Factors Affecting Thermal Weed Control

by

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Abstract

Early thermal weed-control measures were known to be rudimentary and hazardous. Thermal weed control has progressed in sophistication, application, and efficiency and has resulted in many commercial systems available for common row-cropping applications. Flame weeding for established turfgrass is not effective because of the inability to treat weeds without injuring the turfgrass system. Aesthetically this type of treatment would be unacceptable. Therefore, past thermal weed control measures can be refined to utilize direct soil heating by flame from propane burners for the production of a stale seedbed. Initial soil-sterilization and flame heating studies conducted in 2009 and 2010 demonstrated a high potential for reducing weed populations before turfgrass establishment. Many factors can alter the efficacy of this type of thermal treatment including seed heat tolerance, seed depth, thermal conductivity, and soil moisture content. For acceptable weed control utilizing this method, adequate soil temperatures need to be achieved. Planting depth in a Marvyn loamy sand (Fine-loamy, kaolintic, thermic Typic Kanhapudult) and seed heat tolerance research was conducted to evaluate germination and emergence of weed seeds. Large crabgrass (*Digitaria sanguinalis*), Virginia buttonweed (*Diodia virginiana*), and cocks-comb kyllinga (*Kyllinga squamulata*) emerged from 8, 6, and 2 cm maximum planting depths, respectively. Temperature and duration effects on weed germination experiments resulted in 0% germination of large crabgrass, Virginia buttonweed, and cocks-comb kyllinga at 120, 250, and 120°C, respectively, for 5 second heat exposure. Heat transfer studies utilizing a PL8750 Poultry House Flame Sanitizer (Flame Engineering, Inc; LaCrosse, KS) in Marvyn loamy sand at 0.1 volumetric water content (θ) resulted in only surface temperatures adequate to prevent weed germination. Further experimentation resulted in a thermal conductivity of 0.96 W m^{-1} K^{-1}. Compilation of results shows potential for effective present application of thermal weed control in turfgrass management.

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List of Abbreviations and Symbols

2×CEWF	repeat applications of covered emerged weed flaming
2×EWF	repeat applications of emerged weed flaming
Adj	adjusted
AL	Alabama
BTU	British thermal unit
C, °C	degrees Celsius
CEWF	covered emerged weed flaming
C_h	volumetric heat capacity
cm	centimeter
CON	control
CYPES	yellow nutsedge
d	day
D_{50}	decreased 50 percent
DAMST	daily average maximum soil temperature
DAZ	dazomet
DIGSA	large crabgrass
DIQVI	Virginia buttonweed
DSF	direct soil flaming

diam	diameter
ELEIN	goosegrass
EPHMA	spotted spurge
EWF	emerged weed flaming
ft	feet
g	gram
gal	gallon
h	hour
ha	hectare
J	joules
K	Kelvin
kg	kilogram
kPa	kilopascal
kph	kilometer per hour
KYSQ	cock’s-comb kyllinga
LPG	liquefied petroleum gas
LSD	least significant difference
m	meter
mm	millimeter
min	minute
mL	milliliter
MOLVE	carpetweed
OLDCO	old world diamond-flower

OM	organic matter
%	percent
RH	relative humidity
s	second
SOL	solarization
λ	thermal conductivity
TDP	thermal death point
TGRU	Turfgrass Research Unit
θ	volumetric water content
w	week
WAS	weeks after seeding
WAT	weeks after treatment
W h	watt hours
Δ	change

I. Thermal Weed Control Methods and Factors Influencing Efficacy: A Review

Introduction

Thermal weed control methods generate heat to kill weed-seeds and emerged-weeds (Bond et al. 2007). Techniques include soil solarization (Horowitz et al. 1983), flame weeding (Ascard 1990), infrared radiation (Ascard 1998), steaming and hot water (Anon 1999; Trotter 1991), direct heat (Hopkins 1936), electrocution (Vigneault et al. 1990), microwave radiation, electrostatic fields (Diprose et al. 1984), irradiation (Suss and Bacthaler 1968), lasers (Couch and Gangstad 1974), and ultraviolet light (Andreasen et al. 1999).

Soil Solarization

Soil solarization is a method of pest control by heating soil by covering with plastic sheeting (Horowitz et al. 1983). It has been noted as a non-chemical means of reducing weed seed populations (Katan et al. 1976; Egley 1983; Horowitz et al. 1983; Rubin and Benjamin 1983; Standifer et al. 1984; Peachey et al. 2001). Effective solarization requires climates with long sun exposure periods and increased ambient temperatures for sufficient amount of time (Standifer et al. 1984). Solarization has been utilized in horticulture crops like lettuce and garlic (Al-Massom et al. 1993), squash and tomato (Abu-Irmaileh 1991), and other high value crops. High value vegetable crops warrant the increased application cost of solarization (Bell et al. 1988). Applied across multiple locations, solarization has proven to provide adequate control of annual bluegrass (*Poa annua* L.) (Standifer et al 1984; Bell and Laemmlen 1991; Elmore 1991; Peachey et al. 2001). Not all weed species are susceptible to solarizaton (Egley 1990). Many weed species have buried reproductive organs, which make solarization an ineffective thermal weed control method (Bell et al. 1988; Horowitz et al. 1983; Rubin and Benjamin 1984).

Flame Weeding

Other thermal weed control methods utilize an intense wave of heat from a flame to rupture plant cells (Leroux et al. 2001; Bond et al. 2007). This thermal weed control method, called emerged flame weeding, typically utilizes liquefied petroleum gas (LPG) or propane as the fuel source to create intense flame from manufactured burners (Ascard 1995). Systems of flame weeding have been developed from hand-held flamers for small-scale vegetable production (Bowman 1997; Peruzzi et al. 2007) to tractor-mounted systems for large-scale row crop flaming. Factors that influence flame weeding efficacy have been intensely studied, along with technical aspects of the burner apparatus (Ascard 1994, 1995, 1997, 1998). Flaming studies have shown that susceptibility to this type of application varied among species and seedling size (Cisneros and Zandstra 2008).

Soil Flaming

The vast majority of research has focused on open flame units that seek to heat emerged plants (Ascard 1994, 1995, 1997, 1998; Bond and Grundy 2001; Cisneros and Zandstra 2008). Similar to flame weeding, direct heat applications flames the soil surface instead of emerged weeds. Direct heat increases soil temperatures to the weed seed thermal death point. These methods have not been thoroughly explored.

Thermal Weed Control Mode of Action

Although these methods vary in application and efficacy one common factor exists between thermal weed control methods. All thermal weed control methods denaturizing proteins by heat (Parish 1990) resulting in loss of cell function, causing intracellular water expansion (Lague et al. 2001) rupturing membranes (Morelle 1993; Pelletier et al. 1995) to ultimately render death to emerged weeds or weed seeds (Heiniger 1999; Rahkonen and Jokela 2003; Rifai et al. 1996). Due to the response of plants to thermal heat, selectivity between crop and weed species can only be achieved through thermal heat placement.

Weeds contained in agronomic row crops are often difficult to control and mechanical methods can cause crop plant damage. Therefore, flame weeding can provide effective weed control in the crop row where cultivation is difficult (Sivesind et al. 2009). Effective selectivity between crop and weed species can also be achieved by direct heating in row cropping systems. Thermal heat can be applied to the soil between rows to achieve the thermal death point of weed seeds in the soil profile.

Thermal Weed Control for Turfgrass Management

Although effective in row cropping systems, flame weeding is not acceptable thermal weed control method in established turfgrass systems. Selectivity cannot be achieved between unwanted weed species and desired turfgrass grass species due to close proximity. Thermal heat applied to an established system can reduce aesthetic, recreational, and functional turfgrass quality. For any thermal weed control method to be effective in turfgrass systems the application must be conducted prior to turfgrass establishment. Typically classified as pre-emergence thermal weed control, thermal application kills the first flush of weeds. This is often the largest group of weeds to germinate during the season (Cisneros and Zandstra 2008). Pre-emergence thermal weed control applications have also been conducted in small-seeded, slow germinating crops such as onion and carrot (Ascard 1997). As turfgrass establishment by seed is relatively slow compared to that of sod or sprigs reducing weed seed populations by thermal heat prior to turfgrass establishment could possibly shift the competitive advantage from weeds to turfgrass. Thermal weed control methods have shown positive effectiveness in row cropping systems as well as high value vegetable production. It is unknown if similar thermal weed control methods are effective in reducing weed populations prior to turfgrass establishment.

Factors Affecting Thermal Weed Control

The thermal death point is the temperature at which a seed will not germinate after instantaneous or a brief period of heat application (Hopkins 1936). Thermal weed control methods vary in efficacy. This is due to a wide range of influential factors including targeted weed species (Dahlquist et al. 2007; Egley 1990), planting depth (Benvenuti et al. 2001), soil texture (Van Rooyen and Winkerton 1959), soil moisture (Van Duin 1963), thermal conductivity (Patten 1909; Smith 1942), soil chemical properties (Bowers and Hanks 1962; Lang 1878; Ulrich 1894), and soil porosity (Ochsner et al. 2001).

Soil Texture and Burial Depth. Soil texture and seed burial depth are known factors that influence weed emergence. Directly linked to soil texture, soil porosity (Radford and Greenwood 1970) can influence germination and emergence due to gas diffusion of oxygen and volatile toxic metabolites contained in soil air space (Norton 1986; Holm 1972). Sandy soils obtain greater pore space due to increased particle size (Brady and Weil 2002) therefore gas diffusion is increased. This allows for increased emergence in a predominantly sandy soil compared to a soil with increased clay content. For example, jimsonweed (*Datura stramonium* L) emergence was higher in sandy soils (Benvenuti 2003). Increased planting depths can also effect germination and emergence (Benvenuti and Macchia 1995). Large crabgrass was shown to emerge within 8 cm of the soil surface. Approximately 60% large crabgrass populations emerged when buried at 2 cm. At 6 cm, less than 10% large crabgrass populations emerged (Benvenuti et al. 2001). Similar to large crabgrass, 14 d after planting Virginia buttonweed, emergence occurred from depths of 8 cm with maximum emergence (40%) at 2 cm (Baird and Dickens 1991). Green kyllinga (*Kyllinga brevifolia* Rottb.) is also greatly inhibited by planting depth, ceasing emergence at 2 cm (Molin et al. 1997).

Emergence of individual weed seeds varies with planting depths. Surface germination also varies by species. Large crabgrass, buckhorn plantain (*Pantago lanceolata* L.), Virginia buttonweed, giant foxtail (*Setaria faberi* Herrm.) and green kyllinga surface germination is less than buried seed emergence (Benvenuti et al. 2001; Baird and Dickens 1991; Fausy and Renner 1997; Molin et al. 1997). Redroot pigweed (*Amarathus retroflexus* L.), wild mustard [*Brassica kaber* (DC.) L.C. wheeler] and black nightshade (*Solanium nigrum* L.) surface germination is greater than buried seed populations (Benvenuti et al. 2001). These differences can be attributed to many physiological ifactors, ncluding seed carbohydrate reserves (Chauhan and Johnson 2008; Benvenuti 2003), seed coat dormancy (Buhler et al. 1997), water imbibing requirements (Wilson and Witkowski 1998) and inhibitory substances (Baskin and Quarterman 1969). Most importantly these physiological factors differ by plant family and species.

Exposure Time and Temperature. The ability to achieve an optimal temperature for weed seed mortality varies with energy source. Laboratory soil steaming at 90 s required temperatures between 65 and 75 C to kill individual weed species, losing 1 C per 60 s after the heat source was removed (Melander et al. 2002a; Melander et al. 2002b). Mobile steaming units were detrimental to weed species reaching soil temperatures of 70 to 100 C for 3 to 8 min (White et al. 2000a; White et al. 2000b). Heat exposure by solarization may require greater than 65 C (Standifer et al. 1984). Utilizing solarization soil temperatures may exceed the thermal seed threshold for only a short period per d (0 to 2 h); therefore, several days or weeks of application are needed to accumulate sufficient heat exposure (Horowitz and Taylorson 1983).

Thermal weed control efficacy not only depends on energy source but also depends on temperature and duration required to achieve thermal death point (TDP) of targeted weed species. Temperature to achieve thermal weed seed death varies with species (Rubin and Benjamin 1984; Egley 1983, 1990; Linke 1994). Hopkins (1936) reported lethal temperature varied by weed species when exposed to 15 min of thermal heat; wild oat (*Avena fatua* L.) lethal death temperature was 105 C while red root pigweed (*Amaranthus retroflexus* L.) was 85 C. Broadleaf dock (*Rumex obtusifolia* L.) seeds exposed to 75 C thermal temperature ceased germination when averaged across 0.5

to 16 d thermal exposure (Thompson et al. 1997). Effective annual bluegrass (*Poa annua* L.) germination reduction was achieved with a total of 66 h above 45 C (Peachey et al. 2001).

Regardless of the method and weed species, the two primary interactive factors that influence thermal weed control are temperature achieved and exposure time. In general, higher temperatures require shorter duration and lower temperatures require a longer duration. To achieve 100% mortality of barnyardgrass (*Echinochloa crus-galli* L. Beauv.) exposure time varied among temperatures. A short duration (0.17 h) required 70 C for 100% barnyardgrass mortality. When decreasing thermal temperature to 46 C, 16 h exposure period was required for the same result. Longer exposure times were required for common purslane (*Portulaca oleracea* L.) to achieved 100% mortality; 50 C for 56 h. When common purslane seeds were placed in moist soil thermal heat exposure period increased to 7 d for effective germination reduction (Egley 1990). Effective velvetleaf (*Abutilon theophrasti* Medik.) germination inhibition increased exposure temperature 10 C when decreasing exposure time by 9 h (Horowitz and Taylorson 1983). Similar results have been observed in common lambsquarters (*Chenopodium album* L.) and Indian mustard (*Brassica juncea* L. Czern.) (Thompson et al. 1997; Hopkins 1936). These previous studies exemplified that an expenditure of reduced thermal heat exposure time was an increase in temperature for effective decrease in seed germination.

The major limitation to thermal weed seed control methods is low temperature applications. Thermal weed control methods that apply lower temperatures require longer exposure times for adequate weed germination reduction. Longer exposure times decrease the potential treated acreage. Thermal dry heat applications can only treat 1 to 2 ha d^{-1} (Williams 1999). Mobile steaming units can only be applied at 40 to 100 h ha^{-1} (Bond et al. 2007). Other low intensity-long exposure time applications, such as solarization, can require up to a 6-week application (Horowitz et al. 1983). Commonly these thermal weed control methods require extended heat exposure periods.

Research Objectives

1. Studies were designed to test the efficacy of various thermal weed control methods prior to turfgrass establishment on common weed species found in turfgrass production facilities in the South East United States. Various methods included previously studied thermal weed control methods along, with new methods. Results can provide insight on thermal weed control applications, along with the development of new non-chemical weed control methods for turfgrass systems.

2. Due to physiological differences among weed species past weed seed emergence experiments analyze individual weed species separately therefore interactions between weed species cannot be determined. Standardizing emergence response of multiple weeds species will allow for comparison across weed species, planting depth, and soil texture. Also, past seed depth emergence studies report surface germination incorrectly as surface emergence. Research was conducted to determine the effect of soil textures and burial depths and weed seed emergence of three species; large crabgrass (Poaceae), cock's-comb kyllinga (Cyperaceae), and Virginia buttonweed (Rubiaceae) by standardizing emergence relative to surface germination, allowing for comparisons between weed species.

3. Develop a thermal weed control method utilizing a PL8750 flame sanitizer® for stale-seed-bed preparation prior to turfgrass establishment (Hoyle et al. 2011). This application method utilizes intense thermal heat from 6, 3.3×10^5 W h (watt hours) torches, individually reaching approximately 1121 C flame temperature. The increased flame temperature allows heat energy transfer through soil to weed-seed-population location. This method is completely different than all other flame weed control or soil heating techniques utilized in the past. This method also applies a high intensity of heat for a much shorter time duration ($\leq$ 20 s) depending on speed. Therefore, the purpose of this study was to investigate increased thermal temperatures at short exposure periods on large crabgrass (*Digitaria sanguinalis)*, cock's-comb kyllinga (*Kyllinga squamulata)*, and Virginia buttonweed (*Diodia virginiana*) in order to simulate heat exposure.

4. Studies were designed to observed soil temperatures at various depths (0, 1, 3, and 10 cm) after direct heat application of PL-87650 flame sanitizer® at two exposure periods (5 and 20 s) or two volumetric water contents (0.1 and 0.2 θ). Results can determine efficacy of evaluated thermal weed control application on pervious researched weed species. Results also can predict if current method of thermal weed control is applicable if thermal death point and emergence depth of targeted weed species is determined.

5. Studies were designed to observed soil temperatures at various depths (0, 1, and 3 cm) during soil solarization application and use common collected weather data (ambient air temperature, dew point, wet bulb temperature, relative humidity, precipitation, solar radiation, and high temperature) to predict solarization soil

temperatures for the Southeastern United States. Results will predict if current method of thermal weed control is applicable if TDP of targeted weed species is determined.

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II. Altering Weed Populations by Various Thermal Weed Control Methods

Abstract

Thermal heat has been utilized for non-selective weed control methods. A possible way to use thermal weed control methods in a perennial-type turfgrass system is prior to turfgrass establishment. Field research trials were conducted to explore the efficacy of emerged-weed flaming, soil flaming, solarization, and variations of the previous at two application timings. Data were individual weed species relative to control treatment within each replication within each experimental run. Species evaluated included carpetweed, Virginia buttonweed, spotted spurge, large crabgrass, goosegrass, old world diamond-flower, cock's-comb kyllinga, and yellow nutsedge. Turfgrass establishment was not successful in summer research trials. Summer application timing trials resulted in unacceptable turfgrass establishment (≤18%) for all evaluated turfgrass species at 6 weeks after seeding (WAS). Fall application timing trials resulted in >60% tall fescue establishment at 6 WAS for all treatments. Broadleaf and grassy weeds were more easily controlled compared to sedge weeds. Overall, solarization, covered emerged-weed flaming, and split applications of covered emerged-weed flaming were effective treatments. Solarization obtained >80% control of carpetweed, Virginia buttonweed, spotted spurge, large crabgrass, and goosegrass at 6 WAS. Weed control across thermal treatments were equal to or greater than the comparison chemical treatment (389 kg dazomet ha^{-1}). Evaluated thermal weed control methods shows potential for reducing weed populations prior to turfgrass establishment.

Nomenclature: Basamid, dazomet; carpetweed, *Mollugo verticillata* L. MOLVE; cock's-comb kyllinga, *Kyllinga squamulata* Thonn. ex Vahl; goosegrass, *Eleusine indica* L. Gaertn. ELEIN; large crabgrass, *Digitaria sanguinalis* L. Scop. DIGSA; old world diamond-flower, *Oldenlandia corymbosa* L. OLDCO; spotted spurge, *Chamaesyce maculata* L. EPHMA; Virginia buttonweed, *Diodia virginiana* L. DIQVI; yellow nutsedge, *Cyperus esculentus* L. CYPES; 'Sea Spray' seashore paspalum, *Paspalum vaginatum* Swartz.; tall fescue, *Lolium arundinaceum* (Schreb.) S.J. Darbyshire.; 'TifBlair' centipedegrass, *Eremochloa ophiuroides* (Murno) Hack.; 'Zentih' zoysiagrass, Z*oysia japonica* Steud.

Key words: Thermal weed control, methyl bromide alternative, emerged weed flaming, direct soil flaming, soil solarization.

Introduction

Thermal weed control methods utilize heat to kill weed seeds and emerged weeds (Bond et al. 2007). Techniques include soil solarization (Horowitz et al. 1983), flame weeding (Ascard 1990), infrared radiation (Ascard 1998), steaming and hot water (Annon 1999; Trotter 1991), direct heat (Hopkins 1936), electrocution (Vigneault et al. 1990), microwave radiation, electrostatic fields (Diprose et al. 1984), irradiation (Suss and Bacthaler 1968), lasers (Couch and Gangstad 1974; Heisel et al. 2002; Mathiassen et al. 2006), and ultraviolet light (Andreasen et al. 1999).

One of the first thermal weed control methods, soil solarization, heats soil by covering with plastic sheeting (Horowitz et al. 1983). Soil solarization has been noted as a non-chemical means of reducing weed seed populations (Katan et al. 1976; Egley 1983; Horowitz et al. 1983; Rubin and Benjamin 1983; Standifer et al. 1984; Peachey et al. 2001). Effective solarization requires climates with long sun exposure periods and increased ambient temperatures as well as a sufficient amount of time (Standifer et al. 1984). Solarization has been utilized in horticulture crops including lettuce and garlic (Al-Masson et al. 1993), squash and tomato (Abu-Irmaileh 1991), and others. These high value vegetable crops can warrant the increased application cost of solarization (Bell et al. 1988). Solarization has shown successful annual bluegrass (*Poa annua* L.) control (Standifer et al. 1984; Bell and Laemmlen 1991; Elmore 1991; Peachey et al. 2001) although, not all weed species are susceptible (Egley 1990). Many weed species have buried reproductive organs, which makes weed control difficult by solarization (Bell et al. 1988; Horowitz et al. 1983; Rubin and Benjamin 1984).

Most recently utilized in thermal weed control, flame weeding uses an intense wave of heat to rupture plant cells (Hatcher and Melander 2003; Bond et al. 2007). Flame weeding typically utilizes liquefied petroleum gas (LPG) or propane, as the fuel source (Ascard 1995). Flame weeding systems have been developed from hand-held flamers for small-scale vegetable production to tractor-mounted systems for large-scale row crop flaming (Bond and Grundy 2001). Factors influencing flame weeding efficacy have been intensely researched, along with technical aspects of the burner apparatus (Ascard 1994, 1995, 1997, 1998). Preemergent crop flaming studies have demonstrated that susceptibility to thermal heat varied among weed species and seedling size (Cisneros and Zandstra 2008).

The vast majority of research has focused on open flame units that seek to heat emerged plants (Ascard 1994, 1995, 1997, 1998; Bond and Grundy 2001; Cisneros and Zandstra 2008). Similar to flame weeding, direct heat applications the heat directly flames the soil surface instead of emerged weeds. Direct heat applications increases soil temperatures to the weed seed thermal death point (TDP), which is the temperature at which a seed will not germinate after heat application (Hopkins 1936). Many factors influence the efficacy of direct heat, including targeted weed species (Dahlquist et al. 2007; Egley 1990), planting depth (Benvenuti et al. 2001), soil texture (Van Rooyen and Winkerton 1959), soil moisture (Van Duin 1963), thermal conductivity (Patten 1909; Smith 1942), soil chemical properties (Bowers and Hanks 1962; Lang 1878; Ulrich 1894), and soil porosity (Ochsner et al. 2001). These factors contribute to the large variation in efficacy of direct heat applications.

All thermal weed control methods denature proteins by heat (Parish 1990) resulting in loss of cell function and lead to intracellular water expansion (Lague et al. 2001) and ruptured membranes (Morelle 1993; Pelletier et al. 1995). Ultimately these factors render death to emerged plants or seeds (Heiniger 1999; Rahkonen and Jokela 2003; Rifai et al. 1996). Therefore, selectivity between crop and weed species is achieved through thermal heat placement.

Although thermal heat placement can be effective in row cropping systems (Melander and Rasmussen 2001), direct heat and flame weeding are not acceptable thermal weed control methods in established turfgrass systems. Thermal heat applied to an established system can reduce aesthetic and functional turfgrass quality. For any thermal weed control method to be effective in turfgrass systems, application must be conducted prior to turfgrass establishment. Preemergence thermal weed control kills the first flush of weeds, which is often the largest weed germination period during establishment (Cisneros and Zandstra 2008). Preemergence thermal weed control applications have been successfully conducted in small-seeded, slow germinating crops such as onion and carrot (Ascard 1997). Turfgrass establishment by seed is relatively slow, which allows weed seed to germinate. Reducing weed seed populations by thermal heat prior to turfgrass establishment would likely shift the competitive advantage from weeds to turfgrass species. It is unknown if thermal weed control methods are effective in reducing weed populations prior to turfgrass establishment.

Studies were designed to test the efficacy of various thermal weed control methods prior to turfgrass establishment by seed on a variety of weed species commonly found in turfgrass production facilities. The response of many common turfgrass weeds to thermal treatments has not been evaluated. Various methods included previously studied thermal weed control methods along with new cogitations. Results can provide insight on thermal weed control applications along with the basis for development of new non-chemical weed control methods for turfgrass systems.

Materials and Methods

Field experiments were conducted at Auburn University's Turfgrass Research Unit (TGRU) located in Auburn, AL (32°34'38.57"N, 85°29'59.76"W) to determine the effects of various thermal weed control methods on weed populations prior to turfgrass establishment. Field experiments were initiated in summer and fall of 2009 and 2010.

Summer timing. Seeded turfgrass species for summer timing research trials were 'Zenith' zoysiagrass, 'TifBlair' centipedegrass and 'Sea Spray' seashore paspalum. Zoysiagrass, centipedegrass, and paspalum were seeded at 0.15, 0.3, and 0.3 kg per 100 m^2. Soil was a Marvyn loamy sand (fine-loamy, kaolinitic, thermic Typic Kanhapludults) with pH of 5.5 and 2.7% organic matter (OM). Soil was tilled prior to treatment application. Treatments were control (CON), soil-solarization (SOL), dazomet (Basamid® G Soil sterilant, Certis USA LLC, Columbia, MD 21046, 389 kg ha^{-1}) (DAZ), direct soil flaming (DSF), emerged-weed flaming (EWF), soil covered emerged-weed flaming (CEWF) and repeat applications of EWF (2×EWF) and CEWF (2×CEWF). Treatments were applied to 1.7 by 7.6 m plots arranged in a randomized complete block design with four replications and two experimental runs. Thecontrol treatment was tilled 1 d prior to turfgrass establishment. Soil-solarization utilized 6 mil, transparent polyethylene plastic (Husky Polyethylene Plastic®, Poly-America, Grand Prairie, TX 75051) covering the soil surface for 42 d prior to turfgrass establishment. Transparent polyethylene plastic has been found to be more efficient than other colored films for soil solarization (Horowitz 1980; Horowitz et al. 1983). Dazomet was applied 21 d prior to seeding in accordance to label recommendation. The DSF treatment utilized a PL-8750 flame sanitizer® (PL8750 Poultry House Flame Sanitizer®, Flame Engineering Inc., LaCrosse, KS 67548) (Figure 1). Direct soil flaming was applied 1 d before turfgrass establishment at 0.8 kph to directly flame soil surface with no plant vegetation present. Emerged weed flaming was employed similar to DSF but allowing targeted weeds to germinate and emerge for 21 d. After 21 d EWF application was applied to emerged weeds and soil surface 1 d prior to turfgrass establishment. The 2×EWF treatment was applied the same as EWF but weed species were allowed to emerge for two 21 d periods with flame application after each emergence period. The CEWF and 2×CEWF treatments were applied similar to EWF and 2×EWF treatments. During the 21 d germination and emergence period, germination cloth (Seed Guard Fabric, DeWitt Co. Sikeston, MO 63801) was applied to soil surface for CEWF and 2×CEWF treatments. Germination cloth minimized diurnal temperature extremes to increased stimulation of weed population germination. All flame treatments were performed by a tractor-mounted poultry house flame sanitizer, PL-8750 flame sanitizer® (Figure 1). Six parallel 1.15 British thermal unit (BTU) hr^{-1} burners were mounted at the front of the shielded thermal unit directing a 1121 C flame (46 cm by 1 m) at 45° angle onto soil surface. The flame sanitizer utilized liquefied propane (LP) and was operated according to manufacture's recommendations: 0.8 kilometer per hour (kph) and 345 kPa fuel pressure. Treatment application timing was such that turfgrass seeding was on the same day. Treatment regimes can be observed in Table 1. Treatments requiring 42 d prior to turfgrass establishment applications were initiated late May 2009 and early June 2010. Turfgrass seeding was conducted July 17, 2009 or June 30, 2010. Two experimental runs were conducted in 2009 and 2010.

Fall timing. Seeded turfgrass for fall timing research trials was tall fescue (*Lolium arundinaceum* (Schreb.) S.J. Darbyshire). Seeding rate was 1.5 kg per 100 m^2. Research trials for fall timing application were conducted the same as previously stated with the exception of the exclusion of the 2×EWF and 2×CEWF treatments, due to time constrants. Soil solarization was employed for fall timing application 21 d prior to turfgrass establishment. Treatments requiring 21 d prior to turfgrass establishment applications were initiated August 31, 2009 and September 2, 2010. Turfgrass seeding was conducted October1, 2009 and September 22, 2010. Treatment regimes can be observed in Table 2. Two total experimental runs were conducted for fall application timing study with four replications each.

Data collection and analysis. Turfgrass cover was evaluated visually at 6 weeks after seeding (WAS) using a scale of 0 to 100 where 0 = no turfgrass cover and 100 = complete turfgrass cover. Three randomized 1 m^2 subplots were utilized for individual weed species counts 6 WAS. Weed species evaluated in summer timing research trials by individual counts were carpetweed, Virginia buttonweed, spotted spurge, large crabgrass, goosegrass ,and old world diamond-flower. Percent control for each treatment was calculated relative to control treatment within each replication and experimental run using Equation 1:

$$\%C = \left(\frac{N - T}{N}\right) \qquad [1]$$

where C is control, N is number of individual weed species per m^2 in control treatment, and T is number of individual weed species per m^2 in treated plot. Percent control used a scale of 0 to 100 where 0 = no weed control and 100 = complete weed control. Due to increased number of cock’s-comb kyllinga and yellow nutsedge plants, line intersect analysis (36 intersections, 1 m^2 grid) was utilized within same subplots to obtain percent cover weed species. Equation 1 was utilized to obtain percent control of cock's-comb kyllinga and yellow nutsedge with percent cover data. Due to lack of uniformity of other weed species, carpetweed (*Mollugo verticillata* L.) and old world diamond-flower (*Oldenlandia corymbosa* L.) were the only weed species evaluated in fall timing research trials.

Analysis was conducted separately for summer and fall trials and for each evaluation method. ANOVA was performed using PROC GLM procedure in SAS (SAS® v. 9.2 for Windows®. SAS Institute Inc. SAS Campus Drive, Cary, NC 27513.). Contrast statements were conducted according to initial objectives using PROC GLM. Contrasts included: chemical treatment (DAZ) vs. all thermal treatments (SOL, DSF, EWF, CEWF, 2×EWF, 2×CEWF), solarization (SOL) vs. all other thermal treatments (DSF, EWF, CEWF, 2×EWF, 2×CEWF), solarization (SOL) vs. direst soil flaming (DSF), solarization (SOL) vs. all emerged weed flaming treatments (EWF, CEWF, 2×EWF, 2×CEWF), direst soil flaming (DSF) vs. all emerged weed flaming treatments (EWF, CEWF, 2×EWF, 2×CEWF), emerged weed flaming covered (CEWF, 2×CEWF) vs. emerged weed flaming uncovered (EWF, 2×EWF), and single emerged weed flaming treatments (EWF, CEWF) vs. double emerged weed flaming treatments (2×EWF, 2×CEWF) in summer timing trials. Contrast statements were conducted the same for fall timing research studies as summer timing trials excluding the 2×EWF and 2×CEWF treatments as these treatments were not applied.

Results and Discussion

Summer timing. Within each experimental run, there was never a significant treatment by replication interaction for zoysiagrass, centipedegrass, or paspalum trials, therefore data were combined across all runs, by species. Control of weed species by thermal weed control methods is presented in Table 3. Thermal weed control methods and dazomet resulted in various percent control relative to the control treatment. At 6 WAS after seeding, greatest carpetweed control was achieved by solarization (92%). Previous research also reported excellent (100%) broadleaf weed control that included *Mollugo* spp. by solarization (McSorley et al. 2009). The 2 × CEWF treatment controlled carpetweed 90%. All other weed control methods resulted in less than 80% carpetweed control. Dazomet obtained the lowest (52%) carpetweed control 6 WAS (9 weeks after treatment (WAT)). Although Unruh et al. (2002) reported 89% carpetweed control at 6 WAT, weed control by dazomet diminished as time progressed, explaining the reduction in control reported from our study.

Another small-seeded summer annual broadleaf weed, spotted surge, was controlled by the covered emerged weed flaming treatments (Table 3). Double (2×CEWF) and single applications (CEWF) of covered emerged weed flaming resulted in 95 and 87% control, respectively. Similar to carpetweed, dazomet preformed poorly in spotted spurge control resulting in 38% control.

Virginia buttonweed resulted in 95 and 94% control by solarization and dazomet, respectively (Table 3). All other thermal weed control methods obtained less than 75% Virginia buttonweed control. Old-world diamond-flower showed greatest control (93%) by 2×CEWF. Solarization resulted in 57% old-world diamond-flower control.

Solarization was an effective treatment on evaluated grass weed species (Table 3). Large crabgrass and goosegrass resulted in 95 and 89% control, respectively from solarization. Our findings are in contrast to Rosskopf et al. (2010) who reported that solarization treatment resulted in an increase in goosegrass. Although previous results demonstrate that emerged flaming is less effective on grassy weeds than broadleaf weeds (Ascard 1994, 1997) we found excellent control of large crabgrass and goosegrass by emerged weed flaming treatments. Large crabgrass showed 94 and 95% with double emerged weed flaming and covered emerged weed flaming treatments. However both grass weed species were not effectively controlled by direct soil flaming: 50 and 63% control for large crabgrass and goosegrass, respectively.

Yellow nutsedge and cock's-comb kyllinga, both members of the Cyperaceae family, were least influenced by evaluated weed control methods (Table 3). Reports have shown that winter weeds are generally more susceptible to control by solarization, whereas summer weeds, especially *Cyperus* spp. are generally more resistant (Stapleton and DeVay 1986; Egley 1983). Solarization achieved highest control, 72 and 67%, control of cocks-comb kyllinga and yellow nutsedge, respectively, even though reports show that yellow nutsedge or purple nutsedge (*Cyperus rotundus* L.) can not be controlled by solarization (Elmore 1983). Tolerance of yellow and purple nutsedge to thermal heat treatments is likely due to underground reproductive tubers. Dazomet obtained 61% yellow nutsedge control, similar to Unruh et al. (2002) reporting 57% sedge (*Cyperus* spp.) control. Both yellow nutsedge and cocks-comb kyllinga were least controlled by direct soil flaming (50 and 33%, respectively).

Pairwise contrasts conducted on planned comparisons for weed control following chemical and thermal weed control methods are presented in Table 4. Contrasts comparing dazomet to pooled thermal treatment (SOL, DSF, EWF, CEWF, 2×EWF, 2×CEWF) means were significant for carpetweed (P-value=0.033), spotted spurge (P-value=0.001), and goosegrass (P-value=0.040). All other weed species were similar in weed control at P = 0.05 significance level, concluding that pooled thermal treatment methods controlled evaluated weed species just as well or better than dazomet.

Solarization obtained control 70% or greater on all evaluated weed species expect cock's-comb kylling and yellow nutsedge. Contrasts confirm effective weed control by solarization when compared to flame treatments (DSF, EWF, CEWF, 2×EWF, 2×CEWF), DSF, or emerge weed flaming treatments (EWF, CEWF, 2×EWF, 2×CEWF) for all evaluated weed species except old world diamond-flower. Flame treatments, DSF, and emerge flaming treatments vs. SOL obtained approximately a 20% increase of old world diamond-flower control.

Within all the flame treatments, emerged weed flaming treatments controlled all evaluated weed species greater than 70% except cock's-comb kyllinga and yellow nutsedge (Table 4). Pooled emerged weed flaming treatments obtained better control of carpetweed, spotted spurge, large crabgrass, and cock's-comb kyllinga than direct soil flaming at P = 0.01, 0.001, 0.001, and 0.01 level, respectively. No difference was observed in Virginia buttonweed, goosegrass, old world diamond-flower, and yellow nutsedge control by direct soil flaming and pooled emerged weed flaming.

Emerged covered flaming treatments (CEWF, 2×CEWF) vs. emerged uncovered flaming treatments (EWF, 2×EWF) resulted in increased spotted spurge control (91 compared to 69%). No other differences were observed for other evaluated weed species in pairwise contrasts between covering. Single emerged flaming (EWF, CEWF) vs. double emerged flaming (2×EWF, 2×CEWF) also resulted no difference. Covering plots before emerged flaming only increased carpetweed control and flaming twice did not increase control of evaluated weeds.

Fall timing. In general, all treatments were more effective in controlling weeds prior to tall fescue establishment (Table 5). Best performing weed control treatments prior to tall fescue establishment were direct soil flaming and covered weed flaming. All fall timing treatments resulted in excellent carpetweed and old world diamond-flower control (Table 5). Covered emerged-weed flaming resulted in 100% carpetweed and old world diamond-flower control at 6 WAS. All other treatments obtained greater than 94% carpetweed and old world diamond-flower control except dazomet, which resulted in 86% old world diamond-flower control. Old world diamond-flower and carpetweed control by direct soil flaming was 99% for both species.

Pairwise contrasts were conducted on planned comparisons for weed control following chemical and thermal weed control methods (Table 5). No differences were observed for SOL vs. pooled flame treatments (DSF, EWF, CEWF), SOL vs. DSF, SOL vs. pooled emerge flaming (EWF, CEWF), DSF vs. pooled emerge flaming, and EWF vs. CEWF pairwise comparisons. Pooled thermal treatments (SOL, DSF, EWF, CEWF) out-preformed dazomet. Pooled thermal treatments reduced carpetweed and old world diamond-flower 99 and 98%, respectively, different from that of dazomet (94 and 86% control, respectively). Weed control across thermal treatments were equal to or greater than the comparison chemical treatment.

Fall timing thermal weed control applications were observed to have increased control of evaluated weeds compared to summer timing. Increased control is likely due to many summer annual weeds completing their lifecycle, as well as their inability to reestablish at the fall timing. Furthermore, a shift of the competitive advantage from the weed species to turfgrass species could also have occurred. The cool-season turfgrass, tall fescue, is known to establish in a more rapid manner than warm-season turfgrass species therefore possibly outcompeting weeds for light, nutrients, and water (Turgeon 2002). These findings propose that correct timing of thermal weed control methods can possibly increase efficacy.

Turfgrass establishment. For summer timing trials at 6 WAS 'Zenith' zoysiagrass, 'TifBlair' centipedegrass, and 'Sea Spray' seashore paspalum resulted in unacceptable turfgrass establishment: less than 18% turfgrass cover for all species (data not shown). For fall timing trials tall fescue resulted in greater than 60% turfgrass cover for all treatments including control treatment (Table 6). Dazomet obtained highest tall fescue cover (86%) than all other thermal treatments. Direct soil flaming treatment obtained 81% turfgrass cover. Tall fescue in dazomet treated plots not only resulted in the highest turfgrass cover but also obtained a higher visual turfgrass quality and color rating (Data not shown). This was confirmed by contrast comparing turfgrass cover of dazomet vs. all other thermal weed control methods (SOL, DSF, EWF, CEWF) (P-value = 0.045). Contrasts also resulted in a difference between solarization and direct soil flaming (P-value = 0.046). Solarization and direct soil flaming obtaining 70 and 81% turfgrass cover at 6 WAS. No other contrasts resulted in differences between treatments. In conclusion, dazomet and all other thermal weed control methods did not inhibit tall fescue establishment and resulted in successful turfgrass establishment.

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Table 1. Summer application treatment regimes for thermal weed control research trials.[a]

Time[b]	Treatment Process							
d	SOL	DAZ	DSF	EWF	2×EWF	CEWF	2×CEWF	CON
42	Till Soil & Install Solarization Plastic				Till Soil		Till Soil & Install Germination Cloth	
21		Apply Dazomet[c]		Till Soil	Flame Application[d]	Till Soil & Install Germination Cloth	Flame Application & Re-install Germination Cloth	
1	Remove Solarization Plastic		Till Soil & Flame Application	Flame Application	Flame Application	Flame Application	Flame Application	Till Soil
0	Turfgrass Establishment							

[a] Abbreviations: SOL, solarization; DAZ, dazomet; DSF, direct soil flaming; EWF, emerged weed flaming; 2×EWF, 2 × emerged weed flaming; CEWF, covered emerged weed flaming; 2×CEWF, 2 × covered emerged weed flaming; CON, control.

[b] Days before establishing turfgrass species.

[c] Dazomet applied at 389 kg ha^{-1}

[d] PL-8750 Flame Sanitizer®.

Table 2. Fall application treatment regimes for thermal weed control research trials.[a]

Time[b]	Treatment Process					
d	SOL	DAZ	DSF	EWF	CEWF	CON
21	Till Soil & Install Solarization Plastic	Apply Dazomet[c]		Till Soil	Till Soil & Install Germination Cloth	
1	Remove Solarization Plastic		Till Soil & Flame Application [d]	Flame Application	Remove Germination Cloth & Flame Application	Till Soil
0	Turfgrass Establishment					

[a] Abbreviations: SOL, solarization; DAZ, dazomet; DSF, direct soil flaming; EWF, emerged weed flaming; CEWF, covered emerged weed flaming; CON, control; d, day.

[b] Days before establishing turfgrass species.

[c] Dazomet applied at 389 kg ha^{-1}.

[d] PL-8750 Flame Sanitizer®

Table 3. Effects of summer thermal weed control methods on weed control (%) relative to control 6 weeks after seeding (WAS).[a]

		Weed control							
	Treatment	MOLVE	DIQVI	EPHMA	DIGSA	ELEIN	OLDCO	KYSQ	CYPES
		%							
1	Dazomet [c]	52 bc[b]	94 ab	38 d	88 ab	53 c	78 ab	54 ab	61 ab
2	Solarization	92 a	95 a	82 a	95 a	89 a	57 b	72 a	67 a
3	Direct soil flaming	47 c	70 bc	51 cd	50 c	63 bc	69 ab	33 b	50 ab
4	Emerged-weed flaming	82 a	62 c	61 bc	79 b	58 bc	85 ab	62 a	58 ab
5	Covered emerged-weed flaming	80 a	71 abc	87 a	95 a	75 abc	77 ab	68 a	50 ab
6	2×Emerged-weed flaming	75 ab	74 abc	76 ab	94 a	78 ab	74 ab	61 a	49 b
7	2×Covered emerged-weed flaming	90 a	75 abc	95 a	89 ab	61 bc	93 a	61 a	50 ab
	LSD (0.05)	27	24	20	14	24	33	28	18

[a] Abbreviations: weeks after seeding, WAS; conducted twice, 2×; carpetweed, MOLVE; Virginia buttonweed, DIQVI; spotted spurge, EPHMA; large crabgrass, DIGSA; goosegrass, ELEIN; old world diamond-flower, OLDCO; cock's-comb kyllinga, KYSQ; yellow nutsedge, CYPES.

[b] Within columns, means followed by the same letter are not significantly different at $P < 0.05$ level using Fisher's Protected LSD test.

[c] Dazomet applied at 389 kg ha^{-1}.

Table 4. Pooled treatment means and pairwise contrast[a] conducted on summer thermal weed control methods 6 weeks after seeding (WAS).[b]

	Weed control							
Treatment	MOLVE	DIQVI	EPHMA	DIGSA	ELEIN	OLDCO	KYSQ	CYPES
Contrast	% control							
Dazomet [c] (1) vs. thermal (2,3,4,5,6,7)[d]	52 vs. 78 (*)	94 vs. 75	38 vs. 75 (***)	88 vs. 84	53 vs. 75 (*)	78 vs. 76	54 vs. 59	61 vs. 54
SOL (2) vs. flame (3,4,5,6,7)	92 vs. 75	95 vs. 70 (*)	82 vs. 74	95 vs. 81 (*)	89 vs. 67 (*)	57 vs. 80	72 vs. 57	67 vs. 51 (*)
SOL (2) vs. DSF (3)	92 vs. 47 (**)	95 vs. 70	82 vs. 51 (**)	95 vs. 50 (***)	89 vs. 63 (*)	57 vs. 69	72 vs. 33 (**)	67 vs. 50
SOL (2) vs. emerge flaming (4,5,6,7)	92 vs. 82	95 vs. 70 (*)	82 vs. 81	95 vs. 89	89 vs. 68 (*)	57 vs. 82	72 vs. 63	67 vs. 52 (*)
DSF (3) vs. emerge flaming (4,5,6,7)	47 vs. 82 (**)	70 vs. 70	51 vs. 80 (***)	50 vs. 89 (***)	63 vs. 68	69 vs. 82	33 vs. 63 (**)	50 vs. 52
Emerged uncovered flaming (4,6) vs. emerged covered flaming (5,7)	79 vs. 85	68 vs. 73	69 vs. 91 (***)	87 vs. 92	68 vs. 68	79 vs. 85	61 vs. 65	54 vs. 50
Single emerged flaming (4,5) vs. double emerged flaming (6,7)	81 vs. 82	67 vs. 75	74 vs. 85	87 vs. 70	67 vs. 83	81 vs. 84	65 vs. 61	54 vs. 50

[a] Pooled treatment means followed by *, **, *** indicate significance at P = 0.05, 0.01, or 0.001, respectively.

[b] Abbreviations: weeks after seeding, WAS; conducted twice, 2×; carpetweed, MOLVE; Virginia buttonweed, DIQVI; spotted spurge, EPHMA; large crabgrass, DIGSA; goosegrass, ELEIN; old world diamond-flower, OLDCO; cock's-comb kyllinga, KYSQ; yellow nutsedge, CYPES.

[c] Dazomet applied at 389 kg ha^{-1}.

[d] Number following contrasts refer to treatment numbers in Table 3.

Table 5. Effects of fall thermal weed control methods on weed control (%) relative to control 6 weeks after seeding (WAS).[a]

Treatment		Control	
		MOLVE	OLDCO
		%	
1	Dazomet [c]	94 b [b]	86 b
2	Solarization	97 ab	97 a
3	Direct soil flaming	99 a	99 a
4	Emerged-weed flaming	98 ab	97 a
5	Covered emerged-weed flaming	100 a	100 a
	LSD (0.05)	4	7
Contrast		% control [d]	
	Dazomet (1) vs. thermal (2,3,4,5)	94 vs. 99*	86 vs. 98***
	Solarization (2) vs. flame (3,4,5)	97 vs. 99	97 vs. 98
	Solarization (2) vs. direct soil flaming (3)	97 vs. 99	97 vs. 99
	Solarization (2) vs. emerge flaming (4,5)	97 vs. 99	97 vs. 99
	Direct soil flaming (3) vs. emerge flaming (4,5)	99 vs. 99	99 vs. 99
	Emerged uncovered flaming (4) vs. emerged covered flaming (5)	98 vs. 100	97 vs. 100

[a] Abbreviations: weeks after seeding, WAS; change, Δ; carpetweed, MOLVE; old world diamond-flower, OLDCO.

[b] Within columns, means followed by the same letter are not significantly different at 0.05 level using Fisher's Protected LSD test.

[c] Dazomet applied at 389 kg ha^{-1}.

[d] Pooled treatment means followed by *, **, *** indicate significance at P = 0.05, 0.01, or 0.001, respectively.

Table 6. Effects of thermal weed control methods on turfgrass cover (%) 6 weeks after seeding (WAS) pooled over fall-initiated trials in 2009 and 2010.[a]

Treatment		Fescue Cover[b]
		———%———
1	Dazomet [c]	86 a [d]
2	Solarization	70 b
3	Direct soil flaming	81 a
4	Emerged-weed flaming	79 ab
5	Covered emerged weed flaming	76 ab
6	Control	60
	LSD (0.05)	11
Contrast		% cover [e]
	Dazomet (1) vs. thermal (2,3,4,5)	86 vs. 77*
	Solarization (2) vs. flame (3,4,5)	70 vs. 79
	Solarization (2) vs. direct soil flaming (3)	70 vs. 81*
	Solarization (2) vs. emerge flaming (4,5)	70 vs. 78
	Direct soil flmaing (3) vs. emerge flaming (4,5)	81 vs. 78
	Emerged uncovered flaming (4) vs. emerged covered flaming (5)	79 vs. 76

[a] Abbreviations: weeks after seeding, WAS.

[b] Tall fescue

[c] Dazomet applied at 389 kg ha^{-1}.

[d] Within columns, means followed by the same letter are not significantly different at 0.05 level using Fisher's Protected LSD test.

[e] Pooled treatment means followed by *, **, *** indicate significance at $P \leq 0.05$, 0.01, or 0.001, respectively.

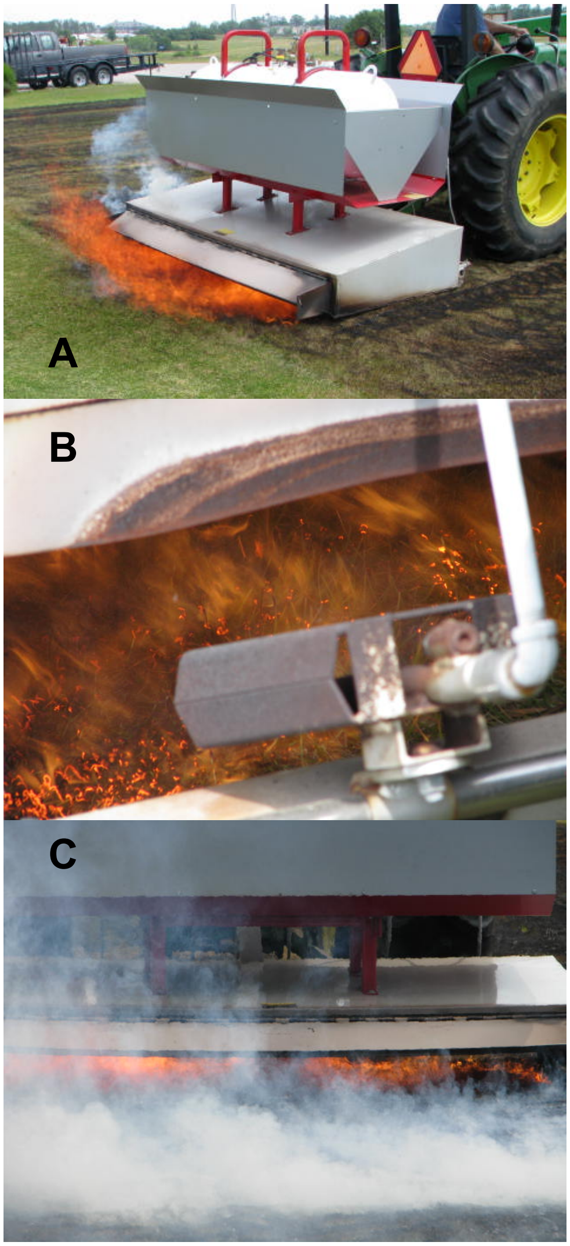

Figure 1. PL-8750 Flame Sanitizer®; A & C. demonstrating thermal weed control. B. 1.15 British thermal unit (BTU) hr^{-1} burner.

III. Soil Texture and Planting Depth Effects Large Crabgrass (*Digitaria sanguinalis* (L.) Scop), Virginia buttonweed (*Diodia virginiana* L.) and Cock’s-comb kyllinga (*Kyllinga squamulata* Thonn. ex Vahl) Emergence

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 were sand, loamy sand, and clay loam, with planting depths of 0, 0.5, 1, 2, 4, 6, and 8 cm. Emergence was standardized relative to surface germination to allow comparisons between 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 evaluated weed species and soil textures emergence decreased as planting depth increased, with greatest percent emergence at the soil surface. The planting depth at which weed seed emergence was decreased 50% (relative to surface germination (D_{50})) was predicted by regression analysis. Large crabgrass emerged from greatest 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 the D_{50} higher in the soils with a greater water-holding capacity.

Nomenclature: large crabgrass, *Digitaria sanguinalis* L. Scop DIGSA; Virginia buttonweed, *Diodia virginiana* L. DIQVI; cock's-comb kyllinga, *Kyllinga squamulata* Thonn. ex Vahl KYSQ.

Key words: emergence depth, soil texture emergence influence.

Introduction

Large crabgrass (*Digitaria sanuguinalis*), Virginia buttonweed (*Diodia virginiana*) and cock's-comb kyllinga (*Kyllinga squamulata*) are common problematic weeds in turfgrass and crop production systems. Large crabgrass and cocks's-comb kyllinga are prolific seed producing summer annuals (McCarty et al. 2001; Lowe et al. 1999). Virginia buttonweed, a perennial dicot, can produce abundant fruit on branched stems reaching 100 cm long (Baird and Dickens 1991). These efficient reproducing weed species are found across vast landscapes encompassing many different soil types and textures.

Weed seed germination depends 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 can influence weed emergence (Chauhan and Johnson 2008; Benvenuti 2003).

Soil texture and seed burial depth are known factors that influence weed emergence. Directly linked to soil texture, soil porosity (Radford and Greenwood 1970) can affect germination and emergence due to diffusion of oxygen and volatile toxic metabolites contained in soil air space (Norton 1986; Holm 1972). Gas diffusion is increased in sandy soils (Brady and Weil 2002). This allows for increased emergence in a predominantly sandy soil compared to a soil with increased clay content, as exemplified by jimsonweed (*Datura stramonium* L.; Benvenuti 2003). Increased planting depth can also affect germination and emergence (Benvenuti and Macchia 1995). Large crabgrass has emerged within 8 cm of the soil surface and approximately 60% of large crabgrass populations emerged when buried at 2 cm. At a 6 cm burial depth less than 10% large crabgrass emerged (Benvenuti et al. 2001). Similar to large crabgrass, at 14 d after planting Virginia buttonweed emergence occurred from planting depths of 8 cm, but maximum emergence (40%) was found at a 2 cm planting depth (Baird and Dickens 1991). Green kyllinga (*Kyllinga brevifolia* Rottb.) is also greatly inhibited by planting depth, ceasing emergence at 2 cm (Molin et al. 1997).

Germination of weed seeds at the soil surface also varies across weed species. Large crabgrass, buckhorn plantain (*Pantago lanceolata* L.), giant foxtail (*Setaria faberi* Herrm.) and green kyllinga all had less germination at the surface as compared to buried seed emergence (Benvenuti et al. 2001; Fausy and Renner 1997; Molin et al. 1997). In contrast, redroot pigweed (*Amarathus retroflexus* L.), wild mustard [*Brassica kaber* (DC.) L.C. wheeler] and black nightshade (*Solanium nigrum* L.) surface germination was greater than when those weed species were buried (Benvenuti et al. 2001). Such differences can be attributed to many physiological characteristics including seed carbohydrate reserves (Chauhan and Johnson 2008; Benvenuti 2003), seed coat dormancy (Buhler et al. 1997), water imbibing requirements (Wilson and Witkowski 1998) and inhibitory substances (Baskin and Quarterman 1969). Most importantly, these physiological factors differ by plant family and species.

Due to physiological differences among weed species, past weed emergence research analyzed individual weed species separately. Therefore, interactions between weed species could not be determined. Standardizing the emergence response of multiple weeds species to a selected planting depth will allow for comparison across weed species and families, to better determine the influence of planting depth and soil texture. Therefore, research was conducted to determine the effect of soil texture and burial depth on weed seed emergence of three species: large crabgrass (Poaceae), cock's-comb kyllinga (Cyperaceae), and Virginia buttonweed (Rubiaceae).

Materials and Methods

Cocks-comb kyllinga and Virginia buttonweed were harvested at the Auburn University Turfgrass Research Unit (32°34'38.57"N, 85°29'59.76W") located in Auburn, AL in summer 2009. Mature cock's-comb kyllinga plants were harvested at three separate locations (≈20 m^2) with a rotary mower (3 cm height), and clippings and seeds allowed to air-dry. Seeds were separated from clippings by sieving. Virginia buttonweed fruits were collected in December 2009 at same location utilizing a 2.5 gallon (gal) vacuum (2.5 gallons/2.5 horsepower wet/dry vacuum, Lowes, Cornelius, NC, 28031) with dried fruits removed from the soil surface surrounding the Virginia buttonweed plants. Sieving then separated fruits from other matter. In natural environments Virginia buttonweed are normally dispersed with fruit tissue surrounding the seeds, and germinate within the intact pericarp. Initial experiments showed that seed separation from pericarp had no effect on germination, therefore seed and pericarp were not separated. Large crabgrass (Elstel Farm and Seeds, 2640 Springdale Road Ardmore, OK 73401, USA) seed was purchased commercially. All collected seeds were mixed within each species to ensure a homogenous seed species mixture. All seeds were stored at 10 C and 50% relative humidity (RH) prior to use.

Soil textures selected for the study 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% OM (organic matter). 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 from Auburn and Marion Junction, AL, respectively, by hand. Sand was a sand/peat (Spagnum Peatmoss, Premier Horticulture Inc., 127 South 5th St, Suite 300, Quakertown, PA 18951) mix with pH 5.2 and 2.7% OM. Sand/peat was thoroughly mixed to a 85:15 (v/v), sand:peat ratio. All soils were autoclaved for sterilization and sieved to remove debris. Soil physical and chemical properties are shown in Table 1. Particle size analysis was determined by < 2mm pipette method (Soil Survey 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 Staff 2004).

Greenhouse trials were initiated in Spring 2010 to determine the effect of soil texture, planting depth and weed species on emergence. The experimental design was a randomized completed block with 4 replications, with two experimental runs. The experiment was arranged as a factorial combination of 3 soil textures, 7 planting depths and 3 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 (2.5 inch conduit PVC pipe, 6.2 cm internal diameter by 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}.

Columns were placed in a controlled environment greenhouse (32°35'12.11"N, 85°29'15.41W") in Auburn, AL. Average greenhouse temperatures were maintained between 23 and 32 C. Normal daytime irradiance was supplemented with sodium-halide overhead lamps supplying 150 μmol m^{-2} s^{-1}. Columns were irrigated daily to maintain field capacity throughout each study. Emerged seeds were counted and removed at 7 d intervals until emergence ceased. A seed was considered emerged when the epicotyl penetrated the soil surface.

For each weed species percent emergence was calculated and standardized within each replication and experimental run, with surface germination counts as the reference point. Standardizing to surface germination was performed because initial research trials indicated maximum germination of all 3 species at the soil surface. Data was analyzed using PROC MIXED in SAS (SAS 2011). Significance level for all comparisons was at P=0.05. Data allowed pooling across experimental runs and nonlinear regression analysis. Percent emergence of weed species and each soil texture was regressed against planting depth using SigmaPlot® (SigmaPlot 11.2® for Windows®. SPSS Inc., 444 North Michigan Avenue, Chicago, IL 60611, USA.). The exponential decay model described large crabgrass, cock's-comb kyllinga, and Virginia buttonweed emergence by soil texture (Chauhan and Johnson 2008). The exponential decay model:

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

(Equation 1) was used in estimating emergence of weed species within each soil texture, where *y* was the response (emergence relative to surface germination), *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 germination (D_{50}), was obtained by calculation. For presentation purposes means with error bars based on the standard error as determined by SAS (2011) were graphed in SigmaPlot which had previously been generated.

Results and Discussion

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

The Table of interaction for soil texture by weed species is presented in Table 2. Large crabgrass resulted in the greatest emergence (across all planting depths) of 67, 76 and 59% emergence in sand, loamy sand, and clay loam, respectively. 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 sand to that in the clay loam) the emergence of cock's-comb kyllinga and Virginia buttonweed increased. This increase in emergence was likely due to an increase in soil water- or nutrient-holding capacity, or both.

The regression analysis (Equation 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) (Figure 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. Although 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), we did not observe that in this study. Additionally, our work show differences from Benvenuti et al (2001) and Chauhan and Johnson (2008) at shallower planting depths as well. For example, at the 0.5 cm planting depth large crabgrass showed a slight increase (1%) in emergence (hormesis effect) although it was not different from germination measured at the surface (t-value = -0.22, P-value = 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 research measured a D_{50} of 3.9 cm for large crabgrass, 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 nearly 0% Virginia buttonweed emergence was observed; while at 6 cm, 6% emergence was observed. Baird and Dickens (1991) reported approximately 22% emergence at 6 cm planting depth which translates to approximately 9% emergence relative to Virginia buttonweed surface germination (31%) (Baird and Dickens 1991). In this work, Virginia buttonweed emergence was greatest at the 0.5 cm planting depth.

Previous studies observed maximum emergence at 2 cm (Baird and Dickens 1991). All current and previous work showed that Virginia buttonweed would have some germination within 8 cm planting depths.

The D_{50} of Cock's-comb kyllinga D_{50} was predicted at 0.8 cm and there was zero emergence at the 4 cm planting depth. Cock's-comb kyllinga in the absence of light does not germinate (Lowe et al. 1999) suggesting seeds are light germination dependent. Seeds buried more than 2 mm below the soil surface usually receive less than 1% incident light (Woolley and Stoller 1978). With the increase in planting depth emergence decreased across all soil types, suggesting light depletion as the primary influence on reduced emergence in 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) (Figure 2). As planting depth increased emergence decreased, regardless of soil texture. The D_{50} was calculated for each soil texture resulting in calculated 50% emergence at depths of 0.9, 2.3, and 1.9 cm for sand, loamy sand, and clay loam, respectively. Benvenuti (2003) observed a linear response between depth of 50% emergence inhibition of jimsonweed (*Daturia stramonium* L.) and soil clay and sand content. Germination inhibition due to burial depth was found to be inversely proportional to clay content and directly proportional to sand content (Benvenuti 2003).

Soils used by Benvenuti (2003) had soil pH ranging from 7.2 to 8.4. Our experimental soils had a pH range of 5.2 to 7.4. Virginia buttonweed and large crabgrass have previously been shown to have decreased germination at increased soil pH

(Chauhan and Johnson 2008; Baird and Dickens 1991), which may explain conflicting results. Soil pH may have influenced weed germination and ultimately emergence.

Current research suggests that emergence of weed seed distributed throughout the soil profile are influenced by soil texture and planting depth. Emergence of weed species of various soil textures responded differently to planting depths. Across all weed species soil texture influenced emergence, suggesting soil properties may play an influential role in emergence.

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Table 1. Chemical and physical characteristics of soil textures in which planting depths were evaluated.[a]

Soil Series	Soil Texture	Water Content[b]	Sand	Silt	Clay	OM	pH
		θ (v/v)		%		mg kg^{-1}	
Sand/Peat[c]	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

[a] Abbreviations: OM, organic matter.

[b] Soil water content at field capacity for soils was predetermined by Witkowska-Walczak et al. 2002, Wehtje et al. 1993, and Wehtje et al. 1987 for sand, loamy sand, and clay loam soil textures, respectively.

[c] Sand: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)[a]	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)

[a] Mean emergence followed by standard error at P = 0.05 significance level.

Table 3. Planting depth at which weed seed emergence was decreased 50%, relative to surface germination (D_{50}) by weed species and soil texture.[a]

Weed Species[b]	Soil Texture[c]	Regression Equation[d]	R^2	D_{50} [e]
				cm
-	Sand	E (%) $= 73.2e^{-0.41x}$	0.98	0.9
-	Loamy sand	E (%) $= 80.3e^{-0.21x}$	0.94	2.3
-	Clay loam	E (%) $= 113.4e^{-0.44x}$	0.98	1.9
large crabgrass	-	E (%) $= 114.3e^{-0.21x}$	0.95	3.9
cock's-comb kyllinga	-	E (%) $= 102.5e^{-0.95x}$	0.96	0.8
Virginia buttonweed	-	E (%) $= 74.8e^{-0.36x}$	0.98	1.1

[a] Abbreviations; E, emergence; x , depth.

[b] Large crabgrass, cock's-comb kyllinga, and Virginia buttonweed pooled across sand, loamy sand, and clay loam soil texture

[c] Sand, loamy sand, and clay loam soil textures pooled across large crabgrass, cock's-comb kyllinga, and Virginia buttonweed species.

[d] Regression Equation 1.

[e] Depth at which weed seed emergence was decreased 50%, relative to surface germination.

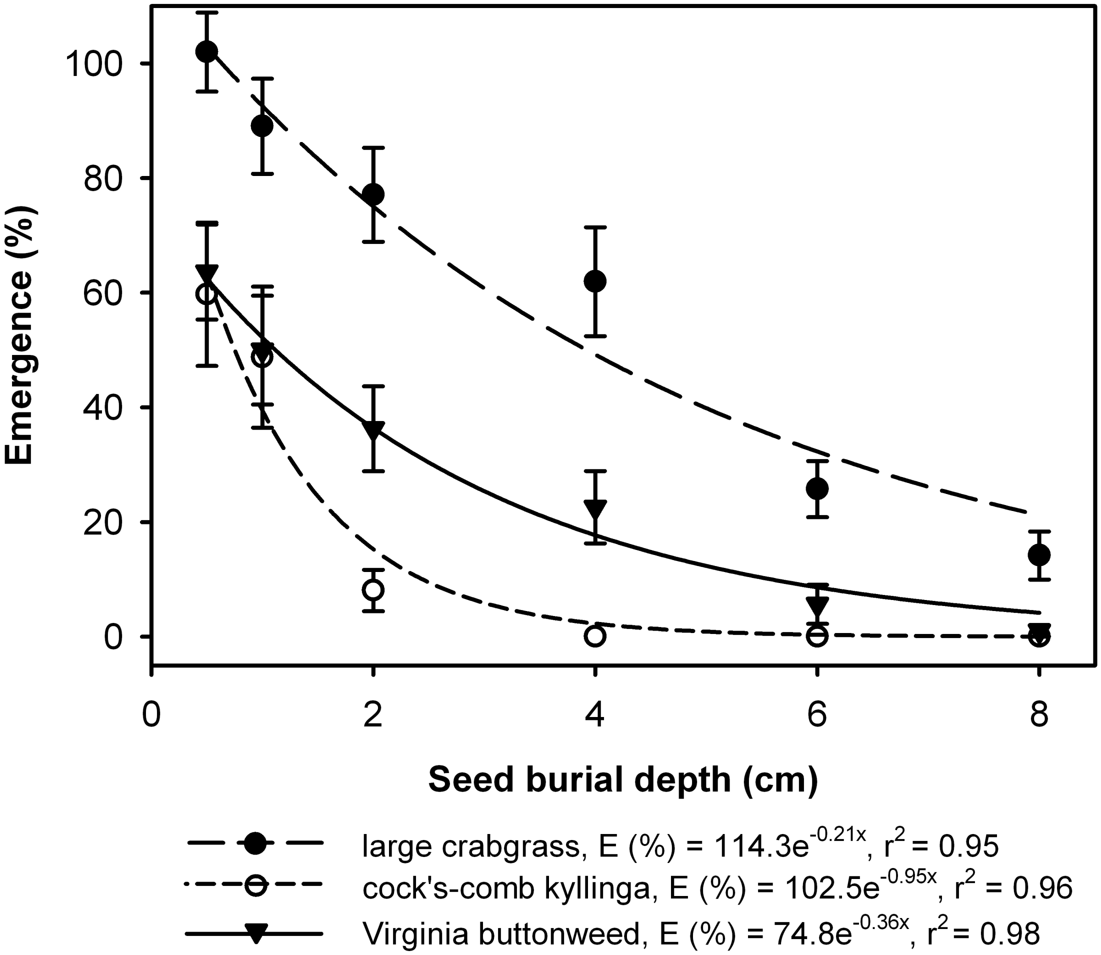

Figure 1. Weed species and planting depth effects on emergence (%) relative to surface germination pooled across soil textures (sand, loamy sand, clay loam). Vertical bars represent standard error at $P = 0.05$ significance level. Abbreviations; E, emergence; x, depth (cm).

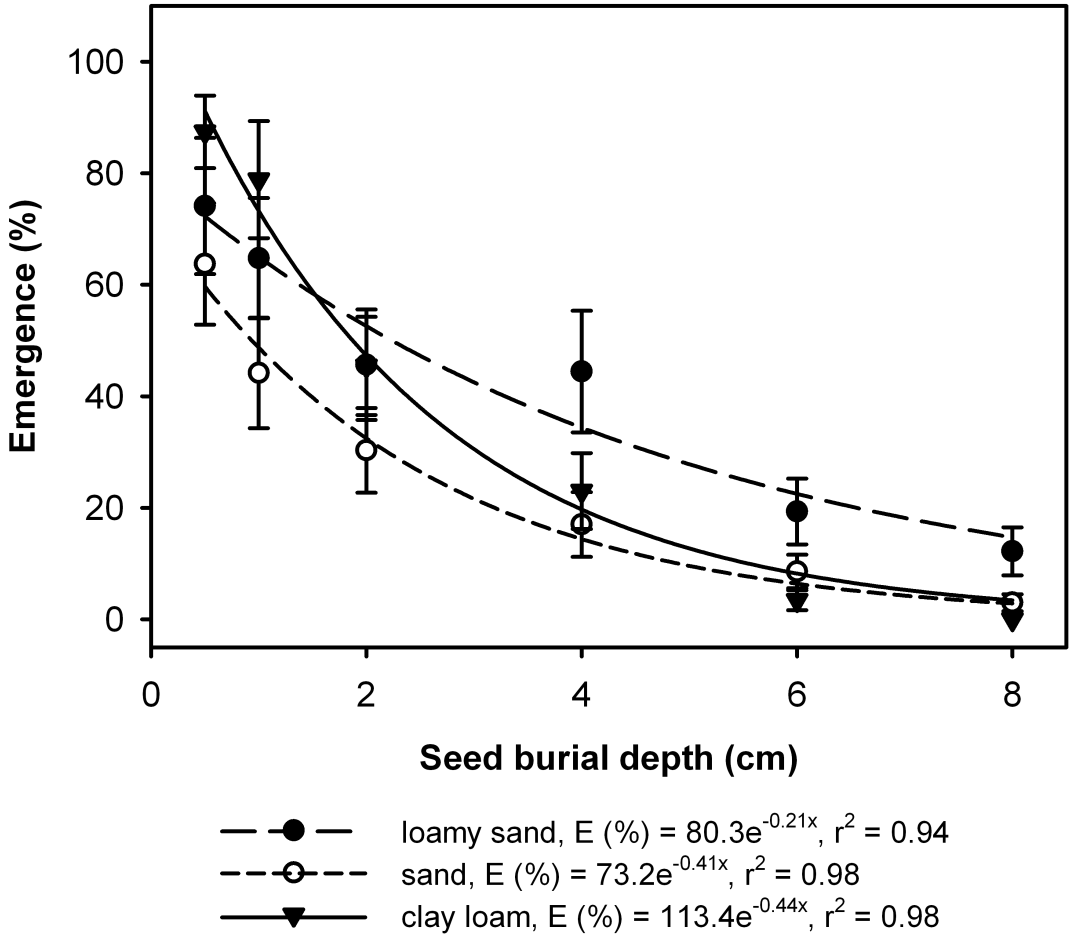

Figure 2. Soil texture and planting depth effects on emergence (%) relative to surface germination pooled across weed species [Large crabgrass (*Digitaria sanuguinalis*), Virginia buttonweed (*Diodia virginiana*), cock's-comb kyllinga (*Kyllinga squamulata*)]. Vertical bars represent standard error at P = 0.05 significance level. Abbreviations; E, emergence (%); x, depth (cm).

IV. Large Crabgrass (*Digitaria sanguinalis* (L.) Scop), Virginia buttonweed (*Diodia virginiana* L.), and Cock's-comb Kyllinga (*Kyllinga squamulata* Thonn. ex Vahl) Mortality Varies With Heat Exposure

Abstract

Thermal heat has been utilized for non-selective weed control methods. These methods are highly variable in application and efficacy. One effective weed-seed-control determining factor is achieving the thermal death point of targeted weed seeds. The thermal death point varies by weed species, temperature, and exposure time. Our objective was to determine the thermal death point of large crabgrass, cock's-comb kyllinga, and Virginia buttonweed at short thermal exposure periods. Studies conducted utilized 5 and 20 s exposure periods for incremental range, 60 to 250 C temperatures. Sigmoid regression curves were used to predict weed seed mortality by temperature and exposure time. A significant interaction between exposure period and temperature occurred for each weed species. Weed species increased in susceptibility to 20 s thermal heat: Virginia buttonweed < cock's-comb kyllinga < large crabgrass. Increasing thermal exposure time from 5 to 20 s reduced thermal temperature by 21 C to achieve 50% mortality for large crabgrass and by 10 C for cock's-comb kyllinga. Virginia buttonweed achieved 50% mortality at 99 C for 5 and 20 s exposure periods. These data indicate that at least 50% weed seed mortality can be achieved at 99 and 103 C for 20 and 5 s exposure periods, respectively, for these weed species.

Nomenclature: large crabgrass, *Digitaria sanguinalis* L. Scop DIGSA; Virginia buttonweed, *Diodia virginiana* L. DIQVI; cock's-comb kyllinga, *Kyllinga squamulata* Thonn. ex Vahl, KYSQ; Thermal death point, TDP.

Key words: thermal weed control, thermal seed death, weed seed mortality.

Introduction

Thermal weed control methods generate heat to kill weed seeds and emerged weeds (Bond et al. 2007). Techniques include soil solarization (Horowitz et al. 1983), flame weeding (Ascard 1995), infrared radiation (Ascard 1998), steaming and hot water (Anon 1999; Trotter 1991; Barberi et al. 2009), direct heat (Hopkins 1936; Ascard et al. 2007), electrocution (Vigneault et al. 1990), microwave radiation (Ascard et al. 2007), electrostatic fields (Diprose et al. 1984), irradiation (Suss and Bacthlar 1968), lasers (Couch and Gangstad 1974; Heisel et al. 2002; Mathiassen et al. 2006), and ultraviolet light (Andreasen et al. 1999). Reaching the thermal weed seed death point determines the efficacy of thermal weed control methods. The threshold temperature required to prevent germination is dependent on weed species, seed moisture level and treatment duration (Riemens 2003).

The ability to achieve the optimal temperature for the required duration varies with energy source. Laboratory soil steaming for 90 s required temperatures between 65 and 75 C to kill individual weed species, losing 1 C per 60 s after the heat source is removed (Melander and Jørgensen 2005). Mobile steaming units are detrimental to weed species reaching soil temperatures of 70 to 100 C for 3 to 8 min (White et al. 2000a; White et al. 2000b). Heat exposure by solarization may require greater than 65 C for extended duration at the seed surface (Standifer et al. 1984). Utilizing solarization soil temperatures may exceed the thermal seed threshold for only a short period per d (0 to 2 h); therefore, several days or weeks of application are needed to accumulate sufficient heat exposure (Horowitz and Taylorson 1983).

Thermal weed control efficacy not only depends on energy source but also can vary because of the temperature and duration requirement of targeted weed species to achieve the thermal death point. Temperature to achieve thermal weed seed death varies with species (Rubin and Benjamin 1984; Egley 1983, 1990; Linke 1994). Hopkins (1936) reported lethal temperature varied by weed species when exposed to 15 min of thermal heat; conditioned seeds (50% relative humidity at 25 C) of wild oat (*Avena fatua* L.) lethal death temperature was 105 C while conditioned seeds of red root pigweed (*Amaranthus retroflexus* L.) was 85 C. Imbibed broadleaf dock (*Rumex obtusifolia* L.) seeds exposed to 75 C thermal temperature ceased germination when averaged across 0.5 to 16 d thermal exposure (Thompson et al. 1997). Effective buried annual bluegrass (*Poa annua* L.) germination reduction was achieved with a total of 66 h above 45 C (Peachey et al. 2001).

Regardless of the method and weed species, the two primary interactive factors that influence thermal weed control are temperature achieved and exposure time. In general, higher temperatures require shorter duration and lower temperatures require a longer duration. To achieve 100% mortality of barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.) exposure time varied among treatment temperatures. A short duration (0.17 h) required 70 C for 100% barnyardgrass mortality. When decreasing thermal temperature to 46 C, 16 h exposure period was required to achieve the same result. Extended exposure periods (56 h) of 50 C were required to achieve 100% common purslane (*Portulaca oleracea* L.) mortality. When common purslane seeds were placed in moist soil thermal heat exposure period increased to 7 d for effective germination reduction (Egley 1990). When decreasing thermal exposure to velvetleaf (*Abutilon theophrasti* Medik.) seeds by 9 h a 10 C increase was required to inhibit germination (Horowitz and Taylorson 1983). Similar results have been observed in common lambsquarters (*Chenopodium album* L.) and Indian mustard (*Brassica juncea* L. Czern.) (Hopkins 1936; Thompson et al. 1997). These previous studies exemplified that an expenditure of reduced thermal heat exposure time was an increase in temperature for effective decrease in seed germination.

The major limitation to thermal weed seed control methods is low temperature applications. Thermal weed control methods that are of lower heat intensity require longer exposure times for adequate weed germination reduction. Longer exposure times decrease the potential treated acreage. Thermal dry heat applications can only treat 1 to 2 ha d^{-1} (Williams 1999). Mobile steaming units can only be applied at 40 to 100 h ha^{-1} (Bond et al. 2007). Other low intensity-longer exposure time applications, such as solarization, can require up to a 6-week application (Horowitz et al. 1983). Commonly these thermal weed control methods achieve extended heat exposure periods.

We are currently testing thermal weed control methods utilizing a PL8750 flame sanitizer® (Figure 1) for stale-seed-bed preparation prior to turfgrass establishment (Hoyle et al. 2011a). This application method utilizes intense thermal heat from 6, 3.3×10^5 W h (watt hours) torches, individually reaching approximately 1121 C flame temperature. This method applies a high intensity of heat for a much shorter time duration (≤ 20 s) depending on speed. Manufacture recommended operating speed of 0.8 kph and fuel pressure 345 kPa. Therefore, the purpose of this study was to investigate increased thermal temperatures at short exposure periods on large crabgrass (*Digitaria sanguinalis)*, cock's-comb kyllinga (*Kyllinga squamulata)*, and Virginia buttonweed (*Diodia virginiana*) in order to simulate heat exposure.

Materials and Methods

Cock's-comb kyllinga (Cyperaceae), a tufted summer annual and Virginia buttonweed (Rubiaceae), a mat-forming spreading perennial herd, were harvested at Auburn University's Turfgrass Research Unit (32°34'38.57"N, 85°29'59.76"W) located in Auburn, AL. Mature cock's-comb kyllinga plants were harvested with a rotary mower in summer 2010. Clippings and seeds were allowed to air-dry. Seeds were separated from clippings by sieving. Virginia buttonweed fruits were collected in December 2010 at same location utilizing a 9.5 L vacuum (Shop-Vac, 9.5 L/2.5 horsepower wet/dry vacuum, Lowes, Cornelius, NC, 28031). Dried fruits were removed from the soil surface surrounding Virginia buttonweed populations. Sieving separated fruits from other matter. Virginia buttonweed seeds are normally dispersed with fruit tissue surrounding the seeds and germinate within the intact pericarp in natural environments. Initial experiments showed no influence on seed germination with separation from pericarps, therefore seed and pericarp were not separated. Large crabgrass (Elstel Farm and Seeds, 2640 Springdale Road, Ardmore, OK 73401) seed was purchased from Elstel Farm and Seeds. All collected seeds were mixed to ensure a homogenous seed species mixture. All seeds were stored at 10 C and 50% relative humidity (RH) prior to use.

Laboratory experiments were conducted at Auburn University to determine the germination response of the common turfgrass weeds to thermal heat. Thirty seeds or fruits were counted, separated, and stored in a cooler (10 C) before heat treatments were applied. A two by seven completely randomized design with factorial treatment arrangement was utilized with temperatures of 60, 80, 100, 120, 160, 200, and 250 C and exposure times of 5 and 20 s. Five s time corresponds to thermal heat exposure of PL8750 flame sanitizer® at recommended manufacture operating speed (0.8 kph). Twenty s time was chosen as a comparison exposure period for developing thermal weed control method utilizing a PL8750 flame sanitizer®. Two experimental runs for each evaluated weed species were conducted with four replications of each combination treatment and included a non-heat treatment. Evaluated weed species were large crabgrass, Virginia buttonweed, and cock's-comb kyllinga. The thermal heating units utilized convection ovens (Euro-Pro Kitchen Convection Toaster Oven, TO36, Euro-Pro Operating LLC, Boston, MA 02459). One convention oven was utilized for seed treatment, denoted as treatment oven (TO). A separate convection oven was utilized to heat ceramic crucibles (Low form crucible, 7.5 diameter 00A 51-K, Coors crucibles, VWR International), denoted as crucible oven (CO). A probe attached to an infrared thermometer (IR2-S Infrared Thermometer with Probe, Turf-Tec International, Tallahassee, FL 32303) was inserted through the top of each convection oven to monitor oven temperature. Before treatment application, TO and CO were set to treatment temperature and confirmed with infrared thermometer. Once convection ovens obtained correct temperature four crucibles were inserted into CO. After 3 min a crucible was removed from CO. Crucible was then confirmed to be at treatment temperature by a separate infrared thermometer. Thirty seeds or fruits of a weed species were placed in crucible. Crucible containing seeds were inserted in TO for desired exposure time. This methodology provided conduction and convection thermal heat transfer simultaneously. Crucibles and seeds were removed from the oven once treated. Following heat treatment, seeds were immediately placed in 9-cm diameter petri dish (Petri Dish, VWR International LLC, Randor, PA) containing two pieces of #2 filter paper (Filterpaper, VWR International LLC, Randor, PA), and moistened with 6 mL of de-ionized water. Petri dishes were secured with parafilm (Parafilm, Pechiney Plastic Packaging, Chicago, IL 60623) and placed in a growth chamber (Growth Chamber, Adaptis A1000PG, Conviron, 590 Berry St Winnipeg, Manitoba, Canada). Environmental conditions in the growth chamber were 50% RH, alternating (day/night) photoperiod and temperature of 16 and 8 h and 30 and 20 C, respectively. Light was applied from fluorescent lamps (650 µmoles m^{-2} s^{-1}, 39 watt T5HO/840 fluorescent lamps, Conviron, 590 Berry St Winnipeg, Manitoba, Canada). Counts were conducted every 7 d until germination ceased, approximately 6 weeks after initiation. A seed was considered germinated if the radicle could be seen. Germinated seeds were counted and removed. Counts were totaled at the conclusion of the study. Seed viability tests were conducted by tetrazolium (Moore 1985) on non-germinated seed. Due to the inability to interpret staining patterns because of lactophenol clearing solution inconsistency, inconclusive results were found. Therefore no viability data are presented. Studies have reported non-viable ungerminated seeds after thermal heat treatments (Dahlquist et al. 2007). Germination counts were converted to mortality relative to the non-treated seeds.

Mortality of large crabgrass, Virginia buttonweed, and cock's-comb kyllinga influenced by exposure time and temperature was analyzed using SAS (SAS 2011). Data were combined for analysis across experimental runs. For all weed species, increasing thermal temperatures allowed for nonlinear regression analysis. Mortality for each exposure time and temperature combination was calculated by each replication within each experimental run from total relative germination counts. Percent mortality of each weed species and exposure time was regressed against temperature using SigmaPlot (Sigmaplot 11.2® for Windows®. SPSS Inc., 444 North Michigan Avenue, Chicago, IL 60611, USA). Initial analysis resulted in no hormesis effect (Brain and Cousens 1988). The three-parameter sigmoid regression model (Myers 1986) proved useful in estimating the lethal thermal death temperature for various weeds at different exposure times. Differences in percent mortality of weed species due to temperature treatment and exposure time were determined using the following sigmoid regression model:

$$y = a / \left\{ 1 + e^{\left[-(x - M_{50}) / b \right]} \right\} \qquad [1]$$

where y is the response (percent mortality) at temperature x, M_{50} (temperature to achieve 50% mortality), a is the upper limit (% mortality), and b is the slope (at M_{50}) . Lack-of-fit tests were made in accordance to Seefeldt et al. (1995), Melander and Jørgensen (2005), and Melander and Kristensen (2011) to clarify whether Equation 1 or full ANOVA model gave best description of the data. Models were also compared on the basis of *F*-tests (Melander and Jørgensen 2005; Melander and Kristensen 2011). It was tested whether the parameters in Equation 1 differed between exposure time and temperature from adaptation of Melander and Kristensen (2011) whom tested seedling emergence as a function of experimental factors on soil steaming. A full model was set up which a, b, and M_{50} parameters were dependent on exposure time (5 and 20 s) and temperature (60, 80, 100, 120, 160, 200, and 250 C). As Melander and Kristensen (2011) outlined the model was successively reduced and *F*-tests were used to identify significance between models according to the sum of squares reduction tests described by Brown and Rothery (1993). For presentation purposes means with error bars based on the standard error ($P = 0.05$) as determined by SAS (2011) were graphed in SigmaPlot which had been previously generated.

Results and Discussion

Significant temperature ($F = 621.01$, $P = <0.001$) and exposure time ($F = 121.18$, $P = <0.001$) main effects, as well as an interaction between temperature and exposure time ($F = 73.69$, $P = <0.001$) was observed for large crabgrass. Interaction allowed for non-linear regression model selection. Sigmoid regression curves (Equation 1) explained large crabgrass mortality by temperature for each exposure period (Adj $R^2 \geq 0.97$ for 5 and 20 s models). The equation described data as well as full ANOVA model. Successive model reduction showed that exposure period and temperature influenced the estimation of M_{50} values. Model ultimately resulted in M_{50} estimates representing actual temperature to achieve 50% large crabgrass mortality. A similar conclusion was made for cock's-comb kyllinga and Virginia buttonweed. Cock's-comb kyllinga required the lowest temperature and Large crabgrass required the highest temperature to achieve 50% mortality at 5 s exposure. Large crabgrass required the lowest temperature and Virginia buttonweed required the highest temperature to achieve 50% mortality at 20 s exposure.

Parallel herbicide dose response models could indicate that herbicides are acting on the same site of action if comparing herbicide resistant weed biotypes (Streibig et al. 1993). When comparing thermal temperature exposure times to weed seed mortality, one would assume that thermal heat is acting upon the same site. High thermal heat affects organisms differently by changes in membrane properties (Hendricks and Taylorson 1976, 1979), denaturation of proteins, change in viscosity of membrane lipids (Christiansen 1978; Esser and Souza 1974; Labouriau 1977; Levitt 1969; Volger and Santarius 1981), and heat shock proteins (Coca et al. 1994; Median and Cardemil 1993). Low temperatures may not alter the seed properties enough to increase mortality or affect different physiological aspects of the seeds. At the 5 and 20 s exposure times, lower temperatures simply affect properties of Virginia buttonweed seed differently. Further investigation of Virginia buttonweed seed morphology and thermal heat tolerance could potentially provide insight on physiological changes.

Weed seed mortality. Mortality increased with increasing temperature but varied by weed species and exposure time. Large crabgrass Virginia buttonweed, and cock's-comb kyllinga achieved maximum mortality of 100, 97, and 101%, respectively. Virginia buttonweed achieved 100% mortality by 200 and 150 C for 5 and 20 s exposure times (Figure 2), though sigmoid regression model estimated the maximum mortality at 97%. Sigmoid regression models for each weed species by exposure time were utilized in determining 50% mortality of large crabgrass, cock's-comb kyllinga and Virginia buttonweed (Table 1). Increased exposure time reduced thermal temperature required to achieve 50% mortality in large crabgrass and cock's-comb kyllinga. Increasing thermal exposure time from 5 to 20 s, reduced thermal temperature by 21 C to achieve 50% mortality for large crabgrass and by 10 C for cock's-comb kyllinga. Virginia buttonweed achieved 50% mortality at roughly the same 5 and 20 s exposure thermal temperature, approximately 99 C. Not removing pericarps likely increased Virginia buttonweed heat tolerance; however intact pericarps are more realistic of field germination conditions.

Damaging effects of high temperature may be related to changes in membrane properties (Hendricks and Taylorson 1976, 1979). Egley (1990) reported that seed coat imposed dormancy could be broken with 50 to 60 C temperatures and enhance seed germination. Germination stimulation can be induced by heat when hard seed coats are broken, facilitating imbibing requirements and radicle growth (Herranz et al. 1998).

Antagonistically lower thermal temperature with slightly longer exposure time (20 s) could possibly denaturize Virginia buttonweed pericarps and stimulate germination. Insufficient heat exposure duration at 5 s did not break dormancy or stimulate germination. Eventually increased mortality was observed at increased thermal temperatures at 5 s exposure.

Egley (1990) reported that longer exposure periods at lower temperatures were more destructive to weed seed germination than those of a shorter period at higher temperatures. This conclusion is not comparable with the present data because drastic differences in exposure periods between Egley (1990) and this experiment. Egley (1990) utilized exposure periods ranging from 0.25 to 7 d where exposure periods in this study were 5 and 20 s. Similar to Thompson et al. (1997), all three target weed species reached thermal death points regardless of thermal heat exposure time. The maximum temperature required to prevent germination is more important than the exposure time of heating although exposure time can influence efficacy of thermal heat treatments (Thompson et al. 1997). Although, black nightshade (*Solanum nigrum* L.), hairy galinsoga (*Galinsoga quadriradiata* Cav.), green foxtail (*Setaria viridis* (L.) Beauv.), common purslane (*Portulaca oleracea* L.), and redroot pigweed (*Amaranthus retroflexus* L.) seed germination was severely affected by short exposure to thermal temperatures (Vidotto et al. 2011). Temperature and sprouting ability of *Elytrigia repens* rhizome buds was inversely related to exposure time (Melander et al. 2011). Melander and Kristensen (2011) found no influence of heat duration when soil steaming for 3 to 12 s. Although tested durations in our experiment and Melander and Kristensen (2011) are similar, this experiment resulted in differences in temperature to achieve 50% weed mortality of large crabgrass and cock's-comb kyllinga at 5 and 20 s durations.

Implications for weed control. Large crabgrass, cock's-comb kyllinga, and Virginia buttonweed seeds subjected to a thermal heat of 99 C for 20 s resulted in 50% mortality. Increasing thermal heat by 4 C (103 C) and reducing exposure time 15 s can provide similar mortality as a 20 s exposure period. Thermal weed control measures must achieve these temperatures for short exposure times at the seed surface interface to achieve the thermal death point.

Thermal heat at reported temperatures does not only influence weed seed mortality but can also cause microbial disruptions at any temperature greater than 60 C (DeBano et al. 1998). Also, when intense heat (300 C) is applied to any soil surface negative effects can occur to the soil (Certini 2005). Long or short-term thermal heat influences on soil (DeBano et al. 1998) can affect organic carbon (Giovannini et al. 1988), soil permeability (Imeson et al. 1992), pH (Arocena and Opio 2003), bulk density (Giovannini et al. 1988), and available nutrients (Fisher and Binkley 2000). Although soils are negatively impacted at approximately 300 C, the targeted temperature for effective thermal weed seed population reduction of species used in this study is 103 C but the thermal heat must be present at the seed location.

Thermal heat must transfer through soil to depths where seeds are located, at the sufficient temperature and time to be effective. Heat movement through the soil depends on volumetric proportions of solid, liquid, and gas phases, arrangement of solid particles, and interfacial contact between the solid and liquid (Jury and Horton 2004). Thermal conductivity decreases with decreasing particle size (Patten 1909), increases with bulk density (van Rooyen and Winterkorn 1959), and increases with water content (van Rooyen and Winterkorn 1959; van Duin 1963). Experiments have been conducted to determine maximum emergence depths for large crabgrass, cock's-comb kyllinga, and Virginia buttonweed in various soil textures (Hoyle et al. 2011b) along with heat movement through soil (Van Duin 1963; Ochsner et al. 2001).

Seed moisture also influences seed mortality (Riemens 2003) and affects seed susceptibility to heat (Horowitz and Taylorson 1983). Previous research concluded that dry seeds of barley (*Hordeum vulgare* L.) withstood heat exceeding 100 C (Couture and Sutton 1980). Experiments in our study were conducted on non-imbibed seeds. Therefore, heat effects on seeds can be enhanced by high seed moisture content (Egley 1990; Melander and Jørgensen 2005). Similar to out study, previous research has shown that dry seeds are less susceptible to heat exposure and increased temperatures are needed to attain the same mortality (Egely 1990; Bloemhard et al. 1992; van Loenen et al. 2003; Melander and Jørgensen 2005). For practical execution, this could mean higher soil temperatures might be needed for weed seeds in the upper soil layer where long dry periods precede thermal treatment (Melander and Jørgensen 2005).

Many factors influence thermal weed control methods. Many of these factors can increase thermal weed control efficacy as well as reduce efficacy. Combined knowledge of short exposure time and thermal temperature needed to achieve thermal weed seed death is significant in determining effective short exposure period thermal weed control methods.

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Table 1. Parameter estimates (± standard errors) from fitting Equation 1 to data sets for large crabgrass, Virginia buttonweed, and cock's-comb kyllinga mortality due to exposure temperature.[a]

Weed species	Exposure time	*a*	*b*	M_{50}	*Adj* R^2
	s				
Large crabgrass	5	100.08 ± 0.91	3.03 ± 2.27	103.52 ± 2.69	0.97
	20	100.08 ± 0.91	3.03 ± 2.27	82.75 ± 2.11	0.98
Virginia buttonweed	5	96.53 ± 1.76	15.53 ± 1.95	98.74 ± 2.08	0.90
	20	96.53 ± 1.76	9.94 ± 1.46	98.65 ± 1.59	0.91
Cock's-comb kyllinga	5	101.08 ± 1.85	7.51 ± 0.97	97.08 ± 1.47	0.84
	20	101.08 ± 1.85	7.51 ± 0.97	87.49 ± 1.61	0.90

[a] Sigmoid regression model defined by Equation 1. Abbreviations; *a*, maximum mortality; *b*, slope; M_{50}, temperature to achieve 50% mortality; *Adj*, adjusted.

Figure 1. PL8750 flame sanitizer demonstrating short-term thermal heat exposure period. Red Dragon, Model PL8750 Poultry House Flame Sanitizer, Flame Engineering, Inc. P.O. Box 577 LaCrosse, Kansas 67548

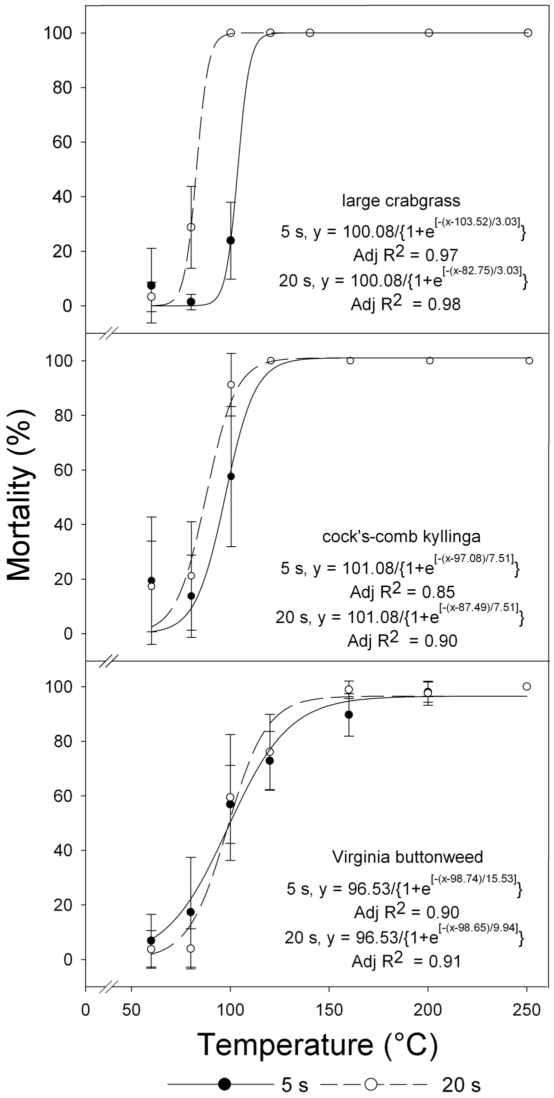

Figure 2. Sigmoid regression models as determined by Equation 1 for large crabgrass, cock's-comb kyllinga, and Virginia buttonweed percent mortality at 5 and 20 s exposure times. Abbreviations; s, second; y, percent mortality; x, temperature (C); Adj, adjusted.

V. Monitoring Thermal Weed Control Methods for Turfgrass Establishment: Thermal Exposure Period and Soil Moisture Content Affect Soil Temperature

Abstract

Thermal weed control methods utilizing a PL-8750 flame sanitizer® are being developed for stale-seed-bed preparation prior to turfgrass establishment. This method applies a high intensity of heat at a short time duration (≤ 20 s) depending on application speed. Field research trials were conducted to explore the effects that soil moisture (10% and 20% volumetric water content) and exposure period (5 and 20 s) have on soil temperature when thermal heat is applied with a PL-8750 flame sanitizer®. Collected data was soil temperatures at 0, 1, 3, and 10 cm depths. Soil temperatures were recorded every s, for duration from 60 s before heat application to 300 s after heat source was removed. Recorded temperatures were used to calculate maximum soil temperature, initial soil temperature, time to achieve maximum soil temperature, amplitude, heating slope and cooling slope. Maximum soil surface temperatures were 158 and 454 °C for 5 and 20 s exposure periods, respectively. An increase in volumetric water content resulted in an increase in maximum soil temperature at the soil surface. Maximum soil surface temperature for 10% and 20% volumetric water content was 48 and 144 °C, respectively. These results can help predict efficacy of evaluated thermal weed control method on weed species where the thermal death point has been determined. Although, many buried weed seeds would not be affected by this type of thermal weed control application, weed seed populations located on the soil surface would be highly susceptible to thermal heat applications and result in increased weed seed mortality.

Additional index key words. Thermal weed control, emerged weed flaming, direct soil flaming, stale-seed-bed preparation, Virginia buttonweed, *Diodia virginiana*, cock's-comb kyllinga, *Kyllinga squamulata,* large crabgrass, *Digitaria sanguinalis*.

Introduction

Thermal weed control methods utilize heat to kill weed seeds and emerged weeds (Bond et al., 2007). Techniques include soil solarization (Horowitz et al., 1983; Bell and Laemmlen, 1991; Elmore, 1991; Peachey et al. 2001), flame weeding (Ascard, 1990, 1994, 1995, 1997; Sivesind et al., 2009), infrared radiation (Ascard, 1998), steaming and hot water (Anon, 1999; Trotter, 1991), direct heat (Hopkins, 1936; Rubin and Benjamin, 1983), electrocution (Vigneault et al,. 1990), microwave radiation, electrostatic fields (Diprose et al., 1984), irradiation (Suss and Bacthlar, 1968), lasers (Couch and Gangstad, 1974; Heisel et al., 2002; Mathiassen et al., 2006), and ultraviolet light (Andreasen et al., 1999). Reaching the thermal death point (TDP) of weed seed determines efficacy of these thermal weed control methods.

We are currently developing thermal weed control methods utilizing a PL-8750 flame sanitizer® (Fig. 1) for stale-seed-bed preparation prior to turfgrass establishment (Hoyle et al., 2011a). This application method utilizes intense thermal heat from 6,

3.3×10^5 W h (watt hours) torches, individually reaching approximately 1121 °C flame temperature. This method also applies a high intensity of heat at a short time duration ($\leq$ 20 s) depending on speed. The intense flame temperature allows heat energy transfer through the soil to weed-seed-population locations by conduction and convection of latent heat.

For this thermal weed control method to be effective in turfgrass systems, application must be conducted prior to turfgrass establishment by a direct heat application. Since turfgrass establishment by seed is relatively slow compared to that of sod or sprigs, reducing weed seed populations by thermal heat prior to turfgrass establishment could possibly shift the competitive advantage from weeds to turfgrass. Thermal weed control methods have shown positive effectiveness in row cropping systems as well as high value vegetable production. It is unknown if similar thermal weed control methods are effective in reducing weed populations prior to turfgrass establishment.

Direct heat applications varies in efficacy. This is due to a wide range of influential factors including targeted weed species (Dahlquist et al., 2007; Rubin and Benjamin, 1984; Egley, 1990; Linke, 1994), planting depth (Benvenuti et al., 2001), treatment duration (Riemens, 2003), soil texture (van Rooyen and Winkerton, 1959), soil moisture (van Duin, 1963), thermal conductivity (Patten, 1909; Smith, 1942), soil chemical properties (Bowers and Hanks, 1962; Lang, 1878; Ulrich, 1894), and soil porosity (Ochsner et al., 2001).

Direct heat applications are highly influenced by thermal conductivity that in return is influenced by soil properties. As soil is a granular medium consisting of solid, liquid, and gaseous phases, thermal conductivity will depend on the volumetric proportions of these components, the size and arrangement of the solid particles, and the interfacial contact between the solid and liquid phases (Jury and Horton, 2004). Thermal conductivity generallydecreases with decreasing particle size (Patten, 1909), increases with bulk density (van Rooyen and Winterkorn, 1959), and increases with water content (van Rooyen and Winterkorn, 1959; van Duin 1963).

Not only does soil properties play and influential role in direct heat thermal weed control efficacy, but the TDP is also important. The temperature necessary to achieve TDP varies with species (Dahlquist et al., 2007; Rubin and Benjamin 1984; Egley 1990; Linke 1994). Previous research by Hoyle et al. (2012) reported that evaluated weed species increased in susceptibility to thermal heat: Virginia buttonweed (*Diodia virginiana* L.) < cock's-comb kyllinga (*Kyllinga squamulata* Thonn. ex Vahl) < large crabgrass (*Digitaria sanguinalis* L. Scop). Susceptibility of these weed species to thermal heat was also influenced by temperature and exposure time. Evaluation of Virginia buttonweed, cock's-comb kyllinga, and large crabgrass resulted in 90% weed seed mortality at 125 and 140 °C for 20 and 5 s exposure periods, respectively (Hoyle et al., 2012). In general, higher temperatures require shorter duration and lower temperatures require a longer duration.

All seed populations are not located on the soil surface but incorporated within the upper soil profile and can emerge from different depths (Benvenuti et al., 2001).

Experiments have been conducted to determine maximum emergence depths for large crabgrass, cock's-comb kyllinga, and Virginia buttonweed in various soil textures (Hoyle et al., 2011b). Large crabgrass emerged from greatest 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 planting depth at which weed seed emergence was decreased 50% (D_{50}) occurred at 3.9, 1.1 and 0.8 cm, respectively.

Studies were designed to investigate the effect of soil temperatures at various depths after direct heat application of PL-87650 flame sanitizer® at two exposure periods or two volumetric water contents. Results are expected to determine the efficacy of evaluated thermal weed control application on previously researched weed species.

Materials and Methods

Thermal conductivity of different soil material. Initial experiments were conducted to determine the thermal conductivity (λ) of three soils at two water contents on May 10 and 16, 2010. The experimental design was a randomized completed block with four replications, with two experimental runs. The experiment was arranged as a factorial combination of three soil textures and two soil water contents (10% and 20% volumetric water content (VWC).

The soil textural classes were loamy sand, clay loam, and sand. The loamy sand was a Marvyn loamy sand (fine-loamy, kaolinitic, thermic Typic Kanhapludults) with pH 5.5 and 2.8% OM (organic matter). The clay loam was a Sumter silty clay (Fine-silty, carbonatic, thermic Rendollic Eutrudepts) with pH 7.4 and 11.1% OM. The loamy sand

and clay loam (upper 20 cm of soil profile) were collected from Auburn and Marion Junction, AL, respectively. The sand was a sand/peat (Spagnum Peatmoss, Premier Horticulture Inc., 127 South 5th St, Suite 300, Quakertown, PA 18951) mix with pH 5.2 and 2.7% OM. The sand/peat was thoroughly mixed to a 85:15 (v/v), sand:peat ratio. All soils were autoclaved for sterilization and sieved to remove debris. Soil physical and chemical properties are shown in Table 1. Particle size analysis was determined by the pipette method (Soil Survey Staff, 2004). Organic matter was calculated from total organic carbon (Baldock and Nelson, 2000) as determined by a dry combustion methods as outlined by Yeomans and Bremner (1991). Soil pH was determined with a 1:1 (soil:water) suspension (Soil Survey Staff, 2004).

Thermal conductivity ($W\ m^{-1}\ K^{-1}$), was determined using Eq. [1], where C_h is volumetric heat capacity ($J\ m^{-3}\ K^{-1}$) and α is the thermal diffusivity ($m^2\ s^{-1}$).

$$\lambda = \alpha\, C_h \qquad [1]$$

C_h was determined for each soil using de Varies Approximation (de Vries, 1963). With Eq. [2] and published values of the specific heats of soil constituents (van Wijk and de Vries, 1963),

$$C_h = \rho_b(c_m\phi_m + c_o\phi_o + c_w\theta_g) \qquad [2]$$

where ρ_b is the bulk density (Mg m^{-3}) on a dry mass basis (1.5 g cm^{-3} for all soils), c the specific heat (kJ kg^{-1} K^{-1}) and ϕ mass fractions for mineral material, organic matter and water with subscripts “m”, ”o”, and “w”, respectively, and θ_g is the gravimetric water content. ϕ_m was calculated from $\phi_m = 1 - \phi_o$ (Soil Survey Staff 2004). A procedure adapted from Chung and Jackson (1954) was used to determine α by measuring the unsteady-state conduction of heat in a cylinder filled with soil.

Exposure period of thermal weed control. Field experiments were conducted at Auburn University’s Turfgrass Research Unit (TGRU) located in Auburn, AL (32°34’38.57”N, 85°29’59.76”W) to determine the effect of two exposure periods of a thermal weed control apparatus on soil temperatures. Field experiments were initiated June 28 and 29, 2011 in a Marvyn loamy sand at 10% VWC (0.1 m^3 m^{-3}) (Table 1). The experimental design was a randomized complete block with four replications and two experimental runs on 2 by 2 m plots. Treatments consisted of two exposure periods, 5 and 20 seconds. The thermal weed control treatment was performed with a tractor-mounted poultry house flame sanitizer, PL-8750 flame sanitizer® (Figure 1). This flame sanitizer has six parallel 1.15 British thermal unit (BTU) hr^{-1} burners mounted at the front of the shielded unit, directing a 1121 °C flame (46 cm by 1 m) at a 45° angle onto the soil surface. The flame sanitizer utilized liquefied propane (LP) and was operated according to manufacture’s recommendations (345 kPa fuel pressure).

Soil moisture impact on thermal apparatus effectiveness. The effect of soil moisture on the effectiveness of the thermal weed control apparatus was investigated at the TGRU site. Field experiments were initiated June 15 and 16, 2011 on a Marvyn loamy sand.

Treatments consisted of two soil moisture levels; 10 and 20% VWC on 2 by 2 m plots. Experimental design was a randomized complete block with four replications, with two experimental runs on 2 by 2 m plots. Plots manually watered to the desired soil water content and depth (10 cm), which was confirmed with a soil moisture probe (Field Scout TDR 300, Spectrum Technologies Inc., 12360 S. Industrial Dr E., Plainfield, IL 60585) and with soil samples. Thermal heat was applied to all treatments via PL-8750 flame sanitizer® operating at 0.8 kilometer per hour (kph) and 345 kPa fuel pressure. A speed of 0.8 kph exposed the soil to approximately 5 s heat pulse from the flame sanitizer.

Data collection. Soil temperatures (°C) at 0 (surface), 1, 3, and 10 cm depths were measured with a thermocouple data logger (HOBO® U12 J, Onset Computer Corporation, Pocasset, MA). The data logger recorded soil temperature at 1 s intervals, from 60 s before heat application to 300 s after the heat source was removed. For each plot at each depth, maximum soil temperature, time to maximum soil temperature, initial soil temperature, amplitude (maximum soil temperature – initial soil temperature), heating slope (Δ °C/Δ s), and cooling slope (Δ °C/Δ s), was recorded or calculated.

Data analysis. Each response was subjected to ANOVA by PROC MIXED in SAS (SAS 2011) and means were separated according to Fisher's Protected LSD at $P = 0.05$ significance level.

Results

Thermal conductivity of different soil material. Thermal conductivities of evaluated soils ranked in the following manner: sand > loamy sand > clay loam (Fig. 2). Also, soils had greater thermal conductivities at the higher water content (Fig. 2). Although there was a range in thermal conductivity values, there was no difference between sand at 10% VWC and loamy sand at 20% VWC. Sand, loamy sand, and clay loam resulted in 1.15, 0.96, and 0.5 thermal conductivity values at 10% VWC, respectively. Sand, loamy sand, and clay loam resulted in 1.45, 1.11, and 0.7 thermal conductivities at 20% VWC, respectively. Results confirm previously reported studies reporting an increase in thermal conductivity with an increase in water content, increase sand content, and decrease in clay content (van Duin, 1963).

Exposure period of thermal weed control. All response variables (maximum soil temperature, time to achieve maximum soil temperature, initial soil temperature, amplitude, heating slope, and cooling slope) resulted in significant soil depth by exposure period interaction (Table 2). Initial soil temperatures decreased with increasing depth, with values ranging from 41 to 30 °C at 0 to 10 cm soil depths.

Soil temperatures increased after the flame treatment was applied at all measured depths, except at 10 cm (Table 2). Maximum soil temperatures between the 5 and 20 s exposure periods were significantly different at 0 cm depth only. Maximum soil surface temperatures were 158 and 454 °C for 5 and 20 s exposure periods, respectively. Although maximum soil temperatures at 1, 3, and 10 cm were numerically greater after the 20 s exposure period than the 5 s, these differences were not significant.

An increase in exposure period resulted in an increase in time to achieve maximum soil temperature (Table 2). Time to achieve maximum temperature for 5 and 20 s exposure periods at the soil surface was 18 and 27 s, respectively. Also, with an increase in depth from 0 to 3 cm, an increase in time to achieve maximum soil temperature was observed. At 10 cm, there was no temperature change after flaming.

Amplitude for thermal exposure period also varied by soil depth. As soil depth increased amplitude decreased, excluding 10 cm soil depth. At 10 cm, amplitude was 0 °C due to no temperature change. Greatest amplitude was observed at the soil surface with 117 and 412 °C for 5 and 20 s exposure period, respectively. No differences in amplitude where observed at 1 cm due to exposure period. At 3 cm depth, soil temperature increased 6 °C from initial soil temperature when exposed to 20 s of thermal heat which was different from that of 5 s exposure (2 °C).

As a function of temperature and time, heating slope was numerically greater for the 20 s exposure period although not statistically different than 5 s. At the soil surface with 20 s exposure period, there was an increase of 19 °C every s until maximum temperature was achieved. An increase in 10 °C every s was observed with 5 s heat exposure. For 5 and 20 s exposure periods, the heating slope was greater at the soil surface than any other soil depth.

No cooling slope was observed from the 5 s exposure period at 3 cm depth and from 10 cm depth with 5 and 20 s exposure period (Table 2). Degree of change for cooling slope was less than that of heating slope. Greatest back slope (-1.4) was observed on the soil surface after 20 s heat exposure. All other cooling slopes were less than -0.3.

Soil moisture impact on thermal apparatus effectiveness. All response variables (maximum soil temperature, time to achieve maximum soil temperature, initial soil temperature, amplitude, heating slope, and cooling slope) resulted in significant soil depth by volumetric water content interaction at (Table 3). Initial soil temperatures decreased with increasing depth. For 10% and 20% VWC, initial soil temperatures ranged from 28 to 34 °C at 10 to 0 cm soil depths. No change in temperature was observed at 10 cm for 10% and 20% VWC treatments.

An increase in volumetric water content resulted in an increase in maximum soil temperature at the soil surface (Table 3). Maximum soil surface temperature for 10% and 20% VWC was 48 and 144 °C, respectively. No other differences were observed between volumetric water contents and maximum soil temperature at all other soil depths.

Increasing volumetric water content did not influence time to achieve maximum soil temperature (Table 3). Although as depth increased (0 to 3 cm) time to achieve maximum temperature also increased: 23 to 155 s for 10% VWC and 17 to 116 for 20% VWC. Time to achieve maximum temperature at 10 cm was 0 s due to no change in temperature.

Amplitude for volumetric water content also varied by soil depth. At 10 cm, amplitude was 0 °C due to no temperature change. As soil depth increased amplitude decreased, excluding 10 cm soil depth. Greatest amplitude was observed at the soil surface with 13 and 81 °C for 10% and 20% VWC, respectively. No change in amplitude was observed at 1, 3, and 10 cm for 10% and 20% VWC.

As a function of temperature and time, heating slope was numerically greater for 20% VWC although no different than 10% VWC at the soil surface. At the soil surface, there was an increase in 5 °C every s until maximum temperature was achieved at 20% VWC. An increase of 0.7 °C was observed every s at 10% VWC. For 10% and 20% VWC, the heating slope was greater at the soil surface than any other soil depth. At both water contents the heating slope was less than 1 for all depths 1 and greater.

No cooling slope was observed at 3 and 10 cm depth at 10% and 20% VWC (Table 3). Degree of change for cooling slope was less than that of heating slope. Greatest back slope (-0.3) was observed on the soil surface at 10% VWC. All other cooling slopes were less than -0.15.

Discussion

Soil surface temperatures observed from 5 and 20 s heat exposure applied by flame sanitizer show potential in reducing viable populations of weed seeds. A 5 s exposure period with flame sanitizer raised soil temperature 117 °C at the soil surface with 10% VWC from 41 to 158°C in 18 s. These temperatures would be sufficient to achieve 100, 100, and 90 % mortality of large crabgrass, cock's-comb kyllinga and Virginia buttonweed seed, respectively according to Hoyle et al. (2012) with 5 s exposure. A 20 s exposure period with flame sanitizer raised soil temperature 412 °C at soil surface at 10% VWC from 41 °C to 454 °C in 27s. These temperatures would also be sufficient to achieve 100, 100, and 90 % mortality of large crabgrass, cock's-comb kyllinga and Virginia buttonweed seed, respectively according to Hoyle et al. (2012).

Observed soil surface temperatures applied by flame sanitizer on a soil with 20% VWC also show potential in reducing viable populations of weed seeds. A 5 s exposure period with flame sanitizer raised soil temperature 81 °C at the soil surface at 20% VWC from 33 to 144°C in 17 s. These temperatures would be sufficient to achieve 100, 100, and 90 % mortality of large crabgrass, cock's-comb kyllinga and Virginia buttonweed seed, respectively according to Hoyle et al. (2012.

Given that weed seeds are incorporated within the upper soil profile (Benvenuti et al., 2001), sufficient temperatures need to be achieved at increased soil depths for effective control. Large crabgrass can emerged from a 8 cm planting depth and 50% emergence was observed at 3.9 cm depth (Hoyle et al. 2011b). Observed soil temperatures from evaluated flame sanitizer at 1 to 10 cm depths with a 5 or 20 s exposure period were not sufficient to reduce populations below the soil surface. This can also be postulated for Virginia buttonweed and cock's-comb kyllinga buried weed seed as emergence of Virginia buttonweed and cock's-comb kyllinga can occur within 6 and 2 cm of the soil surface, respectively (Hoyle et al 2011b).

Although, buried weed seeds would not be affected by this type of thermal weed control application, weed seed populations located on the soil surface would be highly susceptible to thermal heat applications. Previous research conducted by Hoyle et al. (2011b) resulted in maximum emergence of Virginia buttonweed, cock's-comb kyllinga, and large crabgrass on the soil surface, and emergence was reduced with increasing burial depth. Therefore our results show that 5 and 20 s exposure period at 10% VWC or 5 s exposure period at 20% VWC of direct soil flaming by PL-8750 flame sanitizer® can significantly reduce these weed species populations.

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Table 1. Chemical and physical characteristics of soil textures in which thermal conductivity was evaluated.

Soil Series	Soil Texture	Water Content [y]	Sand	Silt	Clay	OM [z]	pH
		θ (v/v)		%		mg kg^{-1}	
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

[z] OM, organic matter.

[y] Soil water content at field capacity for soils was predetermined by Witkowska-Walczak et al. 2002, Wehtje et al. 1993, and Wehtje et al. 1987 for sand, loamy sand, and clay loam soil textures, respectively.

[x] Sand:peat mixture; 85:15%, v:v.

[w] All soils obtained bulk density of 1.5 g cm^{-3}.

Table 2. Assessing soil temperatures, times and rates of temperature change after 5 and 20 second exposure period with PL-8750 flame sanitizer® application. [z]

Depth	Exposure period			Exposure period		
(cm)	5 s	20 s		5 s	20 s	
	Maximum soil temperature (°C)		LSD [y]	Time to maximum soil temperature (s)		LSD
0	158	454	212	18	27	ns
1	43	45	ns	167	281	ns
3	34	40	ns	345	376	ns
10	29	31	ns	0	0	ns
LSD	37	155		53	64	
	Initial temperature (°C)		LSD	Amplitude (Δ °C)		LSD
0	41	41	ns	117	412	213
1	35	36	ns	8	10	ns
3	32	34	ns	2	6	2
10	29	30	ns	0	0	ns
LSD	2	2		36	55	
	Heating slope (Δ °C/ Δ s)		LSD	Cooling slope (Δ °C/ Δ s)		LSD
0	10	19	ns	-0.3	-1.4	1
1	0.1	0.1	ns	-0.02	-0.006	0.01
3	0.2	0.3	ns	0	0	ns
10	0	0.001	ns	0	0	ns
LSD	3	7		ns	ns	

[z] s, seconds; ns, not significant.

[y] Fisher's Protected LSD calculated at P=0.05 significance level.

Table 3. Assessing soil temperatures, times and rates of temperature change at 10 and 20% VWC (volumetric water content) with PL-8750 flame sanitizer® application at 0.8 kph (approximately 5 s heat pulse exposed to soil).

Depth	VWC			VWC		
(cm)	10%	20%		10%	20 %	
	Maximum temperature (°C)		LSD [y]	Time to maximum temperature (s)		LSD
0	48	144	39	23	17	ns
1	37	35	ns	30	47	ns
3	31	30	ns	155	116	ns
10	28	30	ns	0	0	ns
LSD	4	14		95	ns	
	Initial temperature (°C)		LSD	Amplitude (Δ °C)		LSD
0	34	33	ns	13	81	35
1	32	32	ns	5	3	ns
3	30	30	ns	1	0.2	ns
10	28	29	ns	0	0	ns
LSD	2	2		4	14	
	Heating slope (Δ °C/ Δ s)		LSD	Cooling slope (Δ °C/ Δ s)		LSD
0	0.7	5	ns	-0.03	-0.3	ns
1	0.5	0.07	ns	-0.15	-0.008	0.1
3	0.02	0.004	0.004	0	0	ns
10	0	0	ns	0	0	ns
LSD	0.3	4		0.13	ns	

[z] s, seconds; ns, not significant.

[y] Fisher's Protected LSD calculated at P=0.05 significance level.

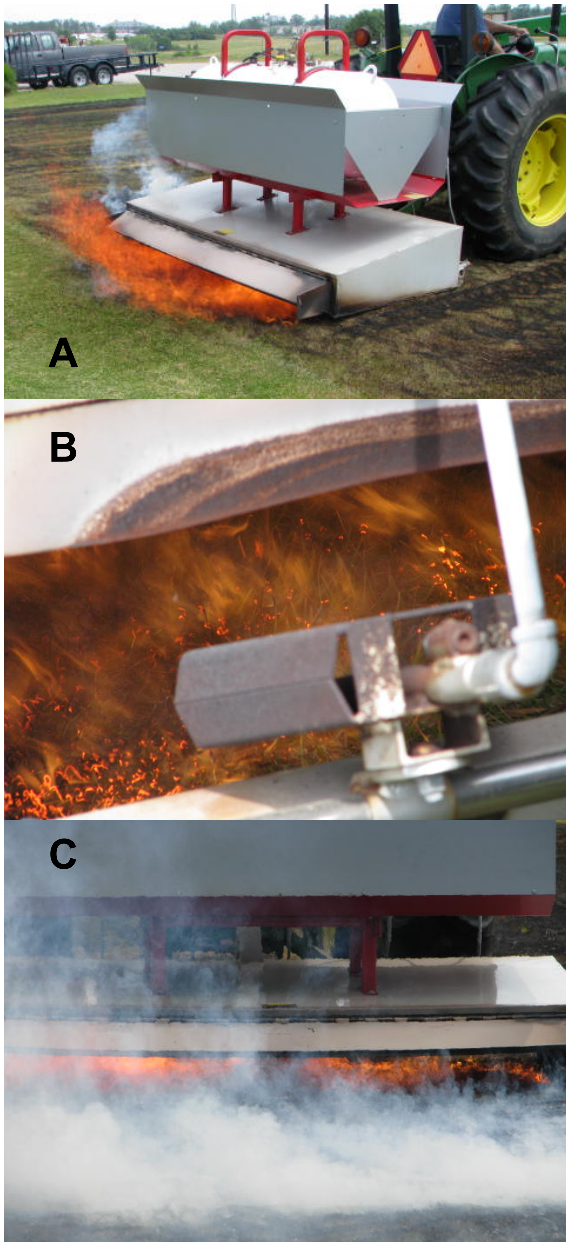

Fig. 1. PL-8750 Flame Sanitizer®; A & C. demonstrating thermal weed control. B. 1.15 British thermal unit (BTU) hr^{-1} burner.

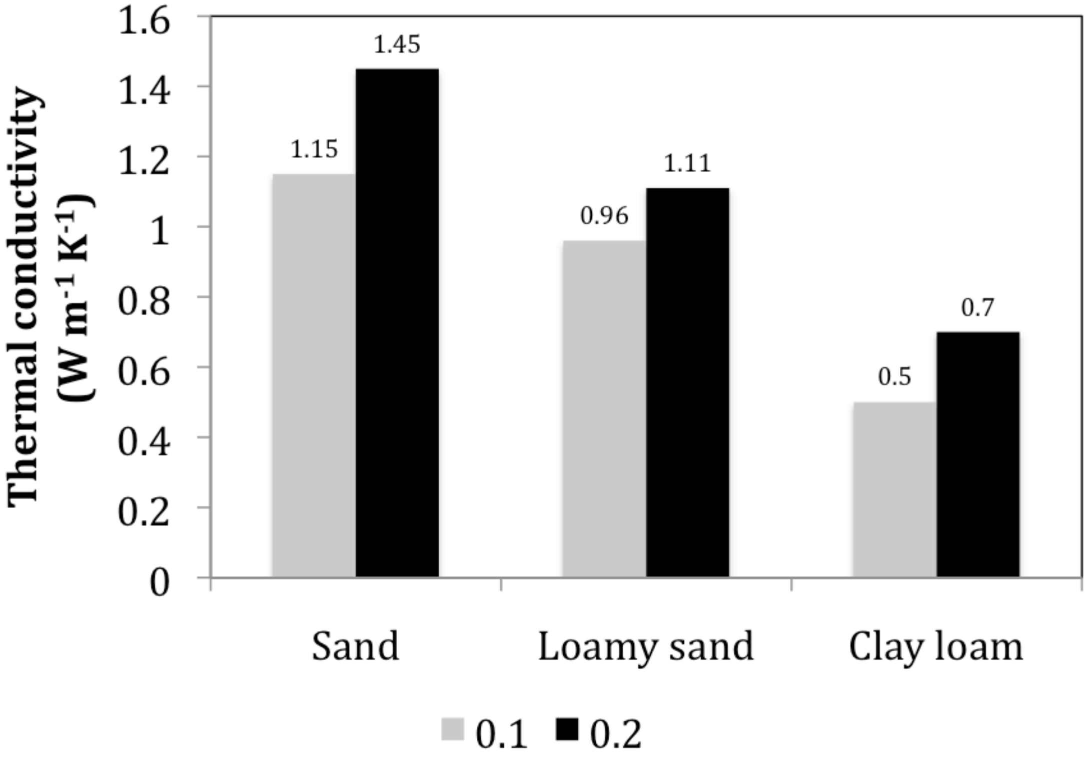

Fig. 2. Soil texture and volumetric water content (θ) effects on thermal conductivity. Means separation by Fisher's Protected LSD (*P* = 0.05). LSD = 0.09.

VI. Monitoring and Predicting Soil Solarization Temperatures for Effective Weed Control in Southeastern United States

Abstract

Thermal weed control method by soil solarization is being utilized for weed control in the Southeastern United States. This is a method pest control that heats soil by covering soil surface with plastic sheeting. Field research trials were conducted to observe soil temperatures at various depths during soil solarization application and to use common collected weather data to predict solarization soil temperatures. Recorded data consisted of soil temperatures at 0, 1, and 3 cm planting depths at 1-hour intervals for 7 days. Soil moisture data was recorded before and after each experimental run by soil moisture probe. Recorded environmental weather data was ambient air temperature, dew point, wet bulb temperature, relative humidity, precipitation, solar radiation, and high temperature. Weather data was recorded hourly for the duration of experiments. Environmental weather data was used to select "best" model by stepwise analysis and predict solarization soil temperature. Soil surface daily maximum soil temperature was 15.5 °C higher for solarization compared to that of the non-treated. At 1 cm depth, soil temperature was 1.6 °C less for solarization treatment compared to non-treated. A 5.8 °C increase in daily maximum average soil temperature at 3 cm was observed in solarization treatments. Daily average maximum soil temperature decreased with increasing soil depth in non-treated treatments. Highest to lowest daily average maximum soil temperatures for solarization followed the trend: 0 > 3 > 1 cm soil depths. Daily maximum average surface solarization temperature of 66.5 °C can be effective for weed control if solarization plastic is applied for a sufficient duration. Factors that predominantly affected soil solarization temperatures were ambient air temperature, dew point, wet bulb temperature, relative humidity, precipitation, and solar radiation. Solar radiation was the main factor influencing soil temperatures (Partial $R^2 = 0.55$ to 0.76). With access to environmental weather data anyone contemplating the use of soil solarization for weed control in the Southeastern United States is able to predict soil temperatures and possibly efficacy on weed species present at their location.

Additional index key words. Thermal weed control, stale-seed-bed preparation, soil solarization, Virginia buttonweed, *Diodia virginiana*, cock's-comb kyllinga, *Kyllinga squamulata,* large crabgrass, *Digitaria sanguinalis*.

Introduction

Thermal weed control methods utilize heat to kill weed seeds and emerged weeds (Bond et al., 2007). Techniques include soil solarization (Horowitz et al., 1983; Bell and Laemmlen, 1991; Elmore, 1991; Peachey et al., 2001), flame weeding (Ascard, 1990, 1994, 1995, 1997; Sivesind et al., 2009), infrared radiation (Ascard, 1998), steaming and hot water (Anon, 1999; Trotter, 1991), direct heat (Hopkins, 1936; Rubin and Benjamin, 1983), electrocution (Vigneault et al,. 1990), microwave radiation, electrostatic fields

(Diprose et al., 1984), irradiation (Suss and Bacthlar, 1968), lasers (Couch and Gangstad, 1974; Heisel et al., 2002; Mathiassen et al., 2006), and ultraviolet light (Andreasen et al., 1999). Reaching thermal death point (TDP) of weed seed determines efficacy of these thermal weed control methods.

Soil solarization is a method of pest control by heating soil by covering with plastic sheeting (Horowitz et al., 1983). It has been noted as a nonchemical means of reducing weed seed populations (Katan et al., 1976; Egly, 1983; Horowitz et al., 1983; Rubin and Benjamin, 1983; Standifer et al., 1984; Peachey et al., 2001). Effective solarization requires climates with long sun exposure periods and increased ambient temperatures for sufficient amount of time (Standifer et al., 1984). Solarization has been utilized in horticulture crops like lettuce and garlic (Al-Massom et al., 1993), squash and tomato (Abu-Irmaileh, 1991), and other high value crops. High value vegetable crops can warrant the increased application cost of solarization (Bell et al., 1988). Applied across multiple locations, solarization has proven to provide adequate control of annual bluegrass (*Poa annua*) (Standifer et al., 1984; Bell and Laemmlen, 1991; Elmore, 1991; Peachey et al., 2001). Although, not all weed species are susceptible to solarizaton (Egley, 1990). Many weed species have buried reproductive organs, which make solarization a difficult thermal weed control method (Bell et al., 1988; Horowitz et al., 1983; Rubin and Benjamin, 1984).

Due to a wide range of influential factors including targeted weed species (Dahlquist et al., 2007; Rubin and Benjamin, 1984; Egley, 1990; Linke, 1994), planting depth (Benvenuti et al., 2001), treatment duration (Riemens, 2003), soil texture (van

Rooyen and Winkerton, 1959), soil moisture (van Duin, 1963), thermal conductivity (Patten, 1909; Smith, 1942), soil chemical properties (Bowers and Hanks, 1962; Lang, 1878; Ulrich, 1894), and soil porosity (Ochsner et al., 2001) soil solarization efficacy varies.

Soil solarization is influenced by thermal conductivity in return is influenced by soil properties. As soil is a granular medium consisting of solid, liquid, and gaseous phases, thermal conductivity will depend on the volumetric proportions of these components, the size and arrangement of the solid particles, and the interfacial contact between the solid and liquid phases (Jury and Horton, 2004). Thermal conductivity decreases with decreasing particle size (Patten, 1909), increases with bulk density (van Rooyen and Winterkorn, 1959), and increases with water content (van Rooyen and Winterkorn, 1959; van Duin, 1963).

Soil properties play and influential role in soil solarization efficacy. The TDP of weed species is also important in determination of thermal weed control efficacy. Temperature to achieve TDP varies with species (Dahlquist et al., 2007; Rubin and Benjamin, 1984; Egley, 1990; Linke, 1994). Previous research by Hoyle et al. (2012) reported that evaluated weed species increased in susceptibility to thermal heat: Virginia buttonweed (*Diodia virginiana* L.) < cock's-comb kyllinga (*Kyllinga squamulata* Thonn. ex Vahl) < large crabgrass (*Digitaria sanguinalis* L. Scop). Susceptibility of these weed species to thermal heat was also influenced by temperature and exposure time. Evaluation of Virginia buttonweed, cock's-comb kyllinga, and large crabgrass resulted in 90% weed seed mortality at 125 and 140 °C for 20 and 5 s exposure periods, respectively

(Hoyle et al., 2012). In general, higher temperatures require shorter duration and lower temperatures require a longer duration.

Ability to predict solarization soil temperatures is critical in determination if one will utilize soil solarization. If environmental conditions are not favorable for solarization then application is not warranted. Currently sufficient amount of recorded environmental weather data is available for Southeastern United States. This weather data is also available to the public. Utilizing available weather data to predict soil solarization temperatures at multiple soil depths along with TDP data could possible determine solarization efficacy.

Studies were designed to observed soil temperatures at various depths during soil solarization application and use common collected weather data to predict solarization soil temperatures for Southeastern United States. Results can determine efficacy of evaluated thermal weed control application on pervious researched weed species. Results also can predict if current method of thermal weed control is applicable if TDP of targeted weed species is determined.

Materials and Methods

Field experiments were conducted at Auburn University's Turfgrass Research Unit (TGRU) located in Auburn, AL (32°34'38.57"N, 85°29'59.76"W) to determine soil temperature differences by soil solarization prior to turfgrass establishment. Field experiments were initiated on May 24, June 1, June 8, and June 15, 2011. Soil was a Marvyn loamy sand (fine-loamy, kaolinitic, thermic Typic Kanhapludults) with pH of 5.5

and 2.7% organic matter (OM). Soil properties are presented in Table 1. Soil was initially prepared by tillage. Vegetation was removed if present by hand before and throughout experiment. Treatments consisted of solarization and a non-treated. Soil-solarization utilized 6 mil, clear polyethylene plastic (Husky Polyethylene Plastic®, Poly-America, Grand Prairie, TX 75051) covering soil surface with edges buried 10 cm. Treatments were arranged as a randomized complete block with 2 replications and 4 experimental runs. Each experimental run was conducted for 7 days (d).

Data collection and analysis. Recorded data consisted of soil temperatures (°C) at 0 (surface), 1, and 3 cm planting depths. Soil temperatures were recorded with thermocouple data logger (HOBO® U12 J, Onset Computer Corporation, Pocasset, MA). Data logger recorded soil temperature at 1 hour (h) interval for 7 d. Soil temperatures were used to calculate daily average maximum soil temperature (DAMST). Soil moisture data was recorded before and after each experimental run by soil moisture probe (Field Scout TDR 300, Spectrum Technologies Inc., 12360 S. Industrial Dr E., Plainfield, IL 60585). Samples of moist soil were also used to confirmed soil moisture content by Soil Survey Staff (2004) laboratory procedures at field state (4B4). Each response was subjected to ANOVA by PROC MIXED in SAS (SAS, 2011) and means were separated according to Fisher's Protected LSD at P = 0.05 significance level. Recorded environmental weather data was ambient air temperature (°C), dew point (°F), wet bulb temperature (°F), relative humidity (%), precipitation (inches), solar radiation (W h m^{-2}), and high temperature (°C at 33 ft elevation). Weather data was recorded hourly for the duration of experiments. Environmental weather data was used to select "best" model by stepwise analysis and predict solarization soil temperature by PROC REG in SAS (SAS, 2011).

Results

Soil moisture. For soil solarization treatment percent volumetric water content increased as time progressed starting from June 1, 2011 (Table 2). At initiation of field experiments (May 24, 2011) both solarization and non-treated treatments obtained 1.8 % volumetric water content. Solarization treatment resulted in 0.03%, 0.53%, 0.7%, and 3.3% volumetric water content on June 1, June 8, June 15, and June 22, 2011, respectively. Non-treated plots decreased in water content from 1.8% to 1% between May 24 and June 8, 2011. Water content increased from 1% to 6.7% from June 8 to June 22, 2011 in non-treated plots.

Daily average maximum soil temperature. No treatment within experimental run and replication interactions were observed ($P > 0.05$) therefore, data were combined for solarization DAMST temperature. However, a significant treatment by depth interaction was observed (F-value=89.24, P-value<0.001). At all evaluated depths soil temperature differed by treatment. Soil temperatures were highest at the soil surface (Table 3). Daily average maximum soil temperature at soil surface was 66.5 and 51 °C for solarization and non-treated, respectively. Soil surface DAMST was 15.5 °C higher for solarization compared to the non-treated. At 1 cm depth, soil temperature was 1.6 °C less for solarization treatment compared to non-treated. A 5.8 °C increase in DAMST at 3 cm was observed in solarization treatments. Daily average maximum soil temperature decreased with increasing soil depth in non-treated. Soil surface, 1, and 3 cm soil depths resulted in 51, 41.5, and 39.9 °C soil temperatures, respectively. Unlike non-treated at 3 cm depth, soil solarization treatment resulted in lowest DAMST (38.1 °C) at 1 cm soil depth. Highest to lowest DAMST for solarization followed the trend: 0 > 3 > 1 cm soil depths.

Prediction of soil solarization temperature. Environmental weather data was linearly related to soil solarization temperatures at 0, 1, and 3 cm soil depth: F-value = 432.02, P-value <0.001; F-value = 161.42, P-value <0.001; F-value = 227.9, P-value <0.001, respectively (Table 4). At soil surface and 1 cm, 7 parameters were utilized to predict soil solarization temperatures. At 3 cm, 6 parameters were utilized to predict soil solarization temperatures. The seven parameters used to predict soil solarization temperatures at 0 and 1 cm soil depth were ambient air temperature, dew point, wet bulb temperature, relative humidity, precipitation, solar radiation, and high temperature. The six parameters used to predict soil solarization temperatures at 3 cm were ambient air temperature, dew point, wet bulb temperature, relative humidity, precipitation, and solar radiation. Linear regression equations are represented in Table 4.

Discussion

Soil moisture. Thermal conductivity is a constant in determination of soil heat flux (Jury and Horton, 2004). Soil heat flux is important in the interaction between soil surface and subsurface energy transfer this is influenced by surface cover, soil moisture, and solar irradiance (Sauer and Horton, 2003). Previous research concluded that with an increase in soil water content of Marvyn loamy sand an increase thermal conductivity was observed (Hoyle et al., 1012). Therefore, an increase in thermal conductivity by water content would indirectly increase soil solarization temperatures. Our research resulted in a slight increase in volumetric water content from June 1 to June 22, 2012 for soil exposed to soil solarization (Table 2). Although an increase in volumetric water content was observed an increase in DAMST was not (Data not shown).

As non-treated plots were exposed to environmental elements, increase in water content was due to precipitation events (Fig. 1). An increase in DAMST for the non-treated was not observed (Data not shown).

Daily average maximum soil temperature. Maximum soil temperatures at each depth was reached daily between 1400_{HR} and 1500_{HR} (Data not shown). Similar to previous research maximum soil temperatures were reached at 1430_{HR} in New Delhi, India (Arora and Yaduraju, 1998). Arora and Yanduraju (1998) also reported soil surface temperatures by solarization to be 39 to 63 °C. Our current experiments also resulted in similar soil surface temperatures at 67 °C. Effective weed control lasting 4 months was observed when soil temperatures were raised 7 to 9 °C in Greece (Vizantionpoulos and Katranis, 1993). Temperatures in current experiment were raised 16 and 6 °C to 67 and 46 °C for 0 and 1 cm, respectively. Therefore, current solarization studies show potential in effective weed control.

The DAMST of 66.5 °C achieved through solarization (Table 3) would not be sufficient enough to be detrimental to large crabgrass, cock's-comb kyllinga and Virginia buttonweed seed according to Hoyle et al. (2012). A minimal temperature exposure of

83, 87, and 99 °C for 20 s would be required to achieve 50% mortality of large crabgrass, cock's-comb kyllinga, and Virginia buttonweed, respectively (Hoyle et al. 2012). Although sufficient temperatures were not achieved by current study at short durations, lower soil temperatures may be effective as duration of heat exposure is significantly greater for solarization. Effective weed control by solarization has been reported if temperatures > 65 °C are maintained for long periods of time (Standifer et al., 1984). Duration of solarization for effective weed control can vary from 20 days (Linke, 1994) to 8 weeks (Bond et al., 2007). As our experiment found daily surface solarization DAMST to be 66.5 °C, effective weed control may be achievable if solarization plastic is applied for a sufficient duration.

Prediction of soil solarization temperature. As results from previous solarization studies have been reported to be highly area-specific (Katan et al., 1976; Chen and Katan, 1980; Katan 1980, 1981; Rubin and Benjamin 1983, 1984; Myers et al. 1983; Kassaby 1985; Fahim et al., 1987; Arora and Pandey, 1989; Lodhas et al., 1991, Kumar and Yaduraju, 1992; Arora and Yaduraju, 1998) environmental conditions are very important in predicting soil solarization temperatures. Similar to previous studies soil temperatures under solarization varied with daily environmental conditions (Arora and Yaduraju, 1998). Factors that predominantly affected soil solarization temperatures were ambient air temperature, dew point, wet bulb temperature, relative humidity, precipitation, and solar radiation. Solar radiation obtained highest partial R^2 values in predicting soil temperatures under solarization plastic: 0.76, 0.55, and 0.56 partial R^2 values for 0, 1, and 3, cm, respectively. This also was the main factor affecting soil temperatures of all solarization treatments by Arora and Yaduraju (1998). Common environmental weather data, like the factors recorded for current experimental study, are available for private and public use. This allows producers or non-producers that are debating the use of soil solarization for weed control in the Southeastern United States to predict soil temperatures and efficacy on weed species present at their location.

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Table 1. Chemical and physical characteristics of soil in which soil solarization temperatures were evaluated.

Soil Series	Soil Texture	Water Content [y]	Sand	Silt	Clay	OM [z]	Bulk density	pH	Thermal conductivity [w]	
									0.1 θ	0.2 θ
		θ (v/v)		%		mg kg^{-1}	g cm^{-3}		W m^{-1} K^{-1}	
Marvyn	Loamy sand	0.17	81.37	14.46	4.17	27,800	1.5	5.5	0.96	1.11

[z] OM, organic matter.

[y] Soil water content at field capacity for soil was predetermined Wehtje et al. (1993).

[x] Sand:peat mixture; 85:15%, v:v.

[w] Thermal conductivity at 0.1 and 0.2 volumetric water content determined by Hoyle et al. (2012).

Table 2. Volumetric water content of research plots before and after each experimental run.

Treatment	24 – May	1 – June	8 – June	15 – June	22 - June
	Volumetric water content (%) [z]				
Solarization	1.8	0.03	0.53	0.7	3.3
Non-treated	1.8	1.7	1.0	5.9	6.7
LSD [y]	0.7	1.7	1.8	1.0	1.7

[z] Volumetric water content by soil moisture probe (Field Scout TDR 300, Spectrum Technologies Inc., 12360 S. Industrial Dr E., Plainfield, IL 60585)

[y] Means within columns separated by Fisher's Protected LSD a *P* =0.05.

Table 3. Daily average maximum soil temperatures (DAMST) after solarization treatment.

Depth	Treatment		
(cm)	Solarization	Non-treated	LSD [z]
	DAMST (°C)		
0	66.5	51.0	4.3
1	38.1	41.5	1.6
3	45.7	39.9	2.7
LSD [y]	4.7	3.5	

[z] Means within rows or columns separated by Fisher's Protected LSD a *P* =0.05.

Table 4. Environmental weather data variable selection to predict solarization soil temperatures at multiple depths. [z]

Depth	Model [y]	adj. R^2
0	$\hat{Y} = -42.6 + 5.6X_1 + 1.4X_2 - 4.7X_3 + 0.5X_4 - 17.6X_5 + 0.03X_6 - 1.5X_7$	0.85
1	$\hat{Y} = 20.1 + 1.2X_1 + 0.4X_2 - 0.9X_3 + 0.5X_4 - 4.5X_5 + 0.004X_6 - 0.4X_7$	0.68
3	$\hat{Y} = 4.3 + 2.1X_1 + 0.7X_2 - 2.5X_3 + 0.2X_4 - 4.5X_5 + 0.009X_6$	0.72

[z] "Best" model selection conducted by stepwise regression method in SAS (SAS 2011) by PROC REG.

[y] $\hat{Y}$, solarization soil temperature (°C); X_1, ambient air temperature (°C); X_2, dew point (°F); X_3, wet bulb temperature (°F); X_4, relative humidity (%); X_5, precipitation (inches); X_6, solar radiation (W h m^{-2}); X_7, high temperature (°C at 33 ft elevation)

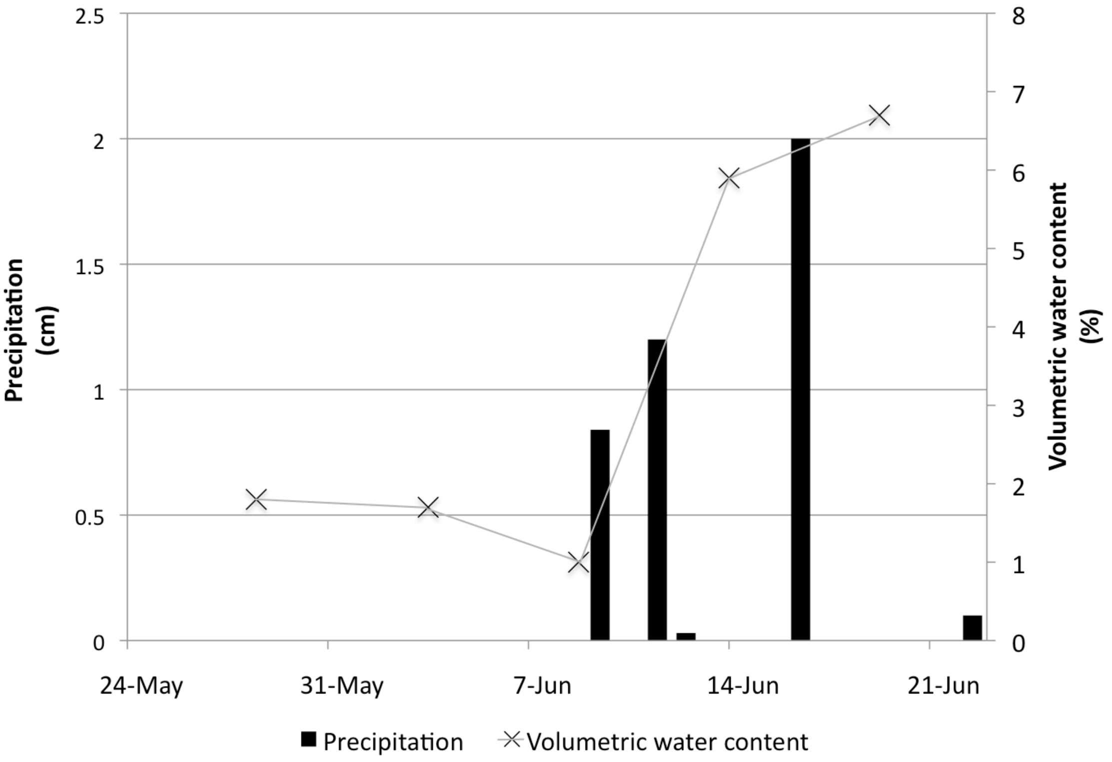

Fig. 1. Influence of precipitation on volumetric water content of non-treated research plots through duration of solarization research trials.

VII. Determination of Soil Surface Temperatures by Fourier's Law for Effective Large Crabgrass (*Digitaria sanguinalis* (L.) Scop), Virginia buttonweed (*Diodia virginiana* L.), and Cock's-comb Kyllinga (*Kyllinga squamulata* Thonn. ex Vahl) Control by PL-8750 Flame Sanitizer®

Information reported from previous individual experiments can be applied to Fourier's Law (Equation 1) ultimately determining the energy transfer rate in the soil profile by PL-8750 flame sanitizer®. Energy rate, *q* can be calculated from Equation [1]:

$$q = \lambda(\Delta T / d) \qquad [1]$$

where λ is thermal conductivity, ΔT is temperature change, and *d* is distance in soil. Further calculations with Fourier's law can determine surface temperature needed for effective weed seed mortality of evaluated species at various environmental conditions.

Initially energy rate was calculated for Marvyn loamy sand at 0.1 and 0.2 θ with predetermined thermal conductivities, and temperature differences from thermal weed control monitoring studies. Energy rate for Marvyn loamy sand at 0.1 and 0.2 θ was 3534 and 3824 BTU hr^{-1} ft^{-2}, respectively as determined from factors presented in Table 1.

Calculation of surface temperature is dependent upon weed species and soil properties. Individual weeds species thermal death point (TDP) and emergence depth are influential factors in determination of surface temperature for effective weed control. In Chapter 4, a 50 and 90% mortality of large crabgrass, cock's-comb kyllinga, and Virginia buttonweed was determined for a 5 and 20 s exposure period (Table 5 in Chapter 4). These TDP values are utilized in determination of ΔT by Equation [2]

$$\Delta \mathrm{T} = S_T - T_x \qquad [2]$$

Where S_T is the surface temperature and T_x is the TDP of the weed species in question. In Chapter 3, a depth to reduce weed seed emergence 50% relative to surface germination (D_{50}) was determined for large crabgrass, cock's-comb kyllinga, and Virginia buttonweed (Table 3 in Chapter 3). Weed species emergence depth is utilized in determination of thermal heat travel in the soil (*d* in Fourier's Law).

Fourier's Law determined two individual surface temperatures for each weed species. The two surface temperatures correspond to a R_{25} and R_{45} value. R_{25} is the effective surface temperature needed to reduce the total weed seed population within 8 cm of the soil surface by 25% utilizing D_{50} and temperature to achieve 50% weed seed mortality. R_{45} is the effective surface temperature needed to reduce the total weed seed population within 8 cm of the soil surface by 45% utilizing D_{50} and temperature to achieve 90% weed seed mortality. Variable values for prediction of R_{25} and R_{45} values in Fourier's Law are presented in Tables 2-4.

Surface temperatures needed to reduce large crabgrass populations by 25 and 45% in Marvyn loamy sand with 0.1 or 0.2 θ was over 980 °F (Table 5). Calculations of R_{25} and R_{45} determined that large crabgrass would be difficult to control with PL-8750 flame sanitizer® due to the increased soil surface temperatures that need to be achieved. Cock's-comb kyllinga seed populations in the soil profile can be reduced with PL-8750 flame sanitizer® application if soil surface temperatures of 360 °F are achieved. Cock's-comb kyllinga is more susceptible to this type of application due to lower TDP and shallower emergence depth. Virginia buttonweed would require greater than 425 °F soil surface temperatures for reduction in seed populations.

Although increased soil surface temperatures must be achieved by direct flame application for reducing weed populations in the soil profile our studies have shown that thermal weed control methods by flame application show potential in reducing weed populations prior to turfgrass establishment.

Table 1. Energy rate for Marvyn loamy sand at 0.1 and 0.2 θ with predetermined thermal conductivities, and temperature differences from thermal weed control monitoring studies.

Volumetric water content	Fourier's Law Variables			
θ	q	λ [a]	ΔT [b]	d [b]
	BTU hr^{-1} ft^{-2}	BTU hr^{-1} ft^{-1} $°F^{-1}$	°F	ft
0.1	3534	0.56	207	0.033
0.2	3824	0.64	196	0.033

[a] Thermal conductivity converted to BTU hr^{-1} ft^{-1} $°F^{-1}$ from values in Figure 2 in Chapter 5.

[b] Change in temperature and distance converted to °F and ft from values in Table 2 and 3 in Chapter 5. 5 s exposure for 0.1 and 0.2 θ by PL-8750 flame sanitizer®

Table 2. Values used for Fourier's Law variables in determination of surface temperature needed to reduce large crabgrass seed population within 8 cm of the soil surface by 25% (R_{25}) or 45% (R_{45}). [a]

θ		Fourier's Law Variables			
		q [b]	λ [b]	ΔT [c]	d [d]
		BTU hr^{-1} ft^{-2}	BTU hr^{-1} ft^{-1} °F^{-1}	S_t - °F (°C)	ft (cm)
0.1	R_{45}	3534	0.56	S_t – 230(110)	0.128(3.9)
	R_{25}	3534	0.56	S_t – 217(103)	0.128(3.9)
0.2	R_{45}	3824	0.64	S_t – 230(110)	0.128(3.9)
	R_{25}	3824	0.64	S_t – 217(103)	0.128(3.9)

[a] Abbreviations: S_t, surface temperature; θ, volumetric water content.

[b] Energy rate for Marvyn loamy sand from Table 1.

[c] Temperature change determined by temperature to achieve 50 or 90% mortality of weed seed at 5 s exposure period (Table 5 in Chapter 4).

[d] Heat travel distance determined by D_{50} values from Table 3 Chapter 3.

Table 3. Values used for Fourier's Law variables in determination of surface temperature needed to reduce cock's-comb kyllinga seed population within 8 cm of the soil surface by 25% (R_{25}) or 45% (R_{45}). [a]

θ		Fourier's Law Variables			
		q [b]	λ [b]	ΔT [c]	d [d]
		BTU hr^{-1} ft^{-2}	BTU hr^{-1} ft^{-1} $°F^{-1}$	S_t - °F (°C)	ft (cm)
0.1	R_{45}	3534	0.56	S_t – 235(113)	0.026(0.8)
	R_{25}	3534	0.56	S_t – 206(97)	0.026(0.8)
0.2	R_{45}	3824	0.64	S_t – 235(113)	0.026(0.8)
	R_{25}	3824	0.64	S_t – 206(97)	0.026(0.8)

[a] Abbreviations: S_t, surface temperature; θ, volumetric water content.

[b] Energy rate for Marvyn loamy sand from Table 1.

[c] Temperature change determined by temperature to achieve 50 or 90% mortality of weed seed at 5 s exposure period (Table 5 in Chapter 4).

[d] Heat travel distance determined by D_{50} values from Table 3 Chapter 3.

Table 4. Values used for Fourier's Law variables in determination of surface temperature needed to reduce Virginia buttonweed seed population within 8 cm of the soil surface by 25% (R_{25}) or 45% (R_{45}). [a]

θ		Fourier's Law Variables			
		q [b]	λ [b]	ΔT [c]	*d* [d]
		BTU hr^{-1} ft^{-2}	BTU hr^{-1} ft^{-1} $°F^{-1}$	S_t - °F (°C)	ft (cm)
0.1	R_{45}	3534	0.56	S_t – 284(140)	0.036(1.1)
	R_{25}	3534	0.56	S_t – 210(99)	0.036(1.1)
0.2	R_{45}	3824	0.64	S_t – 284(140)	0.036(1.1)
	R_{25}	3824	0.64	S_t – 210(99)	0.036(1.1)

[a] Abbreviations: $S_{t,}$ surface temperature; θ, volumetric water content.

[b] Energy rate for Marvyn loamy sand from Table 1.

[c] Temperature change determined by temperature to achieve 50 or 90% mortality of weed seed at 5 s exposure period (Table 5 in Chapter 4).

[d] Heat travel distance determined by D_{50} values from Table 3 Chapter 3.

Table 5. Surface temperature needed to reduce weed seed population within 8 cm of the soil surface by 25% (R_{25}) or 45% (R_{45}). [a]

θ		Large crabgrass	Cock's-comb kyllinga	Virginia buttonweed
		S_t (°F)		
0.1	R_{45}	1038	399	511
	R_{25}	1024	370	437
0.2	R_{45}	994	390	499
	R_{25}	981	361	425

[a] Abbreviations: $S_{t,}$ surface temperature; θ, volumetric water content.