

Research Article

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Corresponding author:

Muthukumar Bagavathiannan;
Email: muthu@tamu.edu

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Evaluation of organic options for Johnsongrass (*Sorghum halepense*) control during winter fallow

Gustavo Camargo Silva¹, Jialin Yu², Leonard Herndon³, Spencer Samuelson¹, Nithya Rajan⁴ and Muthukumar Bagavathiannan⁴ 

¹Graduate Research Assistant, Department of Soil and Crop Sciences, Texas A&M University, College Station, TX, USA; ²Research Scientist, Department of Soil and Crop Sciences, Texas A&M University, College Station, TX, USA; ³Undergraduate Research Assistant, Department of Soil and Crop Sciences, Texas A&M University, College Station, TX, USA and ⁴Professor, Department of Soil and Crop Sciences, Texas A&M University, College Station, TX, USA

Abstract

Johnsongrass [*Sorghum halepense* (L.) Pers.] is one of the most problematic perennial grass weed species in row-crop production across the southern United States. Control of this species is especially challenging in organic systems due to a lack of effective options. A field experiment was conducted at the Texas A&M research farm near College Station, TX, from fall 2019 to spring 2021 to evaluate various nonchemical options for managing *S. halepense* in the fallow season, implemented over 2 yr in the same locations. The treatments included disking once, disking twice, disking + immediate flooding, disking + flush irrigation + flooding, disking twice + flooding after the first frost, periodic mowing, acetic acid treatment, and disking + tarping. Disking + immediate flooding, disking + flush irrigation + flooding, and disking + tarping were the most effective treatments. Compared with the nontreated control plots, these treatments reduced *S. halepense* aboveground density (<9 plants m⁻² vs. 64 plants m⁻²), aboveground biomass (<80 g m⁻² vs. 935 g m⁻²), rhizome biomass (<4 g m⁻² vs. 55 g m⁻²), rhizome node number (<25 nodes m⁻² vs. 316 nodes m⁻²), and rhizome length (<42 cm m⁻² vs. 660 cm m⁻²). Disking twice + flooding after the first frost did not show a consistent impact. Periodic mowing also reduced *S. halepense* density (12 plants m⁻² vs. 64 plants m⁻²) and other variables compared with the control plots at the end of the study in spring 2021. Disking alone once or twice each growing season or repeated application of acetic acid failed to control *S. halepense*. These results indicate that well-timed nonchemical management practices such as tarping and flooding implemented during the winter fallow can be very effective in reducing *S. halepense* densities.

Introduction

Johnsongrass [*Sorghum halepense* (L.) Pers.], a perennial summer grass weed native to the Mediterranean region, is one of the most problematic weed species across the southern United States (McWhorter 1993; McWhorter and Hartwig 1972; Ohadi et al. 2018; Travlos et al. 2018). Several biological characteristics of *S. halepense* contribute to its invasiveness (McWhorter 1961; Taylorson and McWhorter 1969; Warwick et al. 1986). This species has a remarkable ability to reproduce both sexually (seeds) and asexually (rhizomes) (Anderson et al. 1960; Horowitz 1972a, 1973). A single *S. halepense* plant can produce up to 80,000 seeds (Anderson 1996; Monaghan 1979) that can remain viable in the soil for up to 6 yr (Horowitz 1973).

Seedling *S. halepense* (i.e., from seeds) can begin forming rhizomes approximately 3 wk after emergence and can produce about 65 m of rhizomes in 5 m of growth (McWhorter 1961). The rhizomes store carbohydrate reserves and serve as overwintering structures; the axillary and terminal buds produce new vegetative shoots and contribute to reestablishment in the spring (Anderson et al. 1960; McWhorter 1961; Monaghan 1979; Travlos et al. 2019). Some *S. halepense* buds may remain inactive/dormant during environmental stress conditions and regrow when conditions improve (McWhorter 1961). Rhizomes sprout in soil ranging from 15 to 30 C (Hull 1970), whereas seed germination occurs at 20 to 35 C (Taylorson and McWhorter 1969). In southeast Texas, *S. halepense* rhizomes can sprout as early as February (GCS and MB, personal observations). Although *S. halepense* rhizomes cannot survive when the soil temperatures reach below -9 C (McWhorter 1972a; Stoller 1977), winter temperatures in much of the southern United States are not low enough to kill the rhizomes.

Sorghum halepense is an aggressive competitor. Significant yield reductions due to *S. halepense* interference have been documented in economically important crops such as corn (*Zea mays* L.) (Ghosheh et al. 1996; Mitskas et al. 2003), cotton (*Gossypium hirsutum* L.)



(Wood et al. 2002), peanut (*Arachis hypogaea* L.) (Willis et al. 2006), and soybean [*Glycine max* (L.) Merr.] (McWhorter and Hartwig 1972; Williams and Hayes 1984). This species is extremely difficult to control in grain sorghum [*Sorghum bicolor* (L.) Moench] because of a lack of selective herbicide options due to genetic similarities between the two species (Bagavathiannan et al. 2018). Moreover, the potential for gene flow between grain sorghum and *S. halepense* may also complicate management (Ohadi et al. 2018; Sias et al. 2023). Lopez (1988) reported that *S. halepense* could reduce grain sorghum yields by as much as 90% under high densities. In field corn, season-long interference by seed-derived and rhizomatous *S. halepense* reduced grain yields by 57% and 88%, respectively (Mitskas et al. 2003). In addition to competitive interactions, *S. halepense* can also impact crops noncompetitively through allelopathy. Studies have documented the allelopathic activities of *S. halepense* on several crops, such as barley (*Hordeum vulgare* L.), corn, cotton, soybean, and wheat (*Triticum aestivum* L.) (Lolas and Coble 1982; Petrova et al. 2015; Vasilakoglou et al. 2005). Menges (1987) reported that *S. halepense* residues incorporated into the soil inhibited the growth of cabbage (*Brassica oleracea* L.), common sunflower (*Helianthus annuus* L.), and onion (*Allium cepa* L.) by 26%, 10%, and 67%, respectively. Thus, *S. halepense* can severely impact crop yields through multiple mechanisms.

Sorghum halepense is an extremely difficult to control species in organic systems (Samuelson 2020). In conventional fields, *S. halepense* can be managed using postemergence herbicide options such as the acetyl-coenzyme A carboxylase inhibitors (e.g., clethodim, sethoxydim) (Yazlik and Uremis 2016), acetolactate synthase inhibitors (e.g., imazethapyr, nicosulfuron) (Meyer et al. 2015), and the 5-enolpyruvylshikimate-3-phosphate synthase inhibitor glyphosate (McWhorter and Azlin 1978; Travlos et al. 2019), to name a few. However, the activity of non-synthetic herbicides approved for use in organic systems is minimal on *S. halepense*. Acetic acid (CH_3COOH) is a widely used non-synthetic herbicide in organic farming (Domenghini 2020). In previous research, acetic acid applied at a dose ranging from 18% to 30% by volume provided effective weed control, especially when the weeds (e.g., hairy galinsoga [*Galinsoga quadriradiata* Cav.], redroot pigweed (*Amaranthus retroflexus* L.), and large crabgrass [*Digitaria sanguinalis* (L.) Scop.], among other species) were at the 6-leaf stage or smaller (Domenghini 2020; Evans et al. 2011). In greenhouse experiments, Ivany (2010) reported that acetic acid at 20% or 30% concentration applied at 300 L ha^{-1} effectively controlled corn spurry (*Spergula arvensis* L.), common lambsquarters (*Chenopodium album* L.), and wild buckwheat (*Polygonum convolvulus* L.). Abouziena et al. (2009) found that acetic acid at 30% concentration applied at 188 L ha^{-1} provided 95% control of seedling *S. halepense* 1 wk after treatment when the plants were between 4- and 7-cm tall. Other common organic herbicides include citric acid, d-limonene, clove oil, cinnamon oil, and lemongrass oil (Lanini 2010), but no studies have evaluated their efficacy against rhizomatous *S. halepense*.

Repeated mowing can reduce *S. halepense* rhizome growth and prevent seed production (Warwick and Black 1983). Other mechanical control techniques, such as disking and tillage, can effectively control young seedlings; however, fragmentation of rhizomes by tillage can further spread *S. halepense*, especially if sufficient soil moisture is available following tillage (Travlos et al. 2019). McWhorter and Hartwig (1965) reported that repeated disking or tillage operations could deplete rhizomes and reduce *S. halepense* stands as long as seedlings and sprouts are uprooted

and rhizome segments are desiccated. The authors noted that multiple disking operations over the growing season effectively controlled *S. halepense* in soybean fields.

Flooding can be an effective integrated weed management tool (Price et al. 2010; Singh et al. 2006). Flooding impacts plants by creating an anaerobic environment detrimental to plant growth (Saini 2014). McWhorter (1971) reported that flooding effectively controlled *S. halepense* rhizomes, and the best results were obtained when the field was covered with 7 to 10 cm of water before rhizome sprouting. In another study, flooding soil with 5 to 10 cm of water for 1 to 2 wk effectively controlled all freshly planted *S. halepense* rhizomes in both greenhouse and field conditions (McWhorter 1972b). The use of tarping to suppress broadleaf and grass weeds has been well documented (Law et al. 2008; Ricotta and Masiunas 1991; Zhang et al. 2021), and solarization with clear tarping has been shown to effectively kill *S. halepense* rhizomes (Elmore et al. 1993; Stapleton 2012). However, no studies have evaluated black tarping for rhizomatous *S. halepense* control.

Evaluation of different nonchemical management tactics side by side allows for determining relative effectiveness under comparable conditions and helps make informed management decisions. The long fallow season following the harvest of the main cash crop in the southern United States can be utilized for aggressive management of rhizomatous *S. halepense* using nonchemical methods. However, there have been no studies evaluating *S. halepense* control in the fallow season. The objective of this research was to evaluate rhizomatous *S. halepense* control using a number of nonchemical methods implemented during the winter fallow season in southeast Texas.

Materials and Methods

Experimental Site

Field experiments were conducted at the Texas A&M University Research Farm near College Station, TX (30.552226°N, 96.424928°W). The site is characterized by a Ships clay soil type (very fine, mixed, active, thermic Chromic Hapluderts). The experimental site had been managed organically for several years and was left fallow (the field was periodically mowed, but no cash crop was planted) for the 2 yr immediately before the experiment. There was a natural infestation of *S. halepense* at the experimental site in high and uniform densities (19 plants m^{-2}) before the initiation of the experiment (Figure 1).

Treatment Details

The study was conducted from fall 2019 to late spring 2021, comprising two annual cycles, each running from late September to late April, where treatments were applied to the same plots across both years. Nine treatments were implemented in a randomized complete block design with three replications. The study was not repeated across time or location. Each plot measured 15.2-m long and 3.3-m wide. Flooded plots had a soil berm (50-cm tall) built around them. Flooding was accomplished by pumping well water through poly irrigation pipes. The treatments included:

T1: An untreated control, which was mown once at the beginning of the experiment (late September) and left untouched throughout the experiment.

T2: Disking once to a depth of 15 cm in late September.



Figure 1. (A) Initial *Sorghum halepense* densities at the site (September 2019) and (B) an aerial view of the experimental site during the spring regrowth (April 2020).

T3: Disking twice to a depth of 15 cm, once in late September and again after the *S. halepense* had regrown to 30- to 38-cm height in late October.

T4: Disking once to a depth of 15 cm in late September, followed immediately by flooding for 14 d at a 20-cm depth (Figure 2A).

T5: Disking once to a depth of 15 cm in late September, followed by flush irrigation to soil field capacity to encourage emergence/sprouting, then flooding for 14 d at a 20-cm depth when *S. halepense* height was 2.5 to 5 cm. Flush irrigation was accomplished with the same poly pipes used for irrigation.

T6: Disking twice to a depth of 15 cm, once in late September and again after the *S. halepense* had regrown to 30 to 38 cm height in late October, followed by flooding for 14 d at a 20-cm depth after the first frost by late November (plants were 20- to 30-cm tall, going into the dormant stage).

T7: Periodic mowing when the plant growth reaches 30- to 38-cm tall.

T8: Spraying acetic acid (Green Gobbler Concentrated Vinegar, Green Gobbler, Gurnee, IL) undiluted (30% concentration at 188 L ha⁻¹) when *S. halepense* reached 30- to 38-cm tall (Abouziena et al. 2009).

T9: Disking to a depth of 15 cm in late September, followed immediately by installation of black tarp (6-mil polyethylene) (Figure 2B).

The treatments were implemented in the same plots during the two study years to evaluate the impact of repeated applications of these treatments. A sunn hemp (*Crotalaria juncea* L.; Hancock Seed, Dade City, FL) summer cover crop was planted at 33.5 kg ha⁻¹ seeding rate during the cropping season (May to September 2020) in the entire experimental area. The purpose of the cover crop was to



Figure 2. (A) Implementation of flooding treatments and (B) installation of 6-mil black tarp.

simulate an intensive and competitive cash crop during the summer season. The sunn hemp cover was terminated on September 21, 2020, using a roller-crimper. The field was then disked before implementing the second cycle of treatments. The specific dates of field operations for the two study years are provided in Table 1.

Data Collection

Initial *S. halepense* density was determined before implementing the treatments each year. In 2019, when *S. halepense* was uniformly distributed in the experimental site, the average density for the entire field was calculated by randomly placing sixteen 1-m² quadrats throughout the field and counting the number of rhizomatous *S. halepense* shoots in each. Only the rhizomatous *S. halepense* shoots were monitored in this study, because the seedling *S. halepense* that established after fall is less likely to survive the winters in the study location; moreover, the rhizomatous shoots give a good representation of the effectiveness of the treatments. In 2020, densities before treatment implementation were recorded in each plot by placing two 50 cm by 50 cm quadrats and counting the number of rhizomatous shoots in each quadrat. In T5, *S. halepense* sprouting after flush irrigation was quantified in five 50 cm by 50 cm quadrats per plot before flooding. The final *S. halepense* densities for each cycle were recorded on April 17, 2020, and April 28, 2021, in all plots. In 2020, the number

Table 1. Dates of field operations and data collection

| Operation/data collection ^a | Date (Year 1) | Date (Year 2) |
|--|--------------------|-------------------|
| Initial <i>Sorghum halepense</i> density | September 13, 2019 | October 5, 2020 |
| Initial mowing | September 13, 2019 | October 5, 2020 |
| First disking (T2, T3, T4, T5, T6, T9) | September 20, 2019 | October 12, 2020 |
| Tarp installation (T9) | September 22, 2019 | October 14, 2020 |
| Flooding (T4) | October 7, 2019 | October 29, 2020 |
| Irrigation (T5) | October 7, 2019 | October 29, 2020 |
| Second disking (T3, T6) | October 8, 2019 | October 30, 2020 |
| Flooding (T5) | October 14, 2019 | November 5, 2020 |
| Acetic acid application | October 28, 2019 | November 19, 2020 |
| Flooding (T6) | November 15, 2019 | December 7, 2020 |
| Spring <i>S. halepense</i> density | April 17, 2020 | April 28, 2021 |
| Sunn hemp cover crop planting | May 10, 2020 | — |
| Sunn hemp cover crop termination | September 21, 2020 | — |
| Final <i>S. halepense</i> density and rhizomes | — | June 14, 2021 |

^aTreatments: T1, nontreated control; T2, disking once; T3, disking twice; T4, disking + flooding for 14 d; T5, disking + flush irrigation + flooding for 14 d; T6, disking twice + flooding at first frost; T7, periodic mowing; T8, acetic acid application; and T9, disking + black tarping.

of rhizomatous *S. halepense* shoots in each plot was recorded in three 50 cm by 50 cm quadrats, whereas in 2021, data were collected from five 50 cm by 50 cm quadrats. Additionally, at the termination of the experiment in late April 2021, *S. halepense* dry biomass and rhizome density were determined for each plot to assess the cumulative impact of the treatments after 2 yr of implementation. In two 50 cm by 50 cm quadrats per plot, all aboveground *S. halepense* biomass was harvested, dried for 7 d at 60 C, and weighed. In each of those quadrats, all rhizome segments were dug up for a depth of 15 cm. The total linear rhizome length was measured, the number of nodes was counted, and the samples were dried for 7 d at 60 C and weighed for rhizome biomass.

Statistical Analysis

Sorghum halepense aboveground densities were subjected to one-way repeated-measures ANOVA with the generalized linear mixed model (PROC GLIMMIX) in SAS (v. 9.4, SAS Institute, Cary, NC), with data collection timings (spring of 2020, fall of 2020, and spring of 2021) as the repeated measures and each plot as the experimental unit. A heterogeneous autoregressive 1 [ARH(1)] covariance structure was chosen, as it provided the lowest corrected Akaike information criterion value. Treatment means were separated using Tukey's honestly significant difference (HSD) method at $\alpha = 0.05$. The aboveground densities of *S. halepense* between fall 2019 and spring 2021 were compared for each treatment using the Student's *t*-test at $\alpha = 0.05$ in SAS.

Sorghum halepense aboveground biomass, rhizome length, rhizome biomass, and rhizome node number were subjected to one-way ANOVA with the generalized linear mixed model (PROC GLIMMIX) in SAS. Treatment was considered to be the fixed effect, while replication was regarded to be the random effect. A link function (link = log) was used in the GLIMMIX model statement to address potential normality issues. Treatment means were separated using Tukey's HSD method at $\alpha = 0.05$.

Results and Discussion

Our results demonstrated, in a side-by-side comparison, the efficacy of various nonchemical methods for controlling rhizomatous *S. halepense*. Varying levels of *S. halepense* control were observed among the treatments (Figure 3). Disking once (T2), disking twice (T3), disking once + flooding (T4), and periodic

mowing (T7) reduced *S. halepense* densities at the termination of the study in spring 2021 (61%, 54%, 89%, and 85%, respectively), but the treatment impacts were less prominent by spring 2020, just after the first cycle of treatments (Figure 3). Disking + flooding for 14 d after the first frost (T6) reduced *S. halepense* densities in spring 2020, but the effect was inconsistent in the fall 2020 and spring 2021 observations. Disking + flush irrigation + flooding after *S. halepense* sprouting (T5) and disking + installation of black tarp (T9) were the most effective treatments, consistently reducing *S. halepense* densities in all three observation timings (spring 2020, fall 2020, spring 2021). At the end of the study, T5 and T9 reduced *S. halepense* densities by 95% and 97%, respectively. Throughout the study, disking twice + flooding at first frost (T6) and acetic acid application (T8) had the least impact on *S. halepense* densities (Figure 3).

For each treatment, the results of the *t*-tests compared the densities between fall 2019 and spring 2021 showed that disking at the initiation of the experiment + flooding for 14 d (T4), disking at the initiation of the experiment + flush irrigation + flooding for 14 d (T5), periodic mowing (T7), and disking + black tarping (T9) resulted in significantly lower *S. halepense* densities in spring 2021 compared with fall 2019, whereas all other treatments (T1, T2, T3, T6, and T8) had statistically comparable or higher *S. halepense* densities.

With respect to the aboveground biomass at the termination of the study in spring 2021, all treatments reduced aboveground biomass compared with the nontreated control (T1). The most effective treatments were disking + flooding for 14 d (T4), disking + flush irrigation + flooding for 14 d (T5), periodic mowing (T7), and disking + black tarping (T9), which reduced *S. halepense* aboveground biomass by 95%, 98%, 87%, and 91%, respectively. Disking once (T2), disking twice (T3), disking twice + flooding at first frost (T6), and acetic acid application (T8) reduced *S. halepense* aboveground biomass by 56%, 46%, 56%, and 45%, respectively (Figure 4).

With respect to *S. halepense* rhizome growth, disking + flooding for 14 d (T4), disking + flush irrigation + flooding for 14 d (T5), and disking + black tarping (T9) reduced rhizome biomass (93%, 99%, and 99%, respectively), node number (92%, 99%, and 99%, respectively), and total linear length (94%, 99%, and 99%, respectively) compared with the control plots (T1), which had the highest values for these three variables. Disking twice + flooding at first frost (T6) reduced rhizome biomass (73%),

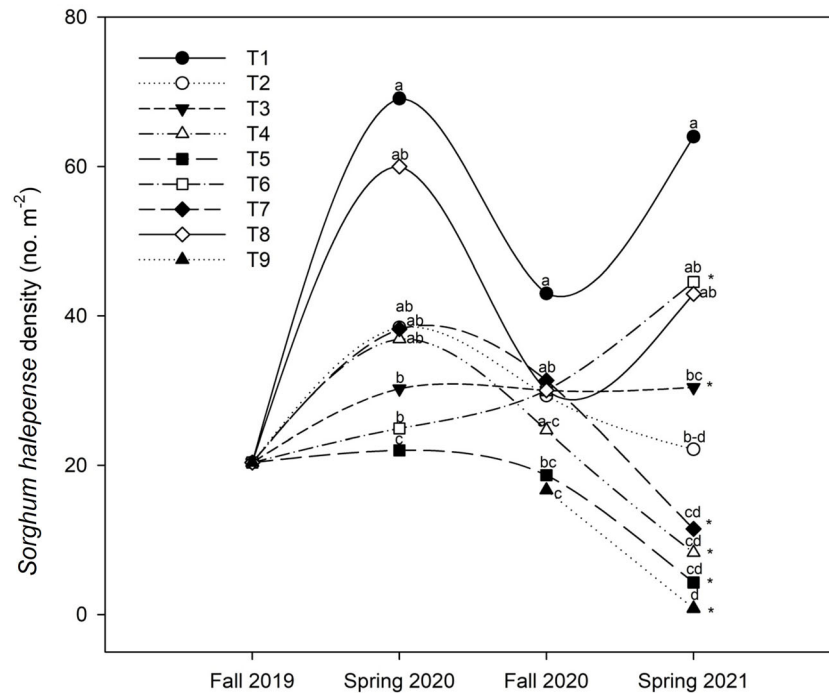


Figure 3. Aboveground *Sorghum halepense* densities were measured in fall 2019, spring 2020, fall 2020, and spring 2021. Treatments included: T1, nontreated control; T2, disking once; T3, disking twice; T4, disking + flooding for 14 d; T5, disking + flush irrigation + flooding for 14 d; T6, disking twice + flooding at first frost; T7, periodic mowing; T8, acetic acid application; and T9, disking + black tarping. Within each observation timing, the mean values followed by the same letter are not significantly different based on Tukey's honestly significant difference (HSD) test ($\alpha = 0.05$). Asterisks (*) indicate significant differences in *S. halepense* densities between fall 2019 and spring 2021, based on Student's *t*-tests at the 0.05 probability level. Data for T9 for Spring 2020 are missing due to an error during data collection.

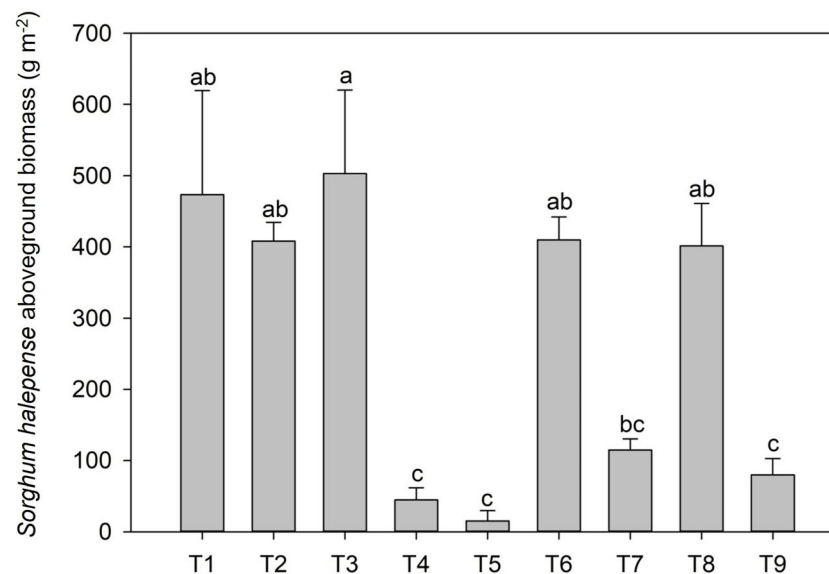


Figure 4. *Sorghum halepense* aboveground biomass at the termination of the study in spring 2021. Treatments included: T1, nontreated control; T2, disking once; T3, disking twice; T4, disking + flooding for 14 d; T5, disking + flush irrigation + flooding for 14 d; T6, disking twice + flooding at first frost; T7, periodic mowing; T8, acetic acid application; and T9, disking + black tarping. The error bars indicate the standard errors of the mean values. Bars topped with different letters are significantly different at the 0.05 significance level, based on Tukey's honestly significant difference (HSD) test.

but not rhizome node number and length. Periodic mowing (T7) reduced rhizome biomass (91%) and total linear length (81%), but not node number. However, disking once (T2), disking twice (T3), and application of acetic acid (T8) did not reduce rhizome biomass, rhizome length, or rhizome node number compared with the control (Table 2).

Results showed that disking alone once or twice was ineffective for controlling *S. halepense*. Disking cuts *S. halepense* rhizomes into smaller pieces, which encourages new shoot growth from each piece and leads to further spread (Horowitz 1972a; McWhorter and Hartwig 1965; Travlos et al. 2019). To achieve effective *S. halepense* control with tillage, frequent disking may be required

Table 2. *Sorghum halepense* rhizome biomass, nodes, and lengths under different nonchemical management treatments in College Station, TX.^a

| Treatment | Rhizome biomass | Rhizome node number | Rhizome length ^b |
|---|----------------------|------------------------|-----------------------------|
| T1: Control | —g m ⁻² — | —no. m ⁻² — | —cm m ⁻² — |
| T2: Disking once at the initiation of the experiment | 109 ± 6 a | 631 ± 71 a | 1,332 ± 53 a |
| T3: Disking at the initiation of the experiment + disking after the <i>S. halepense</i> had regrown to a 30- to 38-cm height | 46 ± 9 a-c | 629 ± 175 a | 1,159 ± 341 ab |
| T4: Disking at the initiation of the experiment + disking after the <i>S. halepense</i> had regrown to a 30- to 38-cm height | 35 ± 2 a-c | 511 ± 192 ab | 468 ± 30 a-c |
| T5: Disking at the initiation of the experiment + flooding for 14 d | 7.4 ± 2.4 cd | 50 ± 18 bc | 83 ± 23 cd |
| T6: Disking at the initiation of the experiment + flush irrigation + flooding for 14 d when <i>S. halepense</i> height was 2.5 to 5 cm | 0.6 ± 0.4 d | 7 ± 4 c | 9 ± 5 d |
| T7: Disking at the initiation of the experiment + disking when <i>S. halepense</i> had regrown to a 30- to 38-cm height + flooding at first frost | 29 ± 5 bc | 195 ± 21 ab | 455 ± 75 a-c |
| T8: Periodic mowing | 10 ± 1 b-d | 101 ± 3 ab | 247 ± 9 b-d |
| T9: Acetic acid application | 56 ± 14 ab | 464 ± 95 ab | 711 ± 150 a-c |
| T10: Disking at the initiation of the experiment + black tarping | 0.3 ± 0.2 d | 5 ± 3 c | 5 ± 3 d |

^aValues followed by the same letter are not significantly different, based on Tukey's honestly significant difference (HSD) test at the 0.05 probability level.

^bTotal linear length of all rhizomes in a square meter (m²) area.

(Johnson et al. 1997). In previous research, McWhorter and Hartwig (1965) reported that repeated disking 10 times at 4- to 6-d intervals effectively controlled *S. halepense*. Frequent disking and exposing the rhizomes to heat or cold can destroy them rapidly (McWhorter 1971), as rhizomes do not survive when exposed to temperatures below -4 C (Warwick et al. 1986) or above 30 C for more than 7 d under dry conditions (Warwick and Black 1983). The effectiveness of disking is also associated with the extent of rhizome desiccation (McWhorter and Hartwig 1965) or freezing (McWhorter 1971). McWhorter and Hartwig (1965) reported that frequent disking operations conducted during the dry summer months usually provide effective control of *S. halepense* in the southern United States. However, rainfall or irrigation immediately following disking could significantly reduce *S. halepense* control (Travlos et al. 2019). In this study, tillage was done only once or twice during the mild fall months in the College Station location, and temperatures (September averages: 33 C high and 21 C low; October averages: 27 C high and 15 C low) were not sufficient to effectively desiccate or freeze the rhizomes. Moreover, soil moisture was not a limitation during the fall season (data not shown), which also favored rhizome survival following disking.

It was also evident that flooding is an effective strategy for *S. halepense* control, but the timing of flooding is critical (Figures 4 and 5C; Table 2). Among the flooding treatments, disking at the initiation of the experiment + flush irrigation + flooding after emergence for 14 d was the most effective treatment that consistently reduced *S. halepense* density, rhizome biomass, rhizome node number, and rhizome length at the termination of the study in spring of 2021, whereas disking at the initiation of the experiment + disking when *S. halepense* had regrown to a 30- to 38-cm height + flooding at first frost (plants were 20- to 30-cm tall, going into the dormant stage) was the least effective flooding treatment.

Flush irrigation following disking likely promoted sprouting of *S. halepense*, which may have increased the susceptibility of *S. halepense* to flooding through breaking of rhizome dormancy and through a reduction in the carbohydrate reserves. Although tolerance to flooding is species specific (Barclay and Crawford 1982), plants with higher carbohydrate reserves tend to withstand anaerobic conditions (i.e., flooding) for longer periods, because they can use anaerobic fermentation to maintain metabolic functions for some time (Raju 2007). The low effectiveness of flooding implemented after frost could be associated with the induction of rhizome dormancy in cold temperatures, which in

turn may have reduced the physiological response to flooding. Rhizomes of some plants adapted to waterlogged soils can survive all winter under complete anoxia (Crawford 2003), indicating that dormancy and cold temperatures can reduce metabolism enough to prevent tissue death. In previous research in growth chambers, McWhorter (1972b) reported that soil and water temperatures play an important role when flooding is used for *S. halepense* control. Submerging rhizomes for 8 d in water at 40 C showed excellent control of rhizomes, whereas only a few rhizomes were killed in water at 10 or 20 C during the same period. In the field conditions, however, 2 and 4 wk of continuous flooding were necessary to kill rhizomes in water at 40 and 30 C, respectively; in water at 15 C, most rhizomes survived across 10 wk. Therefore, flooding for only 2 wk in the winter may not have been enough to control *S. halepense* rhizomes. Flooding for an extended period may be expensive. On the other hand, flooding in the summer months can provide rapid control of *S. halepense*. A study conducted in Arkansas reported 76% to 85% control of *S. halepense* when cotton was rotated with flooded rice (*Oryza sativa* L.) (Frans et al. 1991). In southeast Texas, this can be accomplished during late July to early September after the harvest of cash crops such as corn and grain sorghum. However, irrigation water availability and cost can be significant limitations for this practice. It is also important to notice that flooding can shift the dominance of the weed population from perennial *S. halepense* to annual weeds (Figure 5C).

Mowing significantly reduced *S. halepense* density, above-ground biomass, rhizome biomass, and total linear length, but not node number by the end of the experiment in 2021. However, according to our results, repeated mowing is necessary for good control; the impact of mowing was nonsignificant following the first mowing (fall 2019), at measurements taken in spring 2020 or fall 2020. Repeated mowing for at least 2 yr may be required to adequately control rhizomatous *S. halepense*. Our findings corroborate those of Horowitz (1972b), who also observed reductions in aboveground biomass and rhizome growth of *S. halepense* after 4 mo of repeated mowing. Mowing causes plants to allocate more resources to shoot growth rather than rhizome expansion, so repeated mowing at regular intervals can prevent rhizome growth and spread. Mowing can also reduce the competitiveness of perennial weeds, create openings in the canopy, and favor other weed species that are more tolerant to mowing (Miller 2016).

The acetic acid application was ineffective for the control of *S. halepense*. Previous research that evaluated acetic acid



Figure 5. Photographs of various nonchemical management treatments: (A) impact of tarping on *Sorghum halepense* densities, (B) desiccation of *S. halepense* rhizomes underneath the tarping, and (C) impact of flooding on *S. halepense* densities. Photos were taken in spring 2021.

application on various broadleaf and grass weeds has found that weed control increased with increasing concentrations, but efficacy decreased as plants matured (Moran and Greenberg 2008; Webber et al. 2018). Studies have also suggested that acetic acid is generally more effective on small annual broadleaf weeds than perennial grass weeds (Abouziena et al. 2009; Domenghini 2020; Evans et al. 2011; Webber et al. 2018). Perennial plants have thicker leaves and more protective structures around meristems than annual broadleaf plants (Aguirre et al. 2020). This is true for *S. halepense*, which also has underground rhizomes that are not affected by contact herbicides. Abouziena et al. (2009) noted that 30% acetic acid applied at 188 L ha⁻¹ provided 95% control of seedling *S. halepense* when the plants were 4- to 7-cm tall, but control

declined to 40% when the plants were at 8 to 12 cm. In the present study, acetic acid was applied at 30% concentration on 20- to 30-cm-tall rhizomatous *S. halepense*. Acetic acid could be an effective treatment against young *S. halepense* seedlings, but it is not effective on rhizomatous plants.

Black tarping resulted in one of the lowest aboveground *S. halepense* density and rhizome growth (Figure 5A). Tarping can physically restrict weed growth and development (Lalitha et al. 2010; Zhang et al. 2021). It may also control *S. halepense* rhizomes through the solarization effect (Law et al. 2008). Tarping can raise surface soil temperatures to over 60 C in the summer (Candido et al. 2012) and 45 C in the fall (Horowitz et al. 1983). Solarization has been used to control several weed species in vegetable production systems, including perennials such as nutsedges (*Cyperus* spp.) (Chase et al. 1998; Ricci et al. 1999). Elmore et al. (1993) successfully controlled *S. halepense* and bermudagrass [*Cynodon dactylon* (L.) Pers.] rhizomes with clear plastic tarps. Law et al. (2008) reported that solarization using clear plastic with or without prior tillage decreased *S. halepense* density by more than 56% compared with the bare ground. In this study, we observed that *S. halepense* rhizomes were desiccated underneath the tarping, which might be attributed to soil solarization (Figure 5B).

In summary, disking alone—once or twice—or acetic acid application for two continuous seasons failed to control *S. halepense* effectively. Disking should be done multiple times during the hot, dry season, as McWhorter and Hartwig (1965) recommended. Acetic acid shows potential for annual broadleaf control, but it is not effective against perennial grasses. Repeated mowing for 2 yr effectively controlled *S. halepense* by reducing *S. halepense* density, aboveground biomass, rhizome biomass, and length, but not node number, indicating that the plants were forced to grow shoots at the expense of rhizomes. However, repeated mowing could favor other problematic annual grass species (Miller 2016). Disking followed by flooding for 14 d is an effective approach for managing *S. halepense*. Flooding timing is critical, and flooding during the cold season failed to provide adequate control of *S. halepense*. Flooding is only possible in flat fields and requires structures like berms to keep the water in place. Further, some regions may not have enough water to maintain continuous flood for longer periods, and this method can be very expensive. When flooding is not feasible, the alternative approach of installing tarping can be an excellent option for small areas or high-value crops. Overall, results indicate that well-timed nonchemical management practices implemented during the winter fallow such as tarping and flooding can be very effective in reducing *S. halepense* densities. It is important to recognize that this study was conducted over a 2-yr period to understand the cumulative effects of the treatments implemented during two consecutive winter-fallow seasons. However, due to the extensive effort and resources required to conduct the experiment, it was not repeated in either space or time. As a result, we can infer that the results presented here provide insights into the effect of various nonchemical treatments on *S. halepense* population growth only under these specific conditions.

Future research should evaluate the effectiveness of a program approach that integrates the different tactics that showed promise in this research. Further, experiments should be done to determine whether approaching ineffective treatments in different ways can improve *S. halepense* suppression (e.g., disking followed by rhizome collection and removal). However, tillage is not a preferable option due to soil health concerns and would be

undesirable in no-till organic systems. Thus, more emphasis on conservation practices for *S. halepense* control is imperative. Winter cover crops such as cereal rye (*Secale cereale* L.) may be another useful tool for *S. halepense* control, but this was not included in the current research due to establishment issues during the first year. Future research should investigate cover crops, improving cash crop competitiveness, and other nonchemical tools not included in this research and integrate tactics that can be implemented during the summer cropping season/summer fallow.

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