Soil Texture and Planting Depth Affect Large Crabgrass (*Digitaria sanguinalis*), Virginia buttonweed (*Diodia virginiana*), and Cock's-comb Kyllinga (*Kyllinga squamulata*) Emergence

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Additional index words. emergence, emergence depth, germination, seed bank, soil texture

Abstract. Greenhouse studies were conducted to explore soil texture and planting depth effects on emergence of large crabgrass, Virginia buttonweed, and cock's-comb kyllinga. Soil textures examined were sand, loamy sand, and clay loam with planting depths of 0, 0.5, 1, 2, 4, 6, and 8 cm. Percent emergence was standardized relative to surface emergence to allow comparisons among tested weed species. The three-way interaction of weed species, planting depth, and soil texture was never significant for emergence. Significant interactions occurred between weed species and soil texture, weed species and planting depth, and soil texture and planting depth. For all weed species and soil textures, emergence decreased as planting depth increased with the greatest percent emergence at the soil surface. The planting depth at which weed emergence was decreased 50% [relative to surface emergence (D_{50})] was predicted by regression analysis. Large crabgrass emerged from deepest depths (8 cm) followed by Virginia buttonweed (6 cm) and cock's-comb kyllinga (2 cm). Large crabgrass, Virginia buttonweed, and cock's-comb kyllinga D_{50} occurred at 3.9, 1.1, and 0.8 cm, respectively. Sand, loamy sand, and clay loam D_{50} occurred at 0.9, 2.3, and 1.9 cm, respectively, with D_{50} higher in the soils with greater water-holding capacity.

Large crabgrass [*Digitaria sanguinalis* (L.) Scop.] (Poaceae), Virginia buttonweed (*Diodia virginiana* L.) (Rubiaceae), and cock's-comb kyllinga (*Kyllinga squamulata* Thonn. ex Vahl) (Cyperaceae) are common problematic weeds in turfgrass and crop production systems in the Southeast. Large crabgrass and cock's-comb kyllinga are prolific seed-producing summer annuals (Lowe et al., 1999; McCarty et al., 2001). Virginia buttonweed, a perennial dicot, can produce abundant fruit on branched stems reaching 100 cm in length (Baird and Dickens, 1991). These weed species inhabit landscapes

encompassing many different soil types and textures.

Weed seed germination and emergence depend on many factors, including species, light, temperature, pH, osmotic stress, and oxygen (Baird and Dickens, 1991; Benvenuti, 2003; Benvenuti et al., 2001; Chase et al., 1999; Chauhan and Johnson, 2008; Lowe et al., 1999; Oliveria and Norsworthy, 2006; Woolley and Stoller, 1978). After germination, burial depth, crop residue, soil air permeability, soil aggregation, and seed carbohydrate reserves resulting from seed size can influence weed emergence (Benvenuti, 2003; Chauhan and Johnson, 2008).

Soil texture and seed burial depth reportedly influence weed emergence. Porosity is associated with soil texture (Radford and Greenwood, 1970) and can affect germination and emergence resulting from diffusion of oxygen and volatile toxic metabolites contained in soil air space (Holm, 1972; Norton, 1986). Sandy soils have greater pore space resulting from increased particle size (Brady and Weil, 2002); therefore, gas diffusion may be increased. This allows for increased emergence in a predominantly sandy soil

compared with a soil with higher clay content [e.g., jimsonweed (*Datura stramonium* L.)] (Benvenuti, 2003). Increased planting depth can also affect germination and emergence (Benvenuti and Macchia, 1995). Large crabgrass emerged when seeds were present within 8 cm of the soil surface. Approximately 60% of large crabgrass populations emerged when buried at 2 cm, whereas less than 10% emerged from a depth of 6 cm (Benvenuti et al., 2001). Similar to large crabgrass, Virginia buttonweed emergence 14 d after planting occurred from planting depths of 8 cm, but maximum emergence (40%) was found at a depth of 2 cm (Baird and Dickens, 1991). Green kyllinga (*Kyllinga brevifolia* Rottb.) is also greatly inhibited by deeper planting depths, ceasing emergence at soil depths of 2 cm or greater (Molin et al., 1997).

Emergence of weed seeds at the soil surface also varies across species. Large crabgrass, buckhorn plantain (*Plantago lanceolata* L.), giant foxtail (*Setaria faberi* Herrm.), and green kyllinga all had lower emergence at the surface when compared with emergence from buried seed (Benvenuti et al., 2001; Fausey and Renner, 1997; Molin et al., 1997). In contrast, redroot pigweed (*Amaranthus retroflexus* L.), wild mustard [*Brassica kaber* (DC.) L.C. Wheeler], and black nightshade (*Solanum nigrum* L.) surface emergence was greater than when these weed species were buried (Benvenuti et al., 2001). Such differences can be attributed to physiological characteristics including seed carbohydrate reserves (Benvenuti, 2003; Chauhan and Johnson, 2008), seedcoat dormancy (Buhler et al., 1997), water-imbibing requirements (Wilson and Witkowski, 1998), and inhibitory substances (Baskin and Quarterman, 1969).

As a result of physiological differences among weed species, previous research evaluated emergence of various species separately. Therefore, interactions between weed species could not be determined. Standardizing the emergence response of multiple weed species to a selected planting depth will allow for comparison across weed species and botanical families to better determine if interactions exist among weed species, planting depth, and soil texture. Therefore, research was conducted to determine the effects of soil texture and burial depth on emergence of large crabgrass, cock's-comb kyllinga, and Virginia buttonweed.

Materials and Methods

Cock's-comb kyllinga and Virginia buttonweed were harvested at the Auburn University Turfgrass Research Unit (lat. 32°34'38.57" N, long. 85°29'59.76" W) located in Auburn, AL, in Summer 2009. Mature cock's-comb kyllinga plants were harvested at three separate locations (≈20 m²) with a rotary mower (3 cm height; Honda HRC 216, Alpharetta, GA) and clippings and seeds allowed to air-dry. Seeds were separated from clippings by sieving (2 mm). Virginia buttonweed dried fruits were collected from the soil surface in Dec. 2009 at the same

Received for publication 4 Feb. 2013. Accepted for publication 9 Mar. 2013.

We acknowledge Hunter Perry, Jay McCurdy, Michael Flessner, and Caleb Bristow for research support. Appreciation is also extended to Andy Syvanteck and Patrick Farmer for assistance in weed seed collection and separation. We also express gratitude to individuals who aided in sterilization of soils used in our experiments.

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location using a 9.5-L vacuum (9.5 L/1.9-kilowatt wet/dry vacuum; Lowes, Cornelius, NC). Sieving was performed to separate fruits from other material. Virginia buttonweed propagules are normally dispersed with fruit tissue surrounding the seeds and germinate within the intact pericarp. Initial data indicated seed separation from pericarp had no effect on germination; therefore, seed and pericarp were not separated (data not shown). Large crabgrass (Elstel Farm and Seeds, Ardmore, OK) seed was purchased commercially. Harvested seeds of the same species were mixed to reduce potential variability among collection sites and dates. All seeds were stored dry at 10 °C and 50% relative humidity before use. Preliminary data indicated large crabgrass, cock's-comb kyllinga, and Virginia buttonweed germination 75% or greater. Initial seed viability tests were conducted using tetrazolium (Moore, 1985). Staining patterns from the tetrazolium test were difficult to interpret as a result of inconsistency of the lactophenol clearing solution; therefore, no viability data are presented.

Soil textures for the study were selected to mimic common soils in Alabama and were a loamy sand, clay loam, and sand. Loamy sand was a Marvyn loamy sand (fine-loamy, kaolinitic, thermic Typic Kanhapludults) with pH 5.5 and 2.8% organic matter (OM). Clay loam was a Sumter silty clay (fine-silty, carbonatic, thermic Rendollic Eutrudepts) with pH 7.4 and 11.1% OM. Loamy sand and clay loam soils (upper 20 cm of soil profile) were collected by hand from Auburn and Marion Junction, AL, respectively. Sand was a sand/peat (Sphagnum Peatmoss; Premier Horticulture Inc., Quakertown, PA) mix with pH 5.2 and 2.7% OM. Sand/peat was thoroughly mixed to a 85:15 (v/v), sand:peat ratio. Soil physical and chemical properties are shown in Table 1. Particle size analysis was determined by the less than 2-mm pipette method (Soil Survey Investigation Staff, 2004). Organic matter was calculated from total organic carbon (Baldock and Nelson, 2000) as determined by LECO dry combustion methods outlined by Yeomans and Bremner (1991). Soil pH was determined by soil suspension 1:1 (soil:water) by weight (Soil Survey Investigation Staff, 2004).

Greenhouse trials were initiated in Spring 2010 to determine the effects of soil texture, planting depth, and weed species on emergence. The experimental design was a randomized complete block with four replications and two experimental runs. The experiment was arranged as a factorial combination of three soil textures, seven planting depths, and three weed species. Soil textural classes were loamy sand, clay loam, and sand. Soil planting depths were surface (0), 0.5, 1.0, 2.0, 4.0, 6.0, and 8.0 cm. Weed species were large crabgrass, cock's-comb kyllinga, and Virginia buttonweed. Dry soil was weighed and packed into soil columns (6.4-cm conduit polyvinyl chloride pipe, 6.2 cm internal diameter × 20 cm height) to planting depth. At the desired planting depth, 30 large crabgrass, cock's-comb kyllinga, or Virginia

buttonweed seeds or fruits were placed on the soil surface with no contact between seeds. Soil was then added to create the desired planting depth for each treatment to a final bulk density of 1.5 g·cm⁻³. Preliminary soil settling experiments resulted in seeds remaining at the prescribed planting depth.

Columns were placed in a controlled-environment greenhouse in Auburn, AL. Average greenhouse temperatures were maintained between 23 and 32 °C. Normal daytime irradiance (16 h) was supplemented with sodium-halide overhead lamps supplying 150 μmol·m⁻²·s⁻¹. Columns were irrigated with tap water daily to maintain field capacity throughout each study. Emerged seeds were counted and removed at 7-d intervals until emergence ceased. A seedling was considered emerged when the epicotyl penetrated the soil surface. After 2 weeks of no seedling emergence, the trial was ended.

For each weed species, percent emergence was calculated and standardized within each replication and experimental run with surface emergence counts as the reference point. Standardizing to surface emergence was performed, because initial research trials indicated maximum emergence of all three species at the soil surface (data not shown). Analysis of variance was performed using PROC MIXED in SAS (SAS Version 9.2; SAS Institute Inc., Cary, NC) using the appropriate means square values described by McIntosh (1983). Data were arcsine square-root transformed before analysis (Bowley, 2008). Interpretations were no different from non-transformed data; therefore, non-transformed means were presented for clarity. The significance level for all comparisons was $P = 0.05$. A significant experimental run-by-treatment interaction was not observed; therefore, data were pooled across experimental runs. Non-linear regression was performed to compare percent weed species emergence and soil texture to planting depth using SigmaPlot® (SigmaPlot 11.2® for

Windows®; SPSS Inc., Chicago, IL). The exponential decay model, as used by Chauhan and Johnson (2008) to explain the environmental factors on eclipia [*Eclipta prostrata* (L.) L.] seed germination and emergence, was used to describe large crabgrass, cock's-comb kyllinga, and Virginia buttonweed emergence by soil texture. The exponential decay model:

$$y = a * e^{(-b * x)} \quad [1]$$

(Eq. 1) was used for each weed species within each soil texture, where y was the response (emergence relative to surface emergence), a was the maximum emergence, b was the slope, and x was burial depth. The soil depth at which emergence decreased 50%, relative to surface emergence (D_{50}), was obtained by calculation.

Results and Discussion

For all weed species, emergence was reduced as planting depth increased (analysis of variance not shown). However, the degree of emergence reduction varied with weed species and soil texture. Significant interactions included soil texture by planting depth ($F = 2.16$, $P = 0.012$), soil texture by weed species ($F = 5.26$, $P = 0.002$), and planting depth by weed species ($F = 4.43$, $P < 0.001$). The three-way interaction predicting emergence by soil texture, planting depth, and weed species was insignificant ($F = 1.20$, $P = 0.238$).

The soil texture by weed species interaction data are presented in Table 2. Large crabgrass showed the highest percent emergence (across all planting depths) in sand (67), loamy sand (76), and clay loam (59). The emergence of large crabgrass (76%) in loamy sand was significantly greater than observed in the clay loam (59%), possibly a result of a lower clay content in the loamy sand. As clay content increased (from that in the sand to that in the clay loam), the emergence of cock's-comb kyllinga and Virginia

Table 1. Chemical and physical characteristics of soil textures in which planting depths were evaluated.^z

Soil series	Soil texture	Water content ^y Θ (v/v)	Sand	Silt	Clay	OM (mg·kg ⁻¹)	pH
Sand/peat ^x	Sand	0.09	98.82	0.96	0.22	26,900	5.2
Marvyn	Loamy sand	0.17	81.37	14.46	4.17	27,800	5.5
Sumter	Clay loam	0.35	23.14	40.74	36.12	110,400	7.4

^zOM = organic matter.

^ySoil water content at field capacity for soils was predetermined by Witkowska-Walczak et al. (2002), Wehje et al. (1993), and Wehtje et al. (1987) for sand, loamy sand, and clay loam soil textures, respectively.

^xSand:peat mixture; 85:15%, v:v.

Table 2. Soil texture by weed species interaction effects on emergence (%) relative to surface germination pooled across planting depths (0.5 to 8 cm).

Soil texture	Emergence		
	Large crabgrass	Cock's-comb kyllinga	Virginia buttonweed
	(%)		
Sand	66.9 (± 5.8) ^z	24.5 (± 5.6)	22.8 (± 5.0)
Loamy sand	75.8 (± 5.9)	31.8 (± 7.2)	46.8 (± 6.0)
Clay loam	58.6 (± 6.6)	36.4 (± 6.7)	49.9 (± 5.9)

^zMean emergence followed by standard error at $P = 0.05$ significance level.

buttonweed increased. This increase in emergence was likely the result of an increase in soil water- and/or nutrient-holding capacity (Lund, 1959).

The regression analysis (Eq. 1) of weed species by planting depth adequately predicted weed seed emergence for large crabgrass, cock's-comb kyllinga, and Virginia buttonweed ($R^2 = 0.95, 0.96$, and 0.98 , respectively) (Fig. 1). As planting depth increased, emergence decreased. The calculated D_{50} for each weed species was 3.9, 0.8, and 1.1 cm for large crabgrass, cock's-comb kyllinga, and Virginia buttonweed, respectively. Depth to achieve 0% large crabgrass emergence could not be determined within our range of planting depths. However, large crabgrass and other crabgrass species [Southern crabgrass, *Digitaria ciliaris* (Retz.) Koel. and India crabgrass, *Digitaria longiflora* (Retz.) Pers.] have been reported to have zero emergence within 8-cm planting depth (Benvenuti et al., 2001; Chauhan and Johnson, 2008). Additionally, results from our research differed from Benvenuti et al. (2001) and Chauhan and Johnson (2008) at shallower planting depths. For example, at the 0.5-cm planting depth, large crabgrass showed a slight increase (1%) in emergence (hormesis). However, this was not significantly different from emergence measured at the soil surface ($t = -0.22, P = 0.822$). In other work, this phenomenon was observed in Virginia buttonweed, prostrate spurge [*Chamaesyce humistrata* (Engel. Ex Gray) Small], and other weed species with slight burial at 0.5 to 1 cm (Chancellor, 1964; Krueger and Shaner, 1982; Mohler and Galford, 1997; Wiese and Davis, 1967). The hormesis effect could be attributed to water stress near the soil surface (Benvenuti et al., 2001). Our D_{50} of 3.9 cm for large crabgrass is similar to the 50% emergence value of 4.1 cm previously observed for large crabgrass (Benvenuti et al., 2001).

Virginia buttonweed emergence also decreased with increasing planting depth. At 8 cm depth, Virginia buttonweed emergence was nearly 0%, whereas 6% emergence was observed at 6 cm. Baird and Dickens (1991) reported $\approx 22\%$ emergence at a 6-cm planting depth, which translates to $\approx 9\%$ emergence relative to Virginia buttonweed surface emergence (31%). Virginia buttonweed emergence was greatest at 0.5 cm in our research, whereas previous studies observed maximum emergence at 2 cm (Baird and Dickens, 1991). Baird and Dickens (1991) observed reduced emergence at the soil surface as a result of fluctuating moisture conditions. During our experimentation, we minimized fluctuating moisture conditions by intense and consistent monitoring of research trials to maintain field capacity of each individual specimen. Our finding that Virginia buttonweed could emerge from a planting depth of 8 cm is consistent with previous work on this species. Virginia buttonweed seeds are 4 to 5 mm long and 2 to 3 mm wide (Baird and Dickens, 1991). Larger seeds have increased seed carbohydrate reserves allowing seedlings to emerge

from greater planting depths (Benvenuti, 2003; Chauhan and Johnson, 2008).

The D_{50} of Cock's-comb kyllinga was predicted at 0.8 cm. No emergence was observed at the 4-cm planting depth. Cock's-comb kyllinga does not germinate in the absence of light (Lowe et al., 1999), suggesting germination is light-dependent. Seeds buried more than 2 mm below the soil surface usually receive less than 1% incident light (Woolley and Stoller, 1978). With an increase in planting depth, emergence decreased across all soil types, suggesting light depletion as the primary influence on reduced emergence of cock's-comb kyllinga.

The interaction of soil texture and planting depth was modeled for sand, loamy sand,

and clay loam ($R^2 = 0.98, 0.94$, and 0.98 , respectively) (Fig. 2). Emergence decreased as planting depth increased, regardless of soil texture. The calculated D_{50} for each soil texture was 0.9, 2.3, and 1.9 cm for sand, loamy sand, and clay loam, respectively. Benvenuti (2003) observed a linear response between D_{50} depth of jimsonweed (*Datura stramonium* L.) emergence and soil clay and sand content. Emergence inhibition resulting from burial depth was found to be inversely proportional to clay content and directly proportional to sand content (Benvenuti, 2003).

Benvenuti (2003) used soils ranging in pH of 7.2 to 8.4 and soils in our experiments had a pH range of 5.2 to 7.4. Virginia

Fig. 1. Weed species and planting depth effects on emergence (%) relative to surface emergence pooled across soil textures (sand, loamy sand, clay loam). Vertical bars represent SE at $P = 0.05$ significance level. E = emergence; x = depth (cm).

Fig. 2. Soil texture and planting depth effects on emergence (%) relative to surface emergence pooled across weed species (large crabgrass, Virginia buttonweed, cock's-comb kyllinga). Vertical bars represent SE at $P = 0.05$ significance level. E = emergence (%); x = depth (cm).

buttonweed and large crabgrass have previously exhibited decreased emergence at higher soil pH levels (Baird and Dickens, 1991; Chauhan and Johnson, 2008), which may explain the conflicting results. Soil pH may have influenced weed germination and emergence.

Current research suggests that emergence of weed seed distributed throughout the soil profile are influenced by soil texture and planting depth. For all weed species, emergence was reduced as planting depth increased. Emergence of weed species of various soil textures responded differently to planting depths. This is important during turfgrass renovation practices because deep tillage can redistribute weed seeds present deeper in the profile to the soil surface and may cause an increase emergence. Across all weed species, soil texture influenced emergence, suggesting soil properties may have an influential role in emergence.

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