

The impact of propagule type and burial depth on knotroot foxtail (*Setaria parviflora*) emergence and plant development, compared to other *Setaria* species

Research Article

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Abstract

Knotroot foxtail [*Setaria parviflora* (Poir.) Kerguelen], a perennial *Setaria* species, is becoming more problematic in forage and grazing systems across the southeastern United States. *Setaria parviflora* reproduces through the production of rhizomes and seeds, further complicating management strategies. Significant knowledge gaps exist regarding the biology and control of this species. This research aimed to understand the influence of burial depth on *S. parviflora* propagules and the physiological differences between it and other *Setaria* spp. Experiments were conducted between October 2019 and February 2021 in Clarke County, GA, to investigate the influence of burial depth (1, 2, 4, 8, and 16 cm) on the emergence and growth of *S. parviflora* rhizomes and seeds. Zero emergence was estimated at 8.7, 10.8, and 11.2 cm for small rhizomes, large rhizomes, and seeds, respectively. Therefore, producers could implement tillage events to a depth of 11.2 cm or greater to control *S. parviflora*. A separate study compared *S. parviflora*, yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.], green foxtail [*Setaria viridis* (L.) P. Beauv.], and giant foxtail (*Setaria faberi* Herrm.) plant morphology. Despite similar aboveground appearances, *S. pumila* and *S. parviflora* had different total and belowground biomass 2 to 5 mo after emergence, which suggests differences in root formation and perennialization of *S. parviflora*. The present research determined that burying propagules using tillage could be included in management recommendations concerning *S. parviflora*; however, it should be complemented with herbicide applications during the growing season to assist in controlling *S. parviflora* plants produced by seeds.

Introduction

Setaria spp. exhibit a wide ecological range and can grow on all continents except Antarctica (Dekker 2003). Most of the *Setaria* genus originates from Europe or Asia, while knotroot foxtail [*Setaria parviflora* (Poir.) Kerguelen] is native to the Americas (Dekker 2003). *Setaria parviflora* is a perennial monocot that has become a problematic weed in pasture and hayfields in the southeastern United States (McCullough 2016). Grazing livestock will graze on the species when it is small, before the development of a seedhead (Dyer et al. 2022; Israel et al. 2014; Marten and Andersen 1975). However, they typically avoid it once a seedhead emerges due to oral irritation and the development of ulcers caused by bristles on the spikelet of mature plants (Israel et al. 2014). The equestrian market will not purchase forage infested with *Setaria* spp. because of kidney failure issues associated with high oxalate concentration in the weeds (Rahman et al. 2012).

Current chemical control options for *S. parviflora* are limited in efficacy and registration; therefore, forage producers may resort to pasture renovation to alleviate severe infestations (Israel et al. 2014; Wehtje et al. 2008). Tillage may be conducted as a form of cultural control in which seeds and rhizomes of *S. parviflora* are buried to depths that inhibit emergence. Previous research reported that conventional tillage reduced giant foxtail (*Setaria faberi* Herrm.) and green foxtail [*Setaria viridis* (L.) P. Beauv.] emergence (Buhler and Mester 1991). Carbohydrate storage found within seeds or rhizomes is consumed during plant emergence and the production of aboveground foliage. Therefore, increasing burial depth can delay germination, diminish mature biomass, or increase the incidence of fatal germination (Davis and Renner 2007; Ghersa et al. 2000). Emergence is primarily controlled by temperature; therefore, more deeply buried seeds may have a reduced or delayed emergence from the exhaustion of stored energy within the

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seedling before it reaches the soil surface. Delayed emergence from greater burial depths may enable forage species to outcompete *S. parviflora* if it does emerge. Investigation into burial depths that decrease *S. parviflora* populations may provide alternative cultural control options for this species and reduce heavy reliance on herbicides.

Insight into the growth of *S. parviflora* in comparison with other *Setaria* spp. can further elucidate biological differences and potential opportunities for other integrated management methods. *Setaria parviflora*, yellow foxtail [*S. pumila* (Poir.) Roem. & Schult.], *S. viridis*, and *S. faberi* are all similar weedy species within the *Setaria* genus that cause yield losses in crops and forages (Knake and Slife 1962; Staniforth 1965). Identifying characteristics of aboveground morphological features of *S. parviflora* and *S. pumila* are identical to the untrained eye, causing grower confusion. Both species produce pubescence of similar length along the leaf blade near the ligule and exhibit a similar growth habit. However, excavation reveals an extensive rhizome system indicative of *S. parviflora* after a season of growth, although both plants emerging from rhizomes, and seeds can be present in the field simultaneously (Bryson and DeFelice 2009; Dyer et al. 2022, 2024). Understanding the biology of different *S. parviflora* propagules and how this species compares with annual *Setaria* spp. is crucial to developing effective *S. parviflora* control and management options. Significant differences among *Setaria* spp. may include the timing of seedling emergence and morphological variations in plant height or leaf architecture (Amini et al. 2015). Identifying *Setaria* seedling emergence timings and differences in plant size and phenology could help with species identification, herbicide application timing, or mechanical management strategies such as mowing or burning. Noticeable differences in height and phenology between *S. parviflora* and *S. pumila* and the timing of rhizome creation in *S. parviflora* are crucial for management tactics. Early identification of *S. parviflora* through scouting can improve chemical control through more accurate herbicide selection and application timing, reducing inputs and long-term overreliance on herbicides.

These studies aim to address gaps in the understanding of the influence of burial depth on *S. parviflora* propagule type and biological differences between *S. parviflora* and other *Setaria* spp. Two main objectives of these studies were to (1) determine the effect of burial depth on the emergence of seed and rhizomes of *S. parviflora* and (2) compare phenology and growth of *S. parviflora* and other *Setaria* spp.

Materials and Methods

Two experiments were conducted at Riverbend Greenhouse Complex at the University of Georgia, Athens, GA (33.92958°N, 83.36403°W) from October 2019 to February 2021. The greenhouse conditions were maintained at day/night temperatures of 24 to 29.5 C. Natural light was supplemented with artificial light (high-pressure sodium greenhouse lighting at 90 $\mu\text{mol m}^{-2} \text{s}^{-1}$ photosynthetic photon flux for a 12-h day to approximate summer light intensity and photoperiod). Experimental blocks were arranged along a gradient created by the greenhouse cooling pads and associated fans. A soilless potting media composed of a 2:1 mixture of Turface Athletics MVP high-fired calcined, non-swelling illite clay (6.5 pH) (PROFILE Products, 750 W. Lake Cook Road, Suite 440, Buffalo Grove, IL 60089) and fine-textured silica sand (QUIKRETE, 5 Concourse Parkway, Suite 1900, Atlanta, GA 30328) was used for both experiments. This specific mixture

simplifies the removal of plant roots for biomass collection and has been utilized in similar studies examining root development (Bertucci et al. 2018).

Plant Materials

Setaria parviflora seeds were transplanted from wild progeny collected in Griffin, GA (33.2661°N, 84.2852°W) into 3.78-L pots in the Riverbend Greenhouse Complex at the University of Georgia, Athens, GA (33.92958°N, 83.36403°W) in July 2019. Plants were allowed to mature and set seed over a 5-mo period for seed increase. Mature seeds were harvested in November 2019, placed into paper bags, and refrigerated at 4.5 C for 1 mo. Rhizomes were excavated from wild *S. parviflora* progeny within a forage field in Athens, GA (33.9068°N, 83.3746°W) and separated from aboveground plant biomass. Rhizomes were further separated by weight (size references noted in Figure 1). Rhizomes that weighed 0.375 to 0.725 g were categorized as “small,” while rhizomes approximately 1.6 to 1.8 g were categorized as “large” (Figure 1). Once separated, rhizomes were wrapped in moist paper towels to prevent desiccation, placed in an airtight container, and kept in a refrigerator at 4.5 C for 1 mo to break dormancy. Two weeks before study initiation, *S. parviflora* seed were separated into petri dishes containing 5 ml of water and placed back into the refrigerator at 4.5 C to initiate seed imbibition (Buhler and Hoffman 1999). The viability of the seed source (94%) was determined by longitudinally dissecting 50 seeds and soaking them in a 1% tetrazolium chloride solution using methodology from Borza et al. (2007). Additionally, seeds of *S. faberi*, *S. pumila*, and *S. viridis* were acquired from Azlin Seed Services (112 Lilac Drive, Leland, MS 38756) for the species comparison experiment. Similar methods of vernalization and seed imbibition were applied to these species.

Burial Depth Experiment

Three trial runs were conducted and were terminated 8 wk after planting of *S. parviflora* propagules. The first run of this experiment was initiated in May 2020, and the final two runs of this study were initiated in February 2021. The study was designed as a randomized complete block with five replications. Each propagule type (seed, small rhizome, large rhizome) was planted into a 10-cm-diameter by 30-cm-long PVC pipe (hereafter PVC pot) at one of five planting depths (1, 2, 4, 8, and 16 cm). One rhizome and five seeds were planted into each PVC pipe at the designated depth. The PVC pots were held by wooden stabilizers to keep pots upright and separated into five replications (Figure 2). Stabilizers contained all 15 pots that comprised one replication of the run. The bottoms of the PVC pots were covered with a fiberglass screen mesh (PHIFER, P.O. Box 1700, Tuscaloosa, AL 35403-1700) held in place by an elastic band and placed on top of a 10-cm terracotta tray to retain the soilless media while allowing for water to drain and the roots to access oxygen. The PVC pots were filled to the assigned treatment depths of 1, 2, 4, 8, and 16 cm. Different planting depths required the soilless media to fill the PVC pots to 29, 28, 26, 22, and 14 cm, respectively. Once the PVC pots were filled with soilless media and leveled, the propagule type was placed on top. The seed, small rhizome, and large rhizome assigned to each burial depth in a replication were placed on the prepared seedbed. The remainder of the soilless media was placed on top of the propagule type and filled to the top of the PVC pot. Each PVC pot received overhead watering twice daily until the water ran out of the bottom of the PVC pot to ensure the wetting of the entire pot.



Figure 1. Photograph displaying specimen variation of large and small rhizomes (left and right, respectively) of *Setaria parviflora* utilized in the burial depth study.

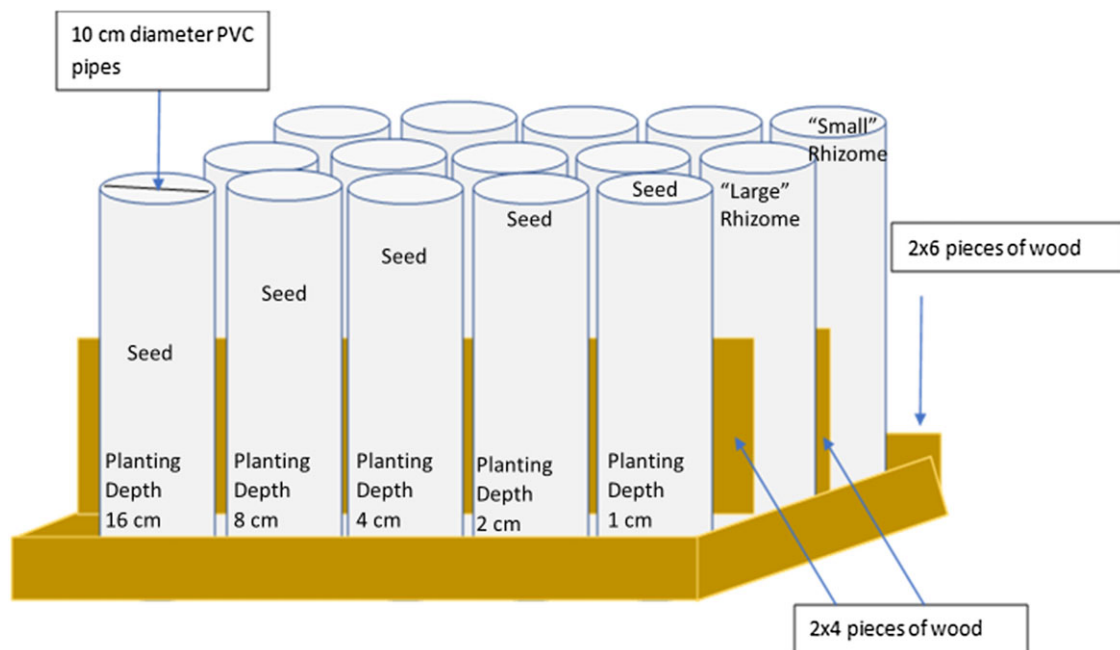


Figure 2. Diagram of *Setaria parviflora* treatments showing wooden stabilizers created to hold experimental PVC pots for the burial depth study.

Emergence was monitored daily during the 8-wk duration of the study. Onetime fertilization of each PVC pot was done 2 wk after emergence using Scotts Miracle-Gro® Water Soluble All Purpose Plant Food fertilizer (14111 Scottslawn Road, Marysville, OH 43041) at a rate of 90 kg ha⁻¹ due to the porous nature of the media and frequent watering. The liquid fertilizer was applied to each pot by mixing 120 ml of water with 7.35 g of the Miracle-Gro® fertilizer (24-8-16). These fertilizer quantities were based on current fertility recommendations for foxtail millet [*Setaria italica* (L.) P. Beauv.], equivalent to 67 to 90 kg ha⁻¹ of nitrogen.

Data were collected at 2-wk intervals after planting and continued to the end of the study (8 wk), when plants were destructively harvested. Plant counts were used to calculate emergence (%), height (cm), and phenology at 2, 4, 6, and 8 wk

after planting (WAP) (Hess et al. 1997; Meier 2018). The study was terminated at 8 WAP because *Setaria* spp. exhibited high rates of germination (>75%) under similar temperature regimes after only 2 wk (Leon et al. 2004; Manthey and Nalewaja 1987); however, additional time was allotted for the emergence of rhizome propagules. At termination, previously mentioned data were collected, followed by a destructive harvest. The destructive harvest included recording the presence of rhizome formation on seedling *S. parviflora* plants, removing the entire plant from the PVC pot, and separating the above- and belowground portions of the plant using hand pruners at the crown of the plant. Harvested belowground samples were cleaned to remove potting mixture residue and placed into paper bags. The collected biomass samples were placed in an IKA Oven 125 Basic Dry benchtop dryer

(2635 Northchase Parkway SE, Wilmington, NC 28405) at 105 C for 72 h until a constant dry weight was reached. Samples were removed from their bags and weighed to determine biomass (g). Total biomass per plant was calculated by adding above- and belowground biomass.

Setaria Species Comparison Experiment

Four trial runs of this experiment were completed from 2019 to late 2020. The first trial was initiated in June 2019, followed by additional runs starting in October 2019, March 2020, and July 2020. Seeds of the four *Setaria* spp. (*S. parviflora*, *S. pumila*, *S. faberi*, and *S. viridis*) were acquired and prepared for planting using the methodology previously described. The study design was a split plot with five harvests over four replications per run. Following plant emergence, seedlings of each species were thinned to 3 plants pot⁻¹. There were five monthly harvest dates with five replications of 3 plants pot⁻¹ of each species. Five replications with 3 plants pot⁻¹ were collected for every harvest date, equivalent to 100 pots and 300 plants for the whole experiment. Ten seeds of each *Setaria* species were planted in individual 3.78-L pots filled with the previously mentioned soilless potting mixture. After planting, a layer of approximately 0.5 cm of soilless media was carefully added, followed by each pot being watered to aid germination. Plants were watered twice daily and fertilized on three separate occasions at 2, 4, and 6 wk after emergence at the same rate previously described for the burial depth experiment.

Data were collected monthly for the trial duration (5 mo). Data were collected on every plant in the study monthly, and a destructive harvest was completed on one pot of each species in each replication. Data collection included plant height (cm) and phenological plant stages (using the BBCH scale) of remaining plants that were determined for each species (Hess et al. 1997; Meier 2018). At each harvest, 20 pots (5 of each *Setaria* species) underwent a destructive harvest. Plants were taken from their respective pots and separated at the soil surface using shears to separate above- and belowground biomass. Belowground biomass was cleaned by dipping roots in a bucket of water to dislodge the soilless media. All above- and belowground biomass for each species was placed in paper bags and put into a benchtop drier at 105 C for 72 h or until reaching a constant weight. Plants were removed from paper bags and weighed to determine above- and belowground biomass (g). Total biomass per plant was calculated by summing the above- and belowground biomass.

Statistical Analyses

Data analysis was conducted using JMP® Pro v. 17.2.0 (SAS Institute Inc., 100 SAS Campus Dr., Cary, NC 27513), and graphs were made using SigmaPlot v. 14.5 (Grafiti LLC, 405 Waverley St., Palo Alto, CA 94301). For the burial depth experiment, means for response variables were tested for ANOVA using the Mixed procedure by propagule type, with run selected as a random factor and depth selected as a fixed factor. For estimating responses for each variable, data were subjected to nonlinear models to predict responses based on burial depth. For emergence, a four-parameter logistics model was fit to the data at $\alpha \leq 0.05$. For comparison of nonlinear responses for emergence, an analysis of means for each of the components of the curve (upper asymptote and lower asymptote) at $\alpha \leq 0.05$ was conducted. Height and biomass data were analyzed using a Gompertz three-parameter model at $\alpha \leq 0.05$. Models were selected based on goodness of fit to the data based on R^2 and root mean-square error values for each model

and are appropriate models for the biological data measured (Knezevic et al. 2002; Ritz et al. 2015).

Response variables from the species comparison experiment (height, aboveground biomass, belowground biomass, and total biomass) were analyzed using ANOVA by harvest date using the Mixed procedure, with run selected as a random factor and species as the fixed factor with means separated using a Fisher's protected LSD at $\alpha \leq 0.05$. Response variables were analyzed by harvest and species.

Results and Discussion

Burial Depth Experiment

Burial depth reduced plant emergence, height, and biomass of each propagule type with increasing depth (Figures 3–5). Model parameters for a four-parameter logistics model indicate no emergence for small rhizome, large rhizome, and seeds at 8.7, 10.8, and 11.2 cm, respectively. A comparison of parameter estimates for the lower and upper asymptote estimates for the four-parameter logistics model indicated no differences between propagules (data not shown). Large rhizomes and seeds exhibited a significant decrease in emergence when propagules were planted at depths greater than 8 cm, while emergence was reduced significantly at 4 cm for small rhizomes (Figure 3). Therefore, burial depths starting at 8 cm begin to impact the plant emergence of *S. parviflora*, regardless of the propagule type. Previous research with johnsongrass [*Sorghum halepense* (L.) Pers.] revealed a greater potential for accelerated growth, yielding taller plants with more leaves and tillers from large rhizomes than small rhizomes (Lolas and Coble 1980). Smaller *S. halepense* rhizomes resulted in reduced plant emergence due to the exhaustion of limited carbohydrate reserves during germination and growth through the soil profile. Similar trends were observed when *S. halepense* rhizomes were replanted, with the small rhizomes exhibiting less growth potential and a lower propagation rate, consistent with the low emergence observed in the *S. parviflora* study (Anderson et al. 1960).

Estimates for emergence for 10% (E10) and 25% (E25) were similar for large rhizomes (8.18 and 7.93 respectively) and seeds (8.32 and 8.04 respectively). However, small rhizomes E₁₀ and E₂₅ values were 6.22 and 4.77 cm, respectively. Even at a 1-cm burial depth, small rhizomes emerged at less than 50%. Several factors may have contributed to the reduced plant emergence of small rhizomes compared with those emerging from large rhizomes and seeds. Visual differences in rhizome lignification were observed during the excavation of propagules for trial use. Large rhizomes had greater lignification, indicating more maturity, which may have increased germination and carbohydrate reserves for emergence and biomass accumulation. The difference observed between seed and rhizome performance is comparable to that of *S. halepense*, for which no differences were observed in plant growth between plants that did emerge from seeds and rhizomes (McWhorter 1961). Excavating less mature rhizomes could lead to some desiccation due to decreased lignification, decreasing viability through excessive desiccation, or exhaustion of stored carbohydrates. However, the sensitivity of non-lignified *S. parviflora* to non-edaphic conditions is unknown.

Plant height was affected by propagule type and burial depth (Figure 4). Plants grown from seed were the tallest (except for large rhizomes at a 4-cm burial depth), followed by large rhizomes, and finally, small rhizomes. A reduction in plant height is seen when propagules are buried more than 8 cm from the Gompertz

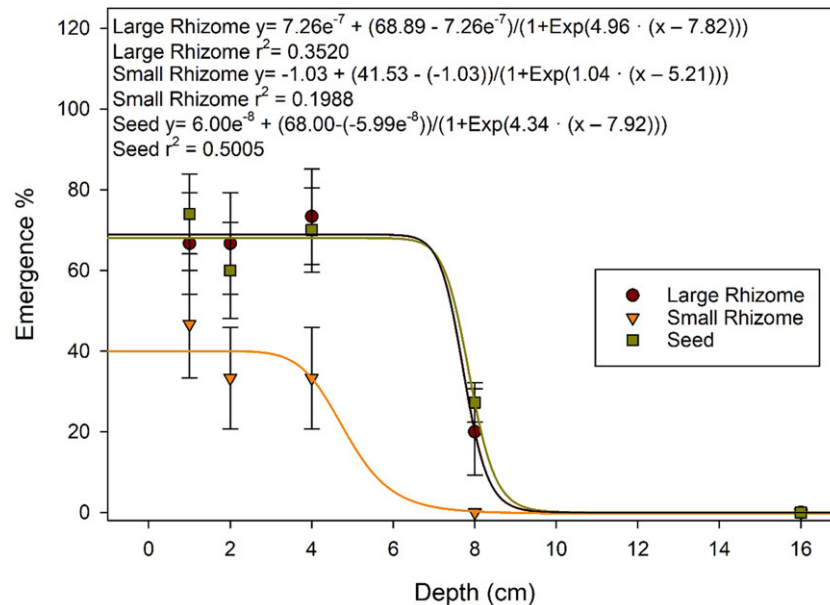


Figure 3. Emergence percentage of *Setaria parviflora* propagule types by burial depth (cm) for each propagule type; large rhizome (1.6 to 1.8 g), small rhizome (0.375 to 0.725 g), and seed regressed using a four-parameter logistics model.

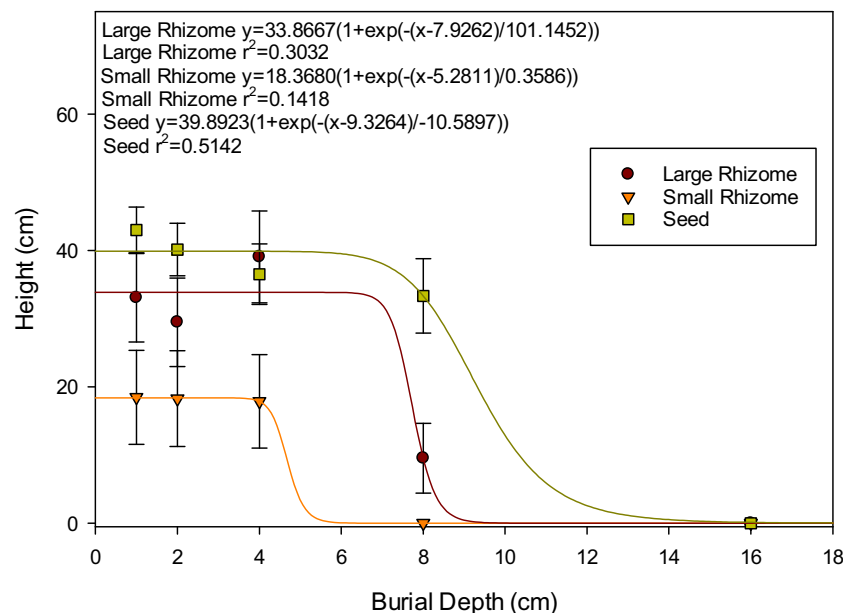


Figure 4. Height (cm) of emerged *Setaria parviflora* propagule types (seed, small rhizome, or large rhizome) by burial depth (cm) regressed using a three-parameter Gompertz model.

3-parameter nonlinear regression prediction. There was no emergence for all propagule types at a burial depth of 16 cm. The model estimated a zero height when propagules are buried at 8.7, 13.5, and 18.1 cm for small rhizomes, large rhizomes, and seeds, respectively. Propagation by seed resulted in the tallest plants, with the greatest average height of 43 cm achieved from the 1-cm burial depth. The tallest plants (averaging 39 cm) originating from large rhizomes were buried at a 4-cm depth. At the same burial depth of 4 cm, small rhizomes averaged 17 to 18 cm. Height response to burial depth was similar to emergence data, with small rhizomes showing a decrease at 4-cm depth, while reductions in height were not observed for seeds and large rhizomes until the 8-

cm depth. The model reported that the height of the propagule types will not decline until burial at 5.28, 7.92, and 10.59 cm for small rhizomes, large rhizomes, and seeds, respectively. These results follow trends similar to those seen in emergence data (Figure 3). Shorter *S. parviflora* plants emerging within forage canopies intercept less light, reducing competition with desirable forage (Patterson 1995). The growth potential of seed is less limited by burial depth when compared with rhizomes. This indicates that tillage may be a viable option for controlling germination of *S. parviflora* rhizomes. Counter to the findings in this study, previous research reported that the emergence of *S. halepense* from rhizomes was greater than from seeds, particularly when these

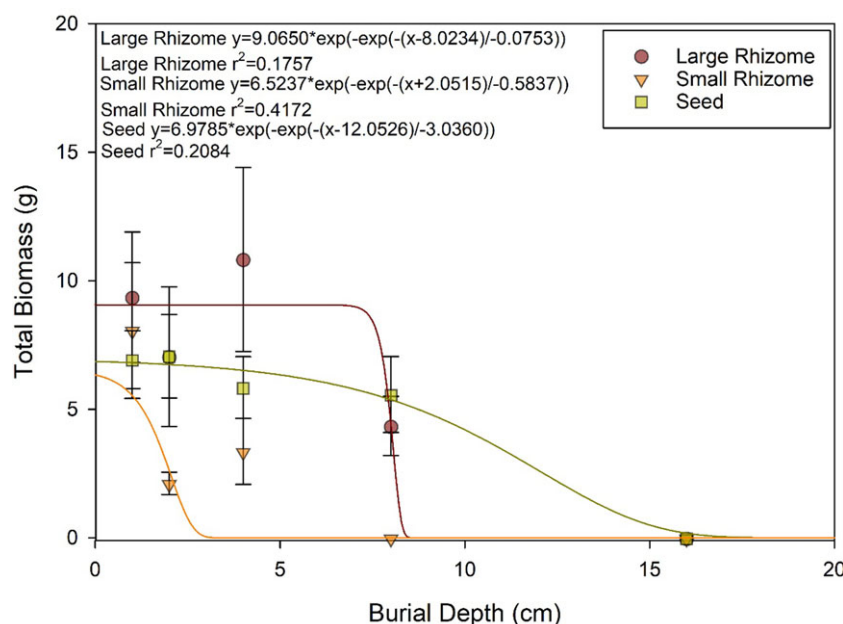


Figure 5. Total biomass (g) of *Setaria parviflora* propagule types (seed, small rhizome, or large rhizome) by burial depth (cm) regressed using a three-parameter Gompertz model.

propagules were located 10.2-cm deep in the soil profile (McWhorter 1972).

Data for total biomass followed trends similar to those reported for other response variables (Figure 5). As burial depth increased, total biomass production decreased. Total biomass for both rhizome sizes dropped significantly at the 8-cm depth. Estimations based on the Gompertz three-parameter model indicated that total biomass would reach 0 at depths of 5.9, 14.9, and 17.9 cm for small rhizomes, large rhizomes, and seeds, respectively. *Setaria parviflora* seeds have the most growth potential at the largest range of burial depths. Although seeds appear to be less affected by deep burial, greater control of *S. faberi* was reported in response to deep tillage of a moldboard plow compared with no-till or conservation tillage systems (Chauhan et al. 2006). A deep-tillage event only suppressed emergence from seed by approximately 20% compared with rhizomes. Control will increase if *S. parviflora* seeds are buried by a tillage event, but additional management methods may be needed to control *S. parviflora* emerging from seeds. The large rhizome and seed emerged at 8 cm, but plants emerging from seed outperformed those emerging from large rhizomes for height and total biomass at that burial depth. One study examining tall fescue [*Lolium arundinaceum* (Schreb.) S.J. Darbyshire; syn.: *Schedonorus arundinaceus* (Schreb.) Dumort.] suggests that biomass generated from seed should be larger than that from rhizomes, because resources are only allocated to shoot production (Matthew et al. 2001). Every mature propagule type can spread viable seeds. According to previous research, *S. parviflora* plants that mature, regardless of propagule origin, have the potential to set 150 to 300 viable seeds during the growing season in just 4 wk (Forcella et al. 2000). Germination of most *Setaria* spp. from seed can be controlled with preemergence herbicides, reducing the proliferation and emergence, but plants emerging from rhizomes are not well controlled with preemergence herbicides, indicating a need for a multipronged approach for management (Dyer et al. 2024).

Growers can identify the presence of *S. parviflora* by pulling plants and confirming the presence of rhizomes after only a single season; because *S. parviflora* can germinate from both seed and rhizome, both plant types will be present in the field. This is a relatively quick and easy method to ensure the correct identification of the species before deciding to renovate a pasture or hayfield. However, renovation of a pasture or hayfield using tillage should be considered a last resort for producers, as it is time-consuming and expensive and potentially creates a situation for other weedy species to become established. Therefore, a combination approach is essential, using tillage to address the rhizomes of *S. parviflora* and an efficacious herbicide program to impact seed germination and seedling emergence from the soil seedbank, such as spring-applied herbicides that are labeled for control of annual *Setaria* spp. (e.g., indaziflam and pendimethalin; Anonymous 2015, 2020; Dyer et al. 2024).

Species Comparison Experiment

The only notable difference in height between species was seen at 3 mo after emergence (MAE), when *S. faberi* and *S. pumila* were taller than *S. viridis* and *S. parviflora* (Figure 6A). Heights across all other times were found to be similar. Although plant morphology was not evaluated, *S. parviflora* tended to be more prostrate compared with the more upright annual *Setaria* species. With results indicating height differences at only the third month after emergence in the greenhouse, it is possible that this difference may not be easily noticeable in a field setting. Future research to differentiate and identify discrepancies in height between *S. parviflora* and *S. pumila* during the growing season is warranted.

No differences were found among the species in aboveground biomass at any of the harvest dates (Figure 6B). However, there were differences in belowground biomass between the different species across most harvest dates (Figure 6C). At 2 MAE, *S. pumila* and *S. parviflora* had greater belowground biomass than *S. viridis*

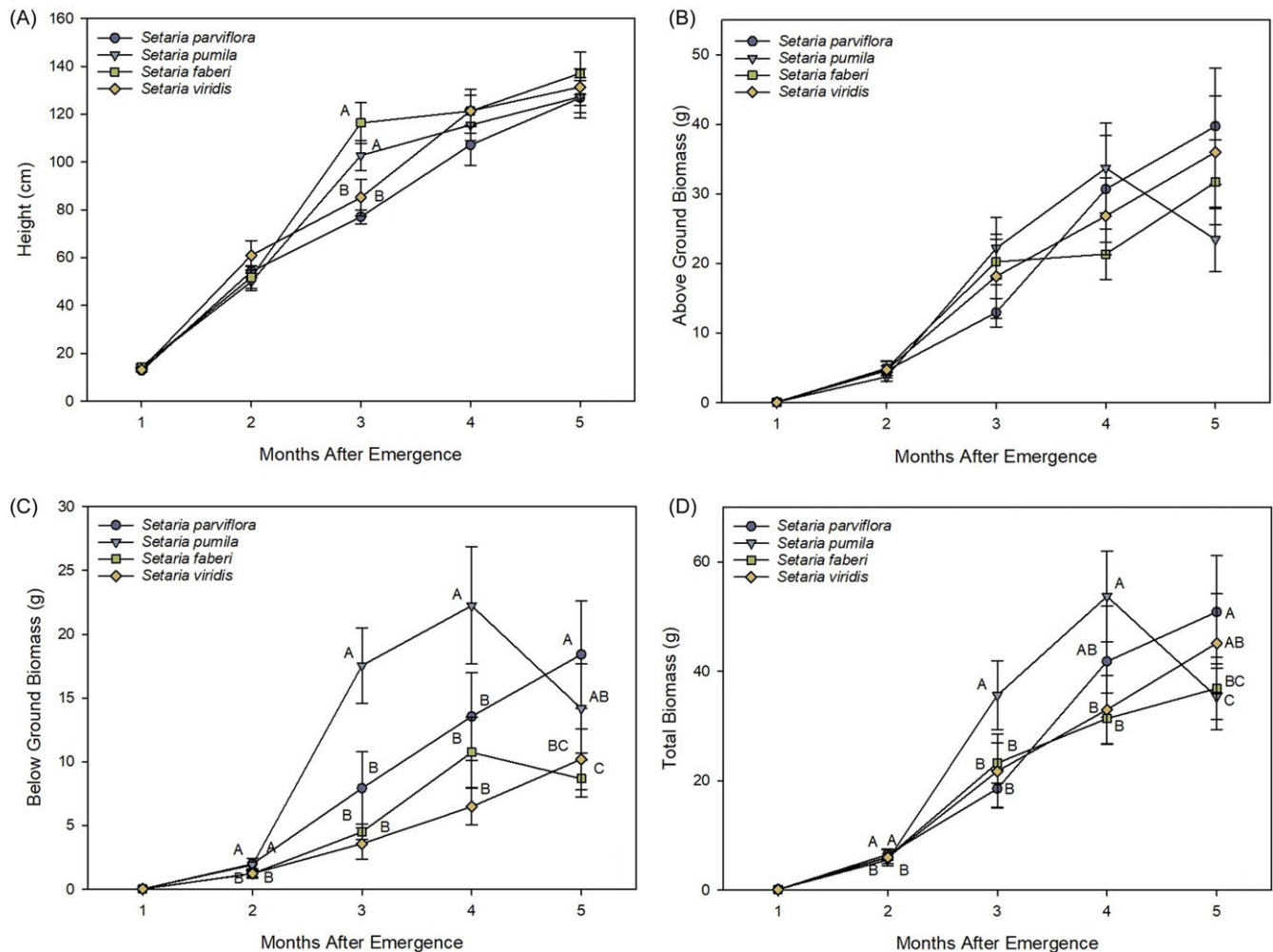


Figure 6. *Setaria* species comparisons of (A) height (cm), (B) aboveground biomass (g), (C) belowground biomass (g), and (D) total biomass (g) over time after emergence (months). Comparisons included *Setaria parviflora*, *Setaria pumila*, *Setaria faberi*, and *Setaria viridis*. Averages bearing the same letter or no letter at that time point indicate no difference for each plant response according to Fisher's protected LSD ($\alpha \leq 0.05$).

and *S. pumila*. By 3 and 4 MAE, *S. pumila* had greater biomass than all other species. At the final harvest (5 MAE), *S. parviflora* accumulated more biomass than *S. viridis* and *S. faberi*, while *S. pumila* had more biomass than *S. faberi*. *Setaria pumila* had a large fibrous root system compared with the other species. The high biomass of *S. pumila* fibrous roots could indicate a remarkable ability to compete for water and nutrients compared with other *Setaria* species, outcompeting desirable forage (Zimdahl 2004).

Setaria parviflora belowground biomass continued to increase at each harvest and eventually surpassed the belowground biomass of each of the other three *Setaria* species. This may indicate a shift from fine roots to storage roots with the production and development of rhizomes. At 3 MAE, *S. pumila* had greater total biomass than the other three *Setaria* species (Figure 6D). By 4 MAE, *S. pumila* and *S. parviflora* total biomass was comparable. However, *S. pumila* had more total biomass than *S. viridis* and *S. faberi*. This study showed that even though differences in aboveground biomass were minimal, there are differences in root biomass between closely related *S. parviflora* and *S. pumila*. Despite the high root biomass of *S. pumila*, rhizomes of *S. parviflora* began to form between months 4 and 5, steadily increasing belowground biomass, whereas *S. pumila* had significant amounts of fine fibrous roots compared with *S. parviflora*.

The earliest noted rhizome was found during the third harvest (3 MAE). Out of the approximately 300 *S. parviflora* plants harvested during the study, only 14 rhizomes were discovered. Therefore, this research was not capable of determining the time frame when *S. parviflora* transitioned from vegetative to perennial growth or the rate or percentage of plants emerging from seed that form rhizomes. However, consistent light and temperature conditions in the greenhouse could have impacted rhizome production. Both related *Setaria* species, *S. viridis*, and *S. italica*, have been described as short-day plants whose reproduction is triggered when daylengths are shortened (Doust et al. 2017). Rhizomes of *S. halepense* were shown to have the most carbohydrate flow down to the rhizomes around 4.5 MAE in a greenhouse setting (Anderson et al. 1960). Comparing what emergence was seen from *S. parviflora*, it is important to note that *S. halepense* rhizomes are produced much earlier in the growing season, as early as 18 d after emergence (McWhorter 1961). Future research should investigate the specific environmental factors that cause *S. parviflora* to begin shifting to perennial growth in order to give insight into how long after emergence the *S. parviflora* emerging from seed would need to be controlled before the formation of rhizomes.

Phenological growth stages observed for each species were noted before each plant harvest (Table 1). Phenology was similar at

Table 1. Phenological growth stages of *Setaria* species as described by the BBCH scale at each harvest time.^a

Species	Description of phenological growth stages ^b				
	1 MAE	2 MAE	3 MAE	4 MAE	5 MAE
Giant foxtail (<i>Setaria faberi</i>)	Nine or more true leaves, leaf pairs, or whorls unfolded	Flag sheath just visibly swollen (mid-boot)	First inflorescence fully emerged	Beginning of ripening or fruit coloration	Seed fully ripe
Green foxtail (<i>Setaria viridis</i>)	Seven true leaves, leaf pairs, or whorls unfolded	Flag leaf sheath swollen (late-boot)	30% of flowers open	Fully ripe	End of leaf fall, plants or aboveground parts dead or dormant
Knotroot foxtail (<i>Setaria parviflora</i>)	Nine or more true leaves, leaf pairs, or whorls unfolded	First individual flowers visible (still closed)	Fruits begin to develop	Nearly all fruits reach the final size normal for the species and location	Seed fully ripe
Yellow foxtail (<i>Setaria pumila</i>)	First side shoot visible	Vegetative reproduction organs begin to develop	30% of flowers open	Nearly all fruits reach the final size normal for the species and location	End of leaf fall, plants or aboveground parts dead or dormant

^aBBCH scale as described by Hess et al. (1997).

^bMAE, month(s) after emergence.

each data-collection timing, with *S. parviflora* tending to mature more quickly than the other *Setaria* species. Despite the quick maturation of *S. parviflora*, full plant maturity was observed in *S. pumila* and *S. viridis* between 4 and 5 MAE. Meanwhile, *S. parviflora* and *S. faberi* were not fully mature with seedheads and ripened seeds.

Our study indicates that tillage can be a viable option for control of *S. parviflora*, which is becoming increasingly problematic throughout parts of the southeastern United States. However, the disturbance of an entire pasture could provide opportunities for other species to establish. If a deep-tillage event is needed to bury large and small rhizomes, growers could also utilize preemergence herbicides labeled for control of annual *Setaria* spp. to control *S. parviflora* emerging from seed. Prevention of emergence and seed production is key and could be achieved through the use of preemergence herbicides and promotion of strong forage stands. Spot treatments of nonselective herbicides for control of *S. parviflora* may also provide needed control but would only be efficacious if infestation levels of perennialized plants were low. Tillage may be an option if done in smaller areas with high densities of *S. parviflora*, but more research is needed on control of this species on a larger scale. Future research could examine the growth stage or timing at which rhizome lignification occurs, what specific herbicides and timings are effective on rhizomatous *S. parviflora*, and whether combinations of management such as herbicides, mowing, or burning are effective means of management of this species.

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