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Smooth scouringrush (*Equisetum laevigatum*) control with glyphosate in eastern Washington

Drew J. Lyon[1] and Mark E. Thorne[2]

[1]Professor, Department of Crop and Soil Sciences, Washington State University, Pullman, WA, USA and [2]Associate in Research, Department of Crop and Soil Sciences, Washington State University, Pullman, WA, USA

Research Article

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Author for correspondence:
Drew J. Lyon, Professor, Washington State University, PO Box 646420, Pullman, WA 99164-6420. E-mail: drew.lyon@wsu.edu

Abstract

Smooth scouringrush has invaded no-till production fields across the US Pacific Northwest. The ability of *Equisetum* species to take up and accumulate silica on the epidermis and in cell walls may affect herbicide uptake. The objectives of this study were to measure the silica concentration in smooth scouringrush stems over time, and to determine how time of application affects the efficacy of glyphosate for smooth scouringrush control, with and without the addition of an organosilicone surfactant (OSS). Field studies were conducted at three sites in eastern Washington from 2019 to 2021. Three herbicide treatments (no herbicide, glyphosate, and glyphosate + OSS) were applied at four application times (May, June, July, and August) in 2019 fallow. The silica content of smooth scouringrush stems increased over the course of the 2019 growing season at all three sites. In 2020, smooth scouringrush stem densities were reduced when the 2019 herbicide treatments were applied in late June (12% of no herbicide density) compared to late July (24%) or August (30%). Smooth scouringrush stem densities at all three sites, in both 2020 and 2021, were reduced in the glyphosate + OSS treatment compared to glyphosate alone. In 2021, 2 yr after herbicide application, there was no effect of application timing for the glyphosate treatment without OSS, but stem densities were reduced when glyphosate + OSS was applied in late June (1%) compared with applications in late July (26%) or late August (21%). It is not clear if the cause of reduced glyphosate efficacy with late July and late August applications is the result of increased silica content in smooth scouringrush stems over time. Maximum glyphosate efficacy on smooth scouringrush was achieved with an application in late June and with the addition of an OSS. Control of smooth scouringrush with glyphosate + OSS can be sustained for at least 2 yr after application.

Introduction

Smooth scouringrush is the only *Equisetum* species endemic to North America (Hauke 1960). The aerial stems of smooth scouringrush die back in fall and reemerge in spring. All *Equisetum* species, also known as horsetails, are herbaceous perennials with a very extensive underground rhizome system (Husby 2013). The rhizome system of a colony of field horsetail (*Equisetum arvense* L.) was found to have five successive horizontal layers of rhizomes, connected by vertical rhizomes, in the top 2 m of soil, which was the depth at which the excavators stopped digging and not the maximum depth of rhizome penetration (Golub and Whetmore 1948). The deep, extensive rhizome system gives plants the ability to survive environmental disturbances such as plowing, burial, fire, and drought (Husby 2013). *Equisetum* species are commonly found growing in wetlands, ditches, moist woods, and along roadsides when sufficient groundwater is present. They are commonly found growing in the inland Pacific Northwest (PNW). With the widespread adoption of no-till farming in the PNW (Huggins and Reganold 2008), smooth scouringrush has invaded production fields across the region.

Bernards et al. (2010) evaluated 24 herbicide active ingredients for efficacy on scouringrush (*Equisetum hyemale* L.). Chlorsulfuron and dichlobenil were the only two that provided commercially acceptable control of scouringrush. Only chlorsulfuron is labeled for use in wheat production systems. Kerbs et al. (2019) found chlorsulfuron + MCPA-ester to be a commercially acceptable treatment for smooth and intermediate (*Equisetum* × *ferrissii* Clute) scouringrush control in winter wheat–fallow cropping systems in the PNW.

Unfortunately, chlorsulfuron has a half-life in soil that ranges from 88.5 d at pH 6.2 to 144 d at pH 8.1 at 20 C (Thirunarayanan et al. 1985). This relatively long half-life limits crop rotation flexibility. Growers are interested in other herbicide options that do not constrain crop rotation options. Glyphosate has no soil residual activity, and its systemic activity provides excellent control of many perennial weeds (Baylis 2000). In glasshouse experiments with field horsetail, Coupland and Peabody (1981) reported that ^{14}C-glyphosate was translocated to areas of meristematic activity in the shoot and rhizome apices and nodes; however, the amounts of radioactivity recovered from the roots and rhizomes were small relative to the amount applied. Kerbs et al. (2019) did not achieve commercially acceptable control of smooth scouringrush with glyphosate, glyphosate + saflufenacil, or glyphosate + glufosinate. However, their maximum glyphosate use rate was 1.26 kg ha^{-1}. In preliminary field studies, glyphosate applied at 3.78 kg ha^{-1} provided effective control of smooth scouringrush 1 yr after application, but results varied between locations and time of application (ME Thorne, personal communication). The addition of organosilicone surfactants (OSSs), which are not commonly used with herbicides in the wheat production areas of the PNW, to glyphosate improved glyphosate efficacy and reduced variability of control between locations and time of application.

Equisetum species can take up and accumulate silica, resulting in the highest silica concentrations among vascular plants (Husby 2013). Silica accumulates on the epidermis and is incorporated into cell walls. The outer layer of silica on stems may provide protection from insect feeding and fungal diseases, and reduce water loss through the epidermis. Sapei (2007) reported an increase in silica accumulation in scouringrush from about 6% during early summer growth to about 14% in older stems in the fall. This increase in silica concentration over time, if present in smooth scouringrush, might help explain the variability in glyphosate efficacy observed by Thorne. The objectives of this study were to measure the silica concentration in smooth scouringrush stems over time and to determine how the time of application affects the efficacy of glyphosate, with and without the addition of an OSS, for smooth scouringrush control.

Materials and Methods

Three field sites in eastern Washington containing smooth scouringrush were selected for this study (Table 1). Each site was managed in a no-till fallow system following a previous wheat crop and had been previously sprayed with glyphosate to control winter annual weeds and volunteer wheat prior to emergence of smooth scouringrush. Sites near Steptoe and Edwall, WA were in a 3-yr rotation of winter wheat/spring wheat/fallow. The Steptoe rotation differs from Edwall in that the ground is plowed following the winter wheat crop to facilitate planting the following spring wheat crop, whereas the Edwall site is managed in continuous no-till. The Pullman site is generally managed in a winter wheat/spring wheat/pulse crop rotation; however, the field was no-till fallowed in 2019 following a crop of chickpea (*Cicer arietinum* L.) in 2018. In 2019, initial smooth scouringrush mean densities ± their standard deviations were 80 ± 49, 150 ± 68, and 442 ± 98 stems m^{-2} at Edwall, Pullman, and Steptoe, respectively.

Experimental design at each location was a split-plot randomized complete block, with three herbicide sub-plot treatments per main plot, and four application times as the main-plot effect. The purpose of this design was to contain variability in stem density within main plots to improve comparisons between treated and nontreated sub-plots. Blocks were replicated four times at each location. Sub-plot treatments were glyphosate (RT 3®, containing 660 g L^{-1} of glyphosate in the form of its potassium salt; Bayer AG, 51368 Leverkusen, Germany) with no added surfactant, glyphosate with an OSS (Silwet® L77; Helena Chemical Co., Collierville, TN), and no herbicide. All treatments were applied in 2019 beginning in late May through late August. At Edwall, treatments were applied May 22, June 25, July 25, and August 29. At Pullman, treatments were applied May 28, July 2, July 25, and August 29. At Steptoe, applications were applied June 11, July 2, July 25, and August 28. By late May, many smooth scouringrush stems contained spore-bearing structures, called strobili, at the top of the stems. We did not measure plant biomass in these trials, but maximum stem height at the time of applications ranged from 50 to 60 cm. Main plots at Steptoe and Edwall measured 3 by 9.1 m with sub-plots measuring 3 by 3 m. Because the area at Pullman was limited, main plots were 2.1 by 4.6 m with 2.1- by 1.5-m sub-plots. Herbicides were applied with a hand-held spray boom with six or four TeeJet® (Spraying Systems Co., Glendale Heights, IL) XR11002 nozzles on 50-cm spacing and pressurized with a CO_2 backpack at 4.7 km h^{-1}. Spray output was 140 L ha^{-1} at 172 kPa. In October of 2019, winter wheat was seeded at each trial site by the respective cooperating grower. In April 2021, spring wheat was planted at Pullman and Edwall, and spring barley was planted at Steptoe. All crops were harvested at each farm during August of 2020 (winter wheat) and 2021, but exact dates for each field are unknown. Stem counts in the crops were made prior to crop harvest so that the plot area could be harvested along with the surrounding field. This ensured that the plot area would not be treated differently than normal.

Table 1. Site and soil characteristics.

Site	Latitude, longitude	Silt loam soil series	Soil surface (0–15 cm) pH	Soil surface (0–15 cm) Organic matter content
				%
Edwall, WA	47.4691°N, 117.9257°W	Broadax	6.0	3.1
Pullman, WA	46.7586°N, 117.1968°W	Caldwell	5.5	2.1
Steptoe, WA	47.0039°N, 117.3912°W	Palouse-Thatuna	6.6	2.3

At each herbicide application timing in 2019, samples of approximately 20 smooth scouringrush stems were collected from the nontreated check subplot in each main plot. The samples were bagged, oven-dried at 60 C for a minimum of 72 h, and analyzed by Northwest Agricultural Consultants, Kennewick, WA, for silica concentration. Samples from the Pullman site were analyzed using a wet oxidation method (Haysom and Ostatek-Boczynski 2006). Because of damage to analytical equipment, the Edwall and Steptoe samples were analyzed using hydrochloric acid digestion followed by thermal oxidation (Neumann et al. 2011).

Herbicide efficacy was evaluated by counting smooth scouringrush stem density in all sub-plots in July 2020, 1 yr after treatment, and in June 2021, 2 yr after treatment. Stem density in 2020 was counted in one 0.25-m^2 quadrat per sub-plot at Pullman and Edwall and one 1-m^2 quadrat per sub-plot at Steptoe. In 2021, all counts were made in one 0.25-m^2 quadrat per sub-plot, but all counts were scaled to a 1-m^2 area for analysis. For analysis, sub-plot counts were compared within each main plot as percent density compared to the nontreated check. The density for each herbicide treatment was divided by the density of the nontreated check, thus producing an unbounded continuous variable with a true zero. Therefore, a percentage value ranging between 0 and 99.9 would indicate some level of control compared with the nontreated check, with a zero indicating complete control. Conversely, if the percentage value was >100, the treatment density would have been greater than the nontreated check. Stem biomass was not included in this study, because the focus was on how these treatments affect stem density in the following years, not the year of application. Furthermore, we believed it would have been inappropriate to change the dynamic between the nontreated and treated sub-plots by removing plant material at the time of application.

Statistical Analysis

Silica percent data were converted to decimal proportions and first analyzed using PROC GLIMMIX to evaluate the fixed effects of TIME and LOC with random effects LOC by REP. Because of an interaction between TIME and LOC ($P = 0.002$), TIME was analyzed separately by each LOC; however, it was found that the Edwall and Steptoe data were not different from each other and were combined, whereas the Pullman data differed from both Edwall and Steptoe (data not shown). The combined Edwall and Steptoe data, as percentages, were then regressed over TIME with a quadratic model using PROC REG in SAS. The Pullman data were regressed over time with a linear model. Standard errors of the predicted means were calculated by PROC REG in SAS. All parameters reached the acceptance level of $P \leq 0.05$.

For statistical analysis of stem densities, all percentage differences were divided by 100 and then fourth-root (1/4 power) transformed to decrease heteroscedasticity and to improve normality resulting from a range of treatment efficacies. Improvement was assessed by visually analyzing Q-Q plots and frequency histograms of the studentized residuals. Data were analyzed using PROC GLIMMIX in SAS® (SAS Institute 2019) with location (LOC), time of application (TIME), and herbicide treatment (HERB) as fixed effects. Random effects were replication (REP)-by-TIME nested within LOC. In all analyses, the LaPlace method was used for maximum likelihood estimation, and degrees of freedom were assigned with the containment method. Treatment lsmeans were compared only when the overall treatment effect was significant (DIFF, $\alpha = 0.05$). Lsmeans were back-transformed and converted back to percentages for presentation.

Results and Discussion

The silica content of smooth scouringrush stems increased over the course of the 2019 growing season at all three sites (Figure 1). Average silica content increased from about 5.8% to about 8.6% from late May to late August at Edwall and Steptoe. The data were best fit by the quadratic equation $y = -0.34x^2 + 2.62x + 3.45$ (Adj. $R^2 = 0.69$; $P = 0.013$). At Pullman, average silica content increased from about 3.1% to 6.9%. The data were best fit by the linear equation $y = 1.28x + 1.79$ ($R^2 = 0.6$; $P < 0.001$). These results are similar to those reported by Sapei (2007) in scouringrush, although silica concentrations increased from 6% to 14% in that study.

Silica is a major component of loess soils in the Columbia Plateau and Palouse prairie regions of eastern Washington where dryland farming occurs, with silicon dioxide concentrations exceeding 70% (Sweeney et al. 2007). Inland PNW loess soils are rich in silica, but techniques for assessing amounts of available silica are not well developed (Crusciol et al. 2018). Additionally, smooth scouringrush has a deep, extensive root system (Golub and Whetmore 1948) that can access water and nutrients––also silica––from soil depths >2 m, likely lessening the value of surface soil samples in explaining differences in plant silica content across locations. Consequently, we did not analyze the soil for available silica.

Smooth Scouringrush Stem Densities

In 2020, the year after glyphosate applications in fallow, there was a significant main effect of application timing on smooth scouringrush density ($P = 0.039$) with no significant interactions with site ($P = 0.164$), herbicide treatment ($P = 0.461$), or site-by-herbicide treatment ($P = 0.169$). Smooth scouringrush densities were reduced when herbicide treatments were applied in late June compared to late July or August (Table 2). Late May applications resulted in stem densities that were not different from any of the other application times.

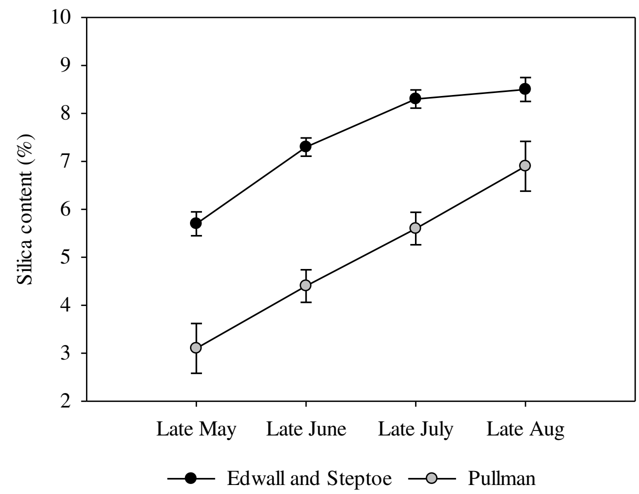

Figure 1. Silica content in smooth scouringrush stems from late May through August. Edwall and Steptoe data are combined and fit with the quadratic equation $y = -0.34x^2 + 2.62x + 3.45$ (Adj. $R^2 = 0.69$; $P = 0.013$). Pullman data are fit with the linear equation $y = 1.28x + 1.79$ ($R^2 = 0.6$; $P < 0.001$). Error bars are standard errors of the predicted means.

There was a significant site-by-herbicide treatment interaction in 2020 ($P < 0.001$) and 2021 ($P = 0.016$), 2 yr after the 2019 glyphosate applications in fallow. Means are presented separately by site for 2020 and 2021 (Table 3). Although smooth scouringrush stem densities at all three sites and both years were reduced in the glyphosate + OSS treatment, compared to glyphosate alone, the relative difference in stem densities between the two treatments was greater at Pullman than at Edwall or Steptoe. This was true in both 2020 and 2021. The reason for this difference between sites is not evident.

In 2021, there was a significant time-by-herbicide treatment interaction ($P = 0.001$). There was no effect of application timing for the glyphosate treatment without OSS, but stem densities were reduced when glyphosate + OSS was applied in late June compared with late July or late August applications (Table 4). The observed response in 2021 to the glyphosate + OSS treatment is similar to the response observed in 2020 for both herbicide treatments (Table 2). This reinforces both the importance of herbicide application timing and the use of an OSS with glyphosate for the control of smooth scouringrush.

It is not clear from this research if the cause of reduced glyphosate efficacy with late July and late August applications compared to late June applications is the result of increased silica content in smooth scouringrush stems over time (Figure 1) or some other factor. For example, increased heat and reduced relative humidity in July and August compared to May and June (Figure 2), may result in more rapid droplet evaporation and reduced uptake of glyphosate. Organosilicone surfactants are known to reduce surface tension of droplets and increase droplet spread, which results in faster droplet evaporation (Li et al. 2019). However, Field and Bishop (1988) observed rapid infiltration of glyphosate through stomata of perennial ryegrass (*Lolium perenne* L.) in solutions containing an OSS. This rapid infiltration of glyphosate solutions containing

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Table 2. Smooth scouringrush control as percent density of nontreated check 1 yr after treatment with glyphosate or glyphosate plus an organosilicone surfactant (OSS) applied at four different timings and averaged across three sites in eastern Washington. Percentages below 100 reflect a reduction in density.

Herbicide application timing[a]	Control[b]	Nontreated check mean stem density[c]
	% of nontreated check	No. of stems m^{-2} ± SD
Late May/early June	13 ab	283 ± 161
Late June/early July	12 b	248 ± 143
Late July	24 a	248 ± 98
Late August	30 a	225 ± 113

[a]Glyphosate applied at 2.52 kg ae ha^{-1}; OSS applied at 0.25% v/v.
[b]Means within a column followed by the same letter are not different at $\alpha = 0.05$.
[c]Nontreated check mean ± standard deviation (SD) provided as a reference for the nontreated stem density at each application timing.

Table 3. Smooth scouringrush control as percent density of nontreated check 1 and 2 yr after treatment with glyphosate or glyphosate plus an organosilicone surfactant (OSS) averaged across four application timings at three sites in eastern Washington. Percentages below 100 reflect a reduction in density.

	Site[b]					
	Edwall		Pullman		Steptoe	
Treatment[a]	2020	2021	2020	2021	2020	2021
	% of nontreated check					
Glyphosate	58 a	84 a	28 a	42 a	53 a	54 a
Glyphosate + OSS	21 b	40 b	0 b	2 b	11 b	9 b
	No. of stems m^{-2}					
Nontreated check[c]	289 ± 127	177 ± 92	141 ± 92	148 ± 84	323 ± 86	259 ± 99

[a]Glyphosate applied at 2.52 kg ae ha^{-1}; OSS applied at 0.25% v/v.
[b]Means within a column followed by the same letter are not different at $\alpha = 0.05$.
[c]Nontreated check mean ± standard deviation (SD) provided as a reference for the nontreated population density at each site.

Table 4. Smooth scouringrush control as percent density of nontreated check 2 yr after treatment with glyphosate or glyphosate plus an organosilicone surfactant (OSS) applied at four different timings and averaged across three sites in eastern Washington. Percentages below 100 reflect a reduction in density.

	Control[b]		
Herbicide application timing[a]	Glyphosate	Glyphosate + OSS	Nontreated check mean stem density[c]
	— % of nontreated check —		No. stems m^{-2} ± SD
Late May/early June	44	10 Ab	193 ± 101
Late June/early July	59	1 B	164 ± 73
Late July	48	26 A	242 ± 127
Late August	86	21 A	178 ± 88

[a]Glyphosate applied at 2.52 kg ae ha^{-1}; OSS applied at 0.25% v/v.
[b]Means within a column followed by the same letter are not different at $\alpha = 0.05$.
[c]Nontreated check mean ± standard deviation (SD) provided as a reference for the nontreated population density at each site.

an OSS may at least partially explain the increased efficacy of the glyphosate + OSS treatment compared to glyphosate alone on smooth scouringrush stem density in this study. Further research is required to determine if this is the case.

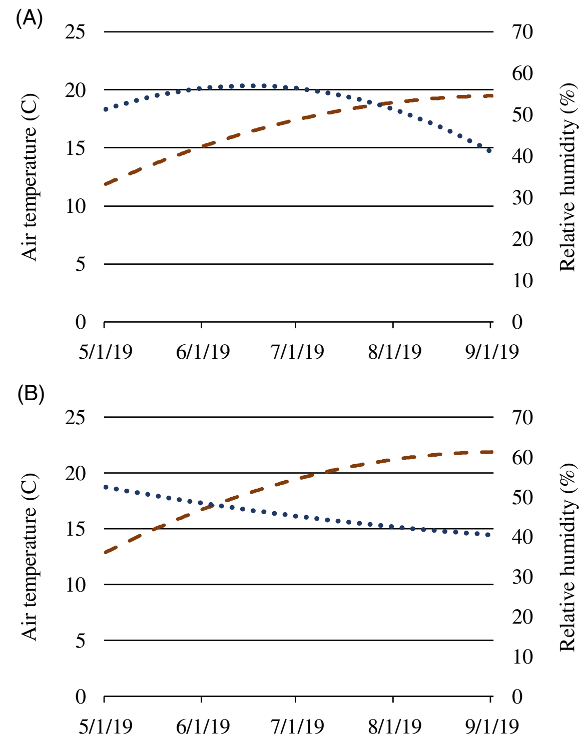

Figure 2. Quadratic trendlines comparing average air temperature (---) and relative humidity (• • •) from May 1 through August 31, 2019 from Washington State University AgWeatherNet (https://weather.wsu.edu/) stations near Pullman, WA (A) and Harrington, WA (B). The Pullman station is closest to the Pullman and Steptoe field sites, whereas the Harrington station is closest to the Edwall field site.

The effect of increasing silica content in smooth scouringrush stems through the growing season (Figure 1) on glyphosate efficacy requires further study. Husby (2013) suggested that the outer layer of silica on stems may provide protection from insect feeding and fungal diseases, as well as reduce water loss through the epidermis, but research is lacking on the effects of silica on the uptake of herbicides. However, glyphosate efficacy on smooth scouringrush the year following application was greater when applied in late June than in late July or August. This same effect of herbicide application timing was also observed 2 yr after glyphosate application, but only when an OSS was added. Glyphosate efficacy on smooth scouringrush was always improved in this study by the addition of an OSS. Whether this increased efficacy with OSS was the result of increased glyphosate uptake through the epidermis, stomata, or both is not known. Although the addition of OSS to glyphosate increased efficacy in this study, under particularly hot and dry environmental conditions, it is possible that the addition of an OSS to glyphosate, which increases droplet spread resulting in faster droplet evaporation (Li et al. 2019), could result in reduced efficacy compared to glyphosate without an OSS.

The results of this study suggest that maximum glyphosate efficacy on smooth scouringrush is achieved by making the application in late June and adding an OSS. Control of smooth scouringrush with glyphosate + OSS can be sustained for at least 2 yr after application. More research is needed to determine if or how stem silica content affects glyphosate efficacy.

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