reported that differences in sensitivity to PGRs existed among cultivars of barley, and Hovin et al. (1973) reported significant effects of clones on the effectiveness of ethephon on reed canarygrass culm segments.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Despite its drawbacks, tillage-Vantage® regimes offer greater potential for reed canarygrass abatement and native species restoration than solitary herbicide use. Coupling tillage to herbicide application led to enhanced suppression of reed canarygrass stem density along with improvements in native species abundance, but lag times were experienced before these improvements appeared. No-till methods of short-circuiting apical dominance with PGRs to make reed canarygrass more susceptible to chemical control have theoretical and practical potential, and merit further investigation.

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Endnote: Vantage® herbicide is currently marketed as Sethoxydim E Pro®.

LITERATURE CITED

Annen, C.A., R.W. Tyser, and E.M. Kirsch. 2005. Effects of a selective herbicide, sethoxydim, on reed canarygrass. Ecological Restoration 23:99-102.

Apfelbaum, S.I., and C.E. Sams. 1987. Ecology and control of reed canarygrass (*Phalaris arundinacea* L.). Natural Areas Journal 7:9-17.

Banks, P.A., and T.N. Tripp. 1983. Control of johnsongrass (*Sorghum halpense*) in soybeans (*Glycine max*) with foliar-applied herbicides. Weed Science 31:628-633.

Beckett, T.H., E.W. Stoller, and L.E. Bode. 1992. Quizalofop and sethoxydim activity as affected by adjuvants and ammonium fertilizers. Weed Science 40:12-19.

Brummer, J.E., J.T. Nichols, R.K. Engel, and K.M. Eskridge. 1994. Efficiency of different quadrat sizes and shapes for sampling standing crop. Journal of Range Management 47:84-89.

Calkins, J.B., B.T. Swanson, and D.L. Newman. 1996. Weed control strategies for field grown herbaceous perennials. Journal of Environmental Horticulture 14:221-227.

Claus, J.S., and R. Behrens. 1976. Glyphosate translocation and quackgrass rhizome bud kill. Weed Science 24:149-152.

Cline, M.G. 1991. Apical dominance. The Botanical Review 57:318-358.

Evans, D.G., and M.H. Miller. 1990. The role of external mycelial network in the effect of soil disturbance upon vesicular-arbuscular mycorrhizal colonization of maize. New Phytologist 114:65-71.

Galatowitsch, S.M., D.C. Whited, R. Lehtinen, J. Husveth, and K. Schik. 2000. The vegetation of wet meadows in relation to their land-use. Environmental Monitoring and Assessment 60:121-144.

Gifford, A.L.S., J.B. Ferdy, and J. Molofsky. 2002. Genetic composition and morphological variation among populations of the invasive grass, *Phalaris arundinacea*. Canadian Journal of Botany 80:779-785.

Gleason, H.A., and A. Cronquist. 1991. Manual of Vascular Plants of Northeastern United States and Adjacent Canada. New York Botanical Garden, New York.

Harker, K.N., and J. Dekker. 1988. Effects of phenology on translocation patterns of several herbicides in quackgrass (*Agropyron repens*). Weed Science 36:463-472.

Harker, K.N., and P.A. O'Sullivan. 1993. Herbicide comparisons on quackgrass (*Elytrigia repens*) within different crop competition and tillage conditions. Weed Science 41:94-99.

Harker, K.N., and J.S. Taylor. 1994. Chlormequat chloride (CCC) pretreatments may enhance quackgrass (*Elytrigia repens*) control with sethoxydim. Weed Technology 8:499-507.

Harker, K.N., and W.H. Vanden Born. 1997. Glyphosate or sethoxydim for quackgrass (*Elytrigia repens*) control in two tillage regimes. Weed Science 45:812-823.

Heide, O.M. 1994. Control of flowering and reproduction in temperate grasses. New Phytologist 128:347-362.

Hicks, C.P., and T.N. Jordan. 1984. Response of bermudagrass (*Cynodon dactylon*), quackgrass (*Agropyron repens*), and wirestem muhly (*Muhlenbergia frondosa*) to postemergence grass herbicides. Weed Science 32:835-841.

Ho, Y.B. 1979. Growth, chlorophyll and mineral nutrient studies on *Phalaris arundinacea* L. in three Scottish lochs. Hydrobiologia 63:33-43.

Holt, I.V. 1954. Initiation and development of the inflorescences of *Phalaris arundinacea* L. and *Dactylis glomerata* L. Iowa State College Journal of Science 28:603-621.

Hovick, S.M., and J.A. Reinartz. 2005. Combination of treatments influence survival of woody species planted to suppress reed canarygrass (Wisconsin). Ecological Restoration 23:126.

Hovin, A.W., B.E. Beck, and G.C. Marten. 1973. Propagation of reed canarygrass (*Phalaris arundinacea* L.) from culm segments. Crop Science 13:747-749.

Johnson, B.G., and K.P. Buchholtz. 1962. The natural dormancy of vegetative buds on the rhizomes of quackgrass. Weeds 10:53-57.

Kilbride, K.M., and F.L. Paveglio. 1999. Integrated pest management to control reed canarygrass in seasonal wetlands of southwestern Washington. Wildlife Society Bulletin 27:292-297.

Klopatek, J.M., and F.W. Stearns. 1978. Primary productivity of emergent macrophytes in a Wisconsin freshwater marsh ecosystem. The American Midland Naturalist 100:320-332.

Landgraff, A., and O. Junttila. 1979. Germination and dormancy of reed canary-grass seeds (*Phalaris arundinacea*). Physiologia Plantarum 45:96-102.

Lavergne, S., and J. Molofsky. 2006. Control strategies for the invasive reed canarygrass (*Phalaris arundinacea* L.) in North American wetlands: the need for an integrated management plan. Natural Areas Journal 26:208-214.

Leakey, R.B., R.J. Chancellor, and D. Vince-Prue. 1975. Parental factors in dominance of lateral buds on rhizomes of *Agropyron repens* (L.) Beauv. Planta 123:267-274.

Lemieux, C., D.C. Cloutier, and G.D. Leroux. 1993. Distribution and survival of quackgrass (*Elytrigia repens*) rhizome buds. Weed Science 41:600-606.

Lesica, P., and B. Martin. 2004. Study evaluates methods for controlling reed canarygrass in sedge meadows (Montana). Ecological Restoration 22:227-228.

Ma, B.L., and D.L. Smith. 1991. Apical development of spring barley in relation to chlormequat and ethephon. Agronomy Journal 83:270-274.

MacArthur, R.H. 1965. Patterns of species diversity. Biological Review 40:510-533.

Magurran, A.E. 1988. Ecological Diversity and Its Measurement. Princeton University Press, Princeton, N.J.

Maurer, D.A, R. Linding-Cisneros, K.J. Werner, S. Kercher, R. Miller, and J.B. Zedler. 2003. The replacement of wetland vegetation by reed canarygrass (*Phalaris arundinacea*). Ecological Restoration 21:116-119.

McIntyre, G.I. 1969. Apical dominance in the rhizome of *Agropyron repens*. Evidence of competition for carbohydrates as a factor in the mechanism of inhibition. Canadian Journal of Botany 47:1189:1197.

McIntyre, G.I. 1971. Apical dominance in the rhizome of *Agropyron repens*. Some factors affecting the degree of dominance in isolated rhizomes. Canadian Journal of Botany 49:99-109.

McIntyre, G.I. 2001. Control of plant development by limiting factors: a nutritional perspective. Physiologia Plantarum 113:165-175.

Moore, T.C. 1989. Biochemistry and Physiology of Plant Hormones, 2nd ed. Springer-Verlag, New York.

Morrison, S.L., and J. Molofsky. 1998. Effects of genotypes, soil moisture, and competition on the growth of an invasive grass, *Phalaris arundinacea* (reed canarygrass). Canadian Journal of Botany 76:1939-1946.

Morrison, S.L., and J. Molofsky. 1999. Environmental and genetic effects on the early survival and growth of the invasive grass *Phalaris arundinacea*. Canadian Journal of Botany 77:1447-1453.

Ott, R.L., and M. Longnecker. 2001. Statistical Methods and Data Analysis, 5th ed. Duxbury, Australia.

Paveglio, F.L., and K.M. Kilbride. 2000. Response of vegetation to control of reed canarygrass in seasonally managed wetlands of southwestern Washington. Wildlife Society Bulletin 28:730-740.

Plant Growth Regulation Society of America. 1990. Plant growth regulator handbook of the Plant Growth Regulation Society of America, 3rd ed. Plant Growth Regulation Society of America, Ithaca, N.Y.

Reinhardt, C., and S.M. Galatowitsch. 2004. Best Management Practices for the Invasive *Phalaris arundinacea* L. (reed canary grass) in Wetland Restorations. Publication, Minnesota Department of Transportation, Minneapolis.

Reyes, C.M. 2004. The feasibility of using prescribed burning to control reed canarygrass (*Phalaris arundinacea* L.) populations in Wisconsin wetlands. M.S. thesis, University of Wisconsin, Madison.

Robertson, J.M., J.S. Taylor, K.N. Harker, R.N. Pocock, and E.C. Yeung. 1989. Apical dominance in rhizomes of quackgrass (*Elytrigia repens*): inhibitory effect of scale leaves. Weed Science 37:680-687.

Shoaf, A.R., and W.C. Carlson. 1992. Stability of sethoxydim and its degradation products in solution, in soil, and on surfaces. Weed Science 40:384-389.

Soule, J.D., and J.K. Piper. 1992. Farming in Nature's Image: an Ecological Approach to Agriculture. Island Press, Washington, D.C.

Strand, L.L. 1993. Integrated Pest Management for Strawberries. Publication 3351, University of California Division of Agriculture and Natural Resources, Oakland.

Taylor, J.S., J.M. Robertson, K.N. Harker, M.K. Bhalla, E.J. Daly, and D.W. Pearce. 1995. Apical dominance in rhizomes of quackgrass (*Elytrigia repens*): The effect of auxin, cytokinins, and abscissic acid. Canadian Journal of Botany 73:307-314.

Trewavas, A. 1981. How do plant growth substances work? Plant, Cell, and Environment 4:203-228.

Vivian-Smith, G. 1997. Microtopographic heterogeneity and floristic diversity in experimental wetland communities. Journal of Ecology 85:71-82.

Wall, D.A., and M.A.H. Smith. 2000. Quackgrass (*Elytrigia repens*) management in flax (*Linum usitatissimum*). Canadian Journal of Plant Science 80:411-417.

Werner, K.J., and J.B. Zedler. 2002. How sedge meadow soils, microtopography, and vegetation respond to sedimentation. Wetlands 22:451-466.

Weyers, J.D.B., and N.W. Paterson. 2001. Plant hormones and the control of physiological processes (Tansley Review no. 129). New Phytologist 152:375-407.

Wilcox, J.C. 2004. Challenges of Replacing Reed Canary Grass (*Phalaris arundinacea* L.) with Native Species. M.S. thesis, University of Wisconsin, Madison.