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Smooth scouringrush (*Equisetum laevigatum*) control with glyphosate is affected by surfactant choice and application time

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Abstract

Smooth scouringrush is a creeping perennial with a high silica content in stems that may impede herbicide uptake. Smooth scouringrush has become a troublesome weed in no-till cropping systems across eastern Washington. In previous field studies, glyphosate provided inconsistent control of smooth scouringrush. The objective of this study was to determine if the addition of an organosilicone surfactant to glyphosate would improve the efficacy and consistency of control through stomatal flooding. To test this hypothesis, glyphosate was applied at three field sites at 3.78 kg ae ha^{-1} alone, with an organosilicone surfactant (OS1 or OS2), an organosilicone plus nonionic surfactant blend, or an alcohol-based surfactant applied during the day or at night. Stem counts were recorded 1 yr after herbicide applications. Five of the six effective treatments observed across the three study sites included organosilicone surfactant or an organosilicone plus nonionic surfactant blend. At two sites, when there was a difference in efficacy between application times; daytime applications were more effective than nighttime applications. These results support the hypothesis of stomatal flooding as a likely mechanism for enhanced efficacy of glyphosate with the addition of an organosilicone surfactant. However, at one site, the treatments containing organosilicone surfactant were more efficacious when applied at night than during the day. At this site, high daytime temperatures and low relative humidity may have resulted in rapid evaporation of spray droplets. The addition of an organosilicone surfactant to glyphosate is recommended for smooth scouringrush control, and daytime treatments are preferred but should be applied when temperatures and humidity are not conducive to rapid droplet drying. Further research is necessary to confirm that stomatal flooding is responsible for improved glyphosate efficacy.

Introduction

Smooth scouringrush is one of 15 living *Equisetum* species (family Equisetaceae). The genus belongs to the ancient plant group Sphenophyta, which arose during the upper Devonian (about 400 million years ago) (Husby 2013; Scagel et al. 1984). *Equisetum* species are all herbaceous creeping perennials with highly reduced leaves and the capability to reproduce either sexually via spores or asexually by rhizomes. Smooth scouringrush stems die back every winter and emerge anew in spring. Stems are rich in silica that accumulates in the epidermis (Sapei et al. 2007). It has been proposed that silica in *Equisetum* species is a substitution for lignin in higher plants that provides mechanical support to stems (Husby 2013; Yamanaka et al. 2012).

Underground rhizome systems are multi-tiered and extensive, with multiple horizontal layers (Golub and Whetmore 1948). The deep, extensive rhizome system allows plants to survive a wide range of conditions and disturbances (e.g., plowing, fire, drought) (Husby 2013). In eastern Washington, smooth scouringrush and other *Equisetum* species are primarily associated with moist habitats such as wetlands, roadsides, field margins, and ditches where water tends to stay on the surface for prolonged periods of time or the groundwater level is near the soil surface. However, with the adoption of conservation tillage systems and chemical fallow in winter wheat (*Triticum aestivum* L.) production systems of eastern Washington (Huggins and Reganold 2008), smooth scouringrush has expanded its habitat into crop production fields.

Two direct control measures for smooth scouringrush management are extensive tillage and chlorsulfuron (WSSA Group 2) (Bernards et al. 2010; Kerbs et al. 2019). Tillage, especially if extensive, is not a viable option in no-till cropping systems, furthermore, the relatively long half-life for chlorsulfuron in soil limits crop rotation options (Brewster and Appleby 1983; Thirunarayanan et al. 1985). Consequently, growers are interested in alternative herbicide options for smooth scouringrush control in no-till cropping systems.

Table 1. Weather conditions at the time of herbicide applications to smooth scouringrush in chemical fallow at three eastern Washington sites (Malden 2020, Reardan 2021, and Rock Lake 2021).

Site	Application date/time	Air temperature	Relative humidity	Wind speed/direction
		C	%	m s^{-1}/compass
Malden	Jul 6/12:00–12:30	27	30	0.4–1.3 SW
Malden	Jul 6/9:40–10:00	21	35	0.4–0.9 SW
Rock Lake	Jul 12/9:30–10:00	27	31	0.9–2.2 SE
Rock Lake	Jul 12/23:30–23:50	23	32	0.4–1.3 NW
Reardan	Aug 10/10:40–11:00	25	31	1.8–3.6 SW
Reardan	Aug 9/20:40–21:00	18	45	0.9 SW

In previous studies, glyphosate has been reported to provide limited control of *Equisetum* species (Bernards et al. 2010; Coupland and Peabody 1981; Kerbs et al. 2019) at rates up to 2.1 kg ae ha^{-1}. However, Lyon and Thorne (2022) found that high rates of glyphosate (3.78 kg ae ha^{-1}) applied alone or with an organosilicone surfactant provided effective control of smooth scouringrush 1 yr after application compared to a nontreated check. Addition of an organosilicone surfactant improved glyphosate efficacy 1 and 2 yr after treatment (YAT) compared to glyphosate applied alone. Glyphosate is a viable herbicide option for growers in eastern Washington because of its lack of soil residual activity and crop rotation restrictions (Carlisle and Trevors 1988). Glyphosate is rapidly inactivated in soil by adsorption to clay particles and organic matter (Sprankle et al. 1975). Organosilicone surfactants can increase surface wetting and stomatal flooding by reducing surface tension of the droplet, which increases herbicide uptake through open stomata (Buick et al. 1992; Field and Bishop 1988; Kaiser 2014; Knoche 1994).

The stomata in *Equisetum* spp. exhibit a diurnal pattern that depends on stem turgor and red light (Husby et al. 2014). It has been reported that *Equisetum hyemale* L. requires blue light for stomatal opening and photosynthetic CO_2 fixation (Doi et al. 2015). However, stomatal conductance in smooth scouringrush has not been reported in the literature.

The objective of this study was to test the hypothesis that the addition of an organosilicone surfactant to glyphosate increases the efficacy of smooth scouringrush control because of stomatal flooding.

Materials and Methods

Field studies were conducted at three sites in eastern Washington. The studies were near Malden (47.26766° N, 117.50191° W; elev. 732 m), Rock Lake (47.24821° N, 117.63221° W; elev. 671 m), and Reardan (47.71503° N, 117.79245° W; 744 m). Studies were initiated in 2020 at Malden and in 2021 at Reardan and Rock Lake. Average annual precipitation recorded from 1991 to 2021 is 467 mm, 434 mm, and 356 mm for Malden, Rock Lake, and Reardan sites, respectively. All three sites were managed with a typical rotation of chemical fallow followed by direct-seeded winter wheat.

A two-factor factorial design with six herbicide treatments and two application timings (day and night) was used. Treatments were applied to 3-m-wide and 9-m-long plots, arranged in a randomized complete block design with four replications. Before herbicide application, initial smooth scouringrush stem counts were taken from two randomly placed 0.25-m^2 quadrats per plot, which were subsequently converted to stems m^{-2}. Initial smooth scouringrush stem density averaged across all plots was 237, 228, and 179 stems m^{-2} at Malden, Rock Lake, and Reardan sites, respectively.

Herbicide treatments consisted of glyphosate alone (RT® 3; Bayer AG, 51368 Leverkusen, Germany) applied at 3.78 kg ae ha^{-1}, glyphosate + organosilicone surfactant (OS1) (Silwet™ L77; Helena Chemical Co., Collierville, TN) applied at 0.5% v/v, glyphosate + organosilicone + nonionic surfactant blend (BLD) (Kinetic®; Helena Chemical Co. Collierville, TN) applied at 0.5% v/v, glyphosate + alcohol-based surfactant (ABS) (Wetcit®; ORO AGRI Inc., Fresno, CA) applied at 0.78% v/v, glyphosate + organosilicone surfactant (OS2) (Syl-Coat®; Wilbur-Ellis Co., San Francisco, CA) at 0.375% v/v. Treatments at Malden did not include glyphosate + OS2. All glyphosate solutions were applied at two different times: day and night. At Malden and Rock Lake, where treatments were applied in early to mid-July, photoperiod was approximately 15.25 h, whereas at Reardan, where treatments were applied on August 9, 2021, photoperiod was about 14.25 h.

Herbicide treatments were applied using a CO_2-pressurized backpack sprayer equipped with six nozzles with a 51-cm nozzle spacing using TeeJet® AIXR11002 (Spraying Systems, Co., Glendale Heights, IL) nozzles at Rock Lake and Reardan, and TeeJet® XR11002 nozzles at Malden. The change to an air induction nozzle in 2021 was made to reduce the risk for particle drift. Although foliar coverage may be greater with the extended-range nozzle used in 2020 than the air induction nozzle used in 2021, the risk of increased off-target particle drift with the extended-range nozzle was deemed the larger risk. Operating pressures were 172 and 276 kPa for XR and AIXR nozzles, respectively. The sprayer was calibrated to deliver 140 L ha^{-1}. Weather conditions were recorded at each site and application time (Table 1).

Smooth scouringrush stem density was measured in two randomly placed 1-m^2 quadrats from each plot 1 YAT. Stem density measurements were taken on July 1, 2021, at Malden, July 5, 2022, at Reardan, and July 7, 2022, at Rock Lake.

Statistical Analysis

Data were analyzed using general linear mixed models (GLMMIX) in SAS software (SAS Institute 2019) with herbicide solution and time as fixed effects and replication as a random effect. Stem density data were fitted to a negative binomial distribution using the LaPlace maximum-likelihood method. The initial stem density data were included in the model statement as a covariate, and compound symmetry was used as a covariance structure in the random statement because of subsampling in each plot. Comparisons of the day and night treatments for each herbicide were analyzed using a set of orthogonal contrasts in the model at $\alpha = 0.05$.

Results and Discussion

There was a significant location-by-surfactant-by-time interaction (P value = 0.024); therefore, sites were analyzed separately. For

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Table 2. Smooth scouringrush stem density in winter wheat 1 yr after day and night applications of glyphosate plus various surfactants in chemical fallow at Malden, WA in 2021. P values are derived from contrasts day vs night at α = 0.05.

Treatments[a]	Smooth scouringrush control: Day[b]	Smooth scouringrush control: Night	Day vs night[c]
	No. stems m^{-2}		P value
Nontreated	138	___	___
Glyphosate	135	108	0.476
Glyphosate + OS1	60*	89	0.208
Glyphosate + BLD	66*	128	0.048†
Glyphosate + ABS	85	90	0.846
Glyphosate + OS2	___	___	___

[a]Abbreviations: ABS, alcohol-based surfactant; BLD, organosilicone + nonionic surfactant blend; OS1, organosilicone surfactant (Silwet[TM] L77; Helena Chemical Co., Collierville, TN); OS2, organosilicone surfactant (Syl-Coat®; Wilbur-Ellis Co., San Francisco, CA).
[b]An asterisk (*) indicates significant difference from the nontreated check (P < 0.05).
[c]Symbol (†) indicates significant difference day vs night (P < 0.05).

Table 3. Smooth scouringrush stem density in winter wheat 1 yr after day and night applications of glyphosate plus various surfactants in chemical fallow at Rock Lake, WA in 2022. P values are derived from contrasts day vs night at α = 0.05.

Treatments[a]	Smooth scouringrush control: Day[b]	Smooth scouringrush control: Night	Day vs night[c]
	No. stems m^{-2}		P value
Nontreated	145	___	___
Glyphosate	113	118	0.825
Glyphosate + OS1	123	130	0.808
Glyphosate + BLD	115	111	0.868
Glyphosate + ABS	66*	127	0.005†
Glyphosate + OS2	84*	180	0.002†

[a]Abbreviations: ABS, alcohol-based surfactant; BLD, organosilicone + nonionic surfactant blend; OS1, organosilicone surfactant (Silwet[TM] L77; Helena Chemical Co., Collierville, TN); OS2, organosilicone surfactant (Syl-Coat®; Wilbur-Ellis Co., San Francisco, CA).
[b]An asterisk (*) indicates significant difference from the nontreated check (P < 0.05).
[c]Symbol (†) indicates significant difference day vs night (P < 0.05).

each site, orthogonal contrasts were used to compare means from day and night applications within each herbicide treatment, and to compare each herbicide treatment-by-application time mean with the mean of the nontreated check. Our objective was not to compare surfactants, but rather to test the hypothesis that organosilicone surfactants improved glyphosate activity in smooth scouringrush via stomatal flooding.

Malden

Only two treatments, glyphosate + BLD day applied (P value = 0.017), and glyphosate + OS1 day applied (P value = 0.007) reduced smooth scouringrush stem density compared to the nontreated check (Table 2). Only the glyphosate + BLD treatment showed a difference in stem densities between the day and night applications, with the day application having a lower stem density 1 YAT compared to the night application. Glyphosate applied alone resulted in stem densities no different from the nontreated check, whether applied during the day (P value = 0.801) or night (P value = 0.342).

Rock Lake

Two treatments reduced stem density relative to the nontreated check (Table 3). These treatments were glyphosate + OS2 day-applied (P value = 0.044) and glyphosate + ABS day-applied (P value = 0.002). Glyphosate + OS2 and glyphosate + ABS, performed differently between the day and night applications. Stem densities for both treatments were lower with the day applications compared to their night applications. Stem densities when glyphosate was applied alone, either during day or night, were not different from the nontreated check (P values = 0.406 and 0.537, respectively).

Reardan

Only two treatments showed stem densities lower than the nontreated check: glyphosate + OS1 night-applied (P value < 0.001) and glyphosate + OS2 night-applied (P value < 0.001) (Table 4). Two glyphosate treatments had stem densities that differed between day and night applications. These treatments were glyphosate + OS1 and glyphosate + OS2. However, unlike the other two locations, stem densities were lower for the night applications rather than the day applications. Stem density for the glyphosate-applied-alone treatments, whether made during the day or night, were not different from the nontreated check (P values = 0.331 and 0.332, respectively).

Table 4. Smooth scouringrush stem density in winter wheat 1 yr after day and night applications of glyphosate plus various surfactants in chemical fallow at Reardan, WA in 2022. P values are derived from contrasts day vs night at α = 0.05.

Treatments[a]	Smooth scouringrush control: Day[b]	Smooth scouringrush control: Night	Day vs night[c]
	No. stems m^{-2}		P value
Nontreated	88	___	___
Glyphosate	61	62	0.969
Glyphosate + OS1	79	11*	<0.001†
Glyphosate + BLD	71	92	0.495
Glyphosate + ABS	74	59	0.538
Glyphosate + OS2	88	15*	<0.001†

[a]Abbreviations: ABS, alcohol-based surfactant; BLD, organosilicone + nonionic surfactant blend; OS1, organosilicone surfactant (Silwet[TM] L77; Helena Chemical Co., Collierville, TN); OS2, organosilicone surfactant (Syl-Coat®; Wilbur-Ellis Co., San Francisco, CA).
[b]An asterisk (*) indicates significant difference from the nontreated check (P < 0.05).
[c]Symbol (†) indicates significant difference day vs night (P < 0.05).

Numerous studies have reported that herbicide applications made in the morning or mid-day hours perform better than applications made at night or during early-morning hours (Copeland et al. 2019; Johnston et al. 2018; Kalina et al. 2022; Martinson et al. 2002; Miller et al. 2003; Stopps et al. 2017). However, many other factors can affect herbicide efficacy, such as herbicide site of action, plant species, and environmental conditions. Differences we observed between day and night applications could very likely have been influenced by environmental conditions (air temperature, relative humidity, drought stress).

Weather conditions at all three sites were recorded prior to herbicide applications (Table 1). Air temperatures during the day ranged from 25 to 27 C, and relative humidity (RH) ranged between 30% and 31%. Air temperatures at night varied from 18 to 23 C and RH ranged between 32% and 45%. The lowest night temperature (18 C) and the highest RH (45%) occurred at Reardan during the night applications. These weather conditions may have slowed droplet evaporation, resulting in increased herbicide uptake. A severe drought occurred in the Pacific Northwest in the summer of 2021 that reduced winter wheat yields by 44% in

Washington (Ansah and Walsh 2021). The literature suggests that plants exposed to dry soil conditions, water stress, or both have reduced herbicide uptake and translocation compared to nonstressed plants (Alizade et al. 2021; Skelton et al. 2016; Waldecker and Wyse 1985). Treatments applied at Reardan were applied later in the season than those at the other sites; thus, the plants at Reardan may have been experiencing greater drought stress, which may also explain the lower stem density at this site compared to Malden and Rock Lake. Furthermore, droplet evaporation may have been enhanced by the addition of the organosilicone surfactants (Li et al. 2019), which reduce droplet surface tension, allowing the droplet to easily spread over the plant surface (Buick et al. 1993). Consequently, droplets containing organosilicone surfactants evaporate faster than droplets without added organosilicone surfactant. This may help explain the reduced herbicide efficacy for day-applied treatments containing OS1 or OS2 observed at Reardan (Table 4). In addition, silica content in smooth scouringrush stems increases during the growing season, which could potentially affect herbicide efficacy (Lyon and Thorne 2022; Sapei 2007). Silica on a stem surface can decrease transpiration and prevent excessive water loss when plants are exposed to dry conditions and can also interfere with cuticle uptake of herbicides.

Plants are generally photosynthetically active in the morning and mid-day when open stomata can facilitate herbicide absorption, translocation, and efficacy (Field and Bishop 1988). Stomata in *Equisetum* species are unique among vascular plants, with limited active movement and silicified radiating ribs appearing later in stomata ontogeny (Cullen and Rudall 2016). Stomata regulation in *Equisetum* is likely a passive process determined by stem turgor and red light (Cullen and Rudall 2016; Husby et al. 2014). Even though Husby et al. (2014) reported the existence of a diurnal pattern of stomatal conductance in giant horsetail (*Equisetum giganteum* L.), it was not tightly controlled by vapor pressure deficit or temperature, which suggests a passive control. The same authors measured the stomatal conductance in developing and mature stems and reported that mature stems have greatly reduced stomatal conductance. Increased stem temperature may also reduce stomatal conductance to minimize the transpiration when temperatures and vapor pressure deficit are high (Husby et al. 2014). However, nighttime transpiration and conductance also occurs in plants, via stomata or the cuticle. Cuticular conductance during the night is generally low, suggesting that nighttime conductance is mostly influenced by stomatal conductance (Caird et al. 2007; Ogle et al. 2012). Although the results varied across sites, only glyphosate treatments that included the addition of a surfactant resulted in reduced smooth scouringrush stem densities compared to the nontreated check 1 yr after application. At two of three sites, when there was a difference in efficacy between day and night applications, the treatments applied during the day reduced stem densities relative to the same treatments applied at night. At Malden, glyphosate + BLD, which contains an organosilicone surfactant, applied during the day reduced stems 1 YAT compared to the same treatment applied at night. The day application with OS1 did reduce stem density compared with the nontreated check, although there was no difference between the nontreated and the night application. It is possible that OS1 resulted in droplet evaporation, whereas the BLD surfactant resulted in less droplet evaporation and still facilitated stomatal flooding. At Rock Lake, the daytime application of glyphosate + ABS surfactant resulted in reduced stem density 1 YAT, suggesting cuticle uptake (Hess and Foy 2000); however, this was the only time the ABS increased glyphosate efficacy, and we are unclear why the nighttime application did not have the same effect. However, the day application of glyphosate + OS2 did support our hypothesis that an organosilicone surfactant would facilitate uptake during the day if the stomata were open. At Reardan, treatments were applied a month later in the season compared with the other two sites, and the application of glyphosate + OS1 or OS2 only at night resulted in decreased stem densities 1 YAT. These data suggest that OS1 and OS2 resulted in uptake either through the cuticle or more likely through stomata that were either passively open (Husby et al. 2014) or open after dark because of the need for stomatal gas exchange (Resco de Dios et al. 2013). That we did not see a difference for glyphosate alone between either the day or night applications compared with the nontreated check 1 YAT at any location suggests that neither cuticle nor stomatal uptake was occurring. In this study, the glyphosate product applied (RT®3) is reported to contain a proprietary surfactant package, but its surfactants either do not facilitate reduced surface tension and stomata flooding, or they are unable to penetrate the siliceous cuticle of the smooth scouringrush stem.

Although more research is needed to verify the causes for the observed treatment differences, or lack thereof, these results suggest that glyphosate efficacy in smooth scouringrush can be improved by the addition of an organosilicone surfactant; however, these treatments should be made when drought stress is less likely—generally earlier in the growing season (e.g., June or early July, in the Pacific Northwest). Nighttime treatments may be preferred when plants are under drought stress and weather conditions are hot and dry.

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