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Weed Control Using an Enclosed Thermal Heating Apparatus

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Weed control by heat or flaming typically uses flames to burn small weeds, directed away from desired crops. This research studied an enclosed flaming system for weed control before turfgrass establishment. Field research trials were conducted to explore the efficacy of a PL-8750 flame sanitizer at two application timings. Treatments included various application methods of PL-8750 flame sanitizer and common thermal and chemical weed control methods. Data were weed control relative to the control treatment. Species evaluated included carpetweed, Virginia buttonweed, spotted spurge, large crabgrass, goosegrass, old world diamond-flower, cocks-comb kyllinga, and yellow nutsedge. Turfgrass establishment was not successful in summer but was successful in fall. Fall-application timing trials resulted in > 60% tall fescue establishment at 6 wk after seeding (WAS) for all treatments. Summer-application timing trials resulted in unacceptable turfgrass establishment (≤ 18%) for all evaluated turfgrass species at 6 WAS. Broadleaf and grassy weeds were better controlled compared with sedge weeds. Overall, solarization; covered, emerged-weed flaming; and double applications of covered, emerged-weed flaming were the most successful treatments. Solarization controlled carpetweed, Virginia buttonweed, spotted spurge, large crabgrass, and goosegrass > 80% at 6 WAS. Weed control across thermal treatments were equal to or greater than the comparison chemical treatment (dazomet at 389 kg ha^{-1}). Results indicate thermal weed control has potential for reducing weed populations before turfgrass establishment.
Nomenclature: Basamid; dazomet; carpetweed, *Mollugo verticillata* L. MOLVE; cocks-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; tall fescue, *Lolium arundinaceum* (Schreb.) S.J. Darbyshire.
Key words: Thermal weed control, methyl bromide alternative, emerged weed flaming, direct soil flaming, soil solarization.

El control de malezas por calor o llamas usa típicamente llamas para quemar malezas pequeñas al tiempo que se evita el cultivo deseado. Esta investigación estudió un sistema cubierto de llamas para el control de malezas antes del establecimiento del césped. Se realizaron estudios de campo para explorar la eficacia de un desinfectante de llama PL-8750 en dos momentos de aplicación. Los tratamientos incluyeron varios métodos de aplicación del desinfectante de llama PL-8750 y métodos comunes de control de malezas térmico y químico. Los datos fueron control de malezas relativo al tratamiento testigo. Las especies evaluadas incluyeron *Mollugo verticillata*, *Diodia virginiana*, *Chamaesyce maculata*, *Digitaria sanguinalis*, *Eleusine indica*, *Oldenlandia corymbosa*, *Kyllinga squamulata* y *Cyperus esculentus*. El establecimiento del césped no fue exitoso en el verano, pero sí lo fue en el otoño. Los estudios de momento de aplicación en el otoño resultaron en un establecimiento >60% de *Lolium arundinaceum* a 6 semanas después de la siembra (WAS) para todos los tratamientos. Los estudios de momento de aplicación en el verano resultaron en un establecimiento inaceptable del césped (≤18%) para todas las especies de césped evaluadas a 6 WAS. Las malezas de hoja ancha y zacates fueron controladas mejor en comparación con las malezas ciperáceas. En general, solarización; suelo cubierto, control con llamas en malezas emergidas; y aplicaciones dobles de suelo cubierto, control con llamas en malezas emergidas fueron los tratamientos más exitosos. La solarización controló *M. verticillata*, *D. virginiana*, *C. maculata*, *D. sanguinalis* y *E. indica* >80% a 6 WAS. El control de malezas térmico fue igual o mayor en comparación con el tratamiento químico (cazonete a 389 kg ha^{-1}). Los resultados indican que el control térmico de malezas tiene potencial para reducir poblaciones de malezas antes del establecimiento del césped.

Thermal weed control methods use heat to kill weed seeds and emerged weeds (Bond et al. 2007). Techniques include soil solarization (Horowitz et al. 1983), flame weeding (Ascard 1995, 1997, 1998; Sivesind et al. 2009), infrared radiation (Ascard 1998), steaming and hot water (Anonymous 1999; Barberi et al. 2009; Trotter 1991), direct heat (Ascard et al. 2007; Hopkins 1936), electrocution (Vigneault et al. 1990), microwave radiation (Ascard et al. 2007), 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 nonchemical means of reducing weed seed populations (Egley 1983; Horowitz et al. 1983; Katan et al. 1976; Peachey et al. 2001; Rubin and Benjamin 1983; Standifer et al. 1984). Long sun-exposure periods and increased ambient temperatures are required for a sufficient time for effective solarization (Standifer et al. 1984). Solarization has been used in horticulture crops, including lettuce (*Lactuca sativa* L.) and

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garlic (*Allium sativum* L.) (Al-Masson et al. 1993), squash (*Cucurbita maxima* Duchesne), and tomato (*Solanum lycopersicum* L.) (Abu-Irmaileh 1991) These high-value vegetable crops can warrant the increased application cost of solarization (Bell et al. 1988). Solarization has successfully controlled annual bluegrass (*Poa annua* L.) (Bell and Laemmlen 1991; Elmore 1991; Peachey et al. 2001; Standifer et al. 1984), although not all weed species are susceptible (Egley 1990). Many weed species have buried reproductive organs, which make solarization an impractical weed control method (Bell et al. 1988; Horowitz et al. 1983; Rubin and Benjamin 1984).

Most recently used in thermal weed control, flame weeding uses an intense wave of heat to rupture plant cells (Bond et al. 2007; Hatcher and Melander 2003). Flame weeding typically uses liquefied petroleum gas or propane as the fuel source to create the intense flame (Ascard 1995). Flame-weeding systems have been developed from handheld 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 varied among weed species and seedling size (Cisneros and Zandstra 2008).

Most of the 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 apply flames to the soil surface instead of to the emerged weeds. Direct heat increases soil temperatures to the weed seed thermal death point, 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.

We are currently exploring thermal weed control methods using an enclosed heating apparatus (Figure 1). This application method uses intense thermal heat from six 3.3 by 10^5 W h (watt hours) torches, individually reaching approximately 1,121 C flame temperature. This method applies a high intensity of heat for a short time duration (approximately 5 s) depending on application speed. The manufacture recommends operating at a speed of 0.8 kph and fuel pressure 345 kPa. The shielded design can keep combustion gases close to the ground (Bond et al. 2007). The containment of the combustion heat in the enclosed system decreases energy consumption and can allow for faster application speeds (Bertram and Meyer 1996). The enclosed heating apparatus (PL8750 flame sanitizer) can be used for flame weeding, direct heat, or combinations of the two.

All thermal weed-control methods denature proteins by heat (Parish 1990). Plant cell function is then lost, leading to intracellular water expansion (Lague et al. 2001) and ruptured membranes (Morelle 1993; Pelletier et al. 1995), ultimately, resulting in death to emerged plants or seeds (Heiniger 1999; Rahkonen and Jokela 2003; Rifai et al. 1996). Therefore, selectivity between crop and weed species can only be achieved through thermal heat placement.

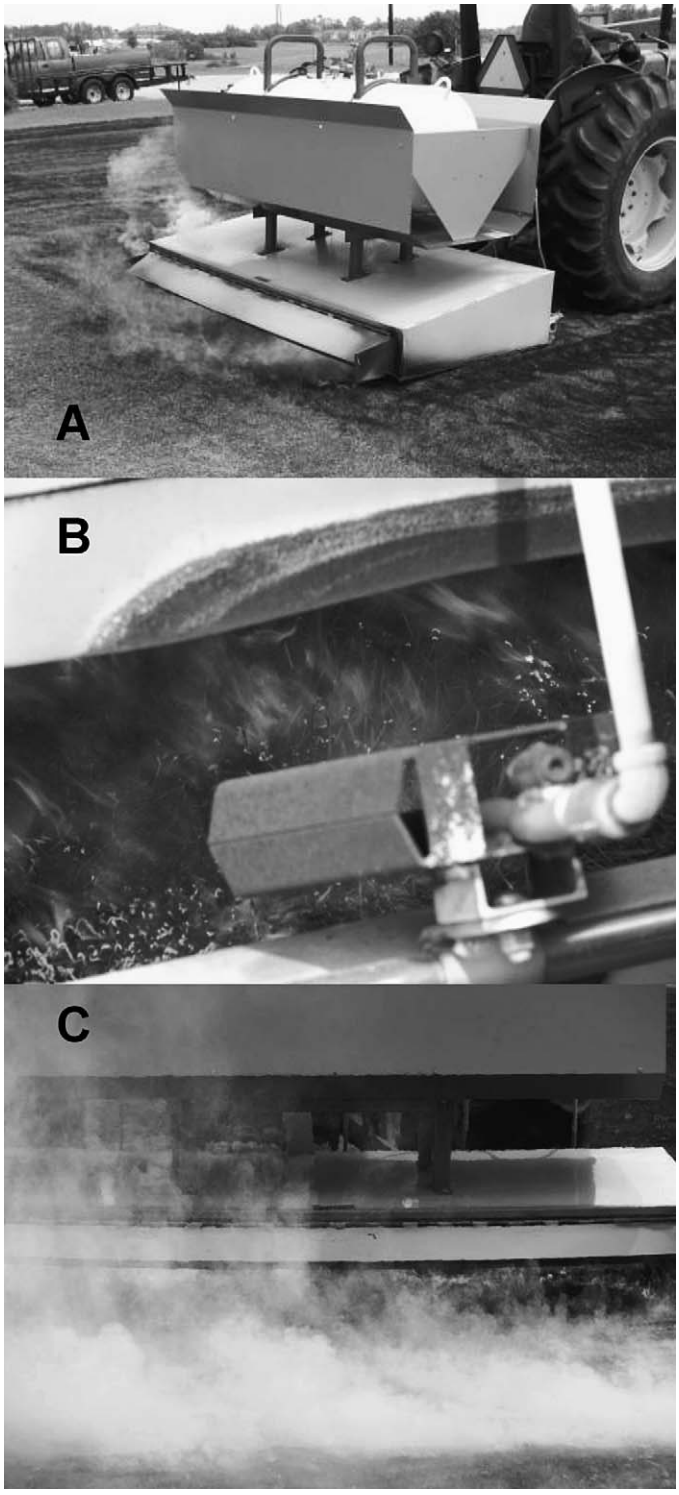


Figure 1. (A and C) PL-8750 flame sanitizer demonstrating thermal weed control. (B) 1.15 Btu h^{-1} burner.

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

Studies were designed to test the efficacy of various thermal weed control methods with an enclosed thermal treatment unit before 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. Evaluated thermal weed control methods included previously studied applications along with new adaptations. Results can provide insight on thermal weed-control applications, along with the basis for development of new, nonchemical weed-control methods for turfgrass systems.

Materials and Methods

Field experiments were conducted at the Auburn University Turfgrass Research Unit 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 before turfgrass establishment. Field experiments were initiated in summer and fall of 2009 and 2010. Dates of trial initiation are referenced in individual timing sections.

Summer Timing. Seeded turfgrass species for summer timing research trials were 'Zenith' zoysiagrass (*Zoysia japonica* Steud.), 'TifBlair' centipedegrass [*Eremochloa ophiuroides* (Munro) Hack] and 'Sea Spray' seashore paspalum (*Paspalum vaginatum* Sw.). Zoysiagrass, centipedegrass, and paspalum were seeded at 0.15, 0.3, and 0.3 kg of pure live seed (PLS) per 100 m^2, respectively. All trials were established on a Marvyn loamy sand (fine-loamy, kaolinitic, thermic Typic Kanhapludults) with a pH of 5.5 and 2.7% organic matter (OM). Soil was tilled before treatment application. Treatments were control (CON); soil-solarization (SOL); dazomet (Basamid G soil sterilant, 389 kg ha^{-1}, Certis USA LLC, Columbia, MD 21046)(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. The CON was tilled 1 d before turfgrass establishment. SOL used 6-mil, transparent, polyethylene plastic (Husky Polyethylene Plastic, Poly-America, Grand Prairie, TX 75051), covering the soil surface for 42 d before 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 before seeding in accordance to label recommendation. The DSF treatment used a PL-8750 flame sanitizer (PL8750 Poultry House Flame Sanitizer, Flame Engineering Inc., La Crosse, 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 before 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 increase 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 Btu h^{-1} burners were mounted at the front of the shielded thermal unit, directing a 1,121 C flame (46 cm by 1 m) at a 45° angle onto soil surface. The flame sanitizer used liquefied propane and was operated according to manufacturer's recommendations: 0.8 km h^{-1} (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 before turfgrass establishment applications were initiated in 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 'Rebel IV' tall fescue. Seeding rate was 1.5 kg of PLS 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. The 2×EWF and 2×CEWF treatments were excluded to ensure recommended time of Rebel IV seeding. Soil solarization was employed for fall timing application 21 d before turfgrass establishment. Treatments requiring 21 d before turfgrass establishment applications were initiated August 31, 2009, and September 2, 2010. Turfgrass seeding was conducted October 1, 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.

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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 and install solarization plastic				Till soil		Till soil and install germination cloth	
21		Dazomet application[c]		Till soil	Flame application	Till soil and install germination cloth	Flame application and reinstall germination cloth	
1	Remove solarization plastic		Till soil and flame application	Flame application	Flame application	Flame application	Flame application	Till soil
0	Turfgrass establishment	Turfgrass establishment	Turfgrass establishment	Turfgrass establishment	Turfgrass establishment	Turfgrass establishment	Turfgrass establishment	Turfgrass establishment

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

[b] Days before establishing turfgrass species.

[c] Dazomet (389 kg ha^{-1}).

Data Collection and Analysis. Turfgrass cover was evaluated visually at 6 wk after seeding (WAS) using a scale of 0 to 100, where 0 is no turfgrass cover, and 100 is complete turfgrass cover. Three randomized 1-m^2 subplots were used 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. Percentage of control for each treatment was calculated relative to control treatment within each replication and experimental run using Equation 1:

$$\%C = [(N - T)/N] \quad [1]$$

where C is control, N is the number of individual weed species per square meter in the control treatment, and T is number of individual weed species per square meter in the treated plot. Percentage of control used a scale of 0 to 100, where 0 is no weed control, and 100 is complete weed control. Because of the increased number of cocks-comb kyllinga and yellow nutsedge plants, line intersect analysis (36 intersections, 1-m^2 grid) was used within same subplots to obtain percentage of cover weed species. Equation 1 was used to obtain the percentage of control of cocks-comb kyllinga and yellow nutsedge with percentage of cover data. Because of the lack of uniformity of other weed species, carpetweed and old world diamond-flower 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 DAZ vs. all thermal treatments (SOL, DSF, EWF, CEWF, 2×EWF, 2×CEWF); SOL vs. all other thermal treatments (DSF, EWF, CEWF, 2×EWF, 2×CEWF); SOL vs. DSF; SOL vs. all emerged, weed-flaming treatments (EWF, CEWF, 2×EWF, 2×CEWF); 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 for summer-timing trials, excluding the 2×EWF and 2×CEWF treatments because those treatments were not applied.

Results and Discussion

Summer Timing. Data allowed for pooling of weed control over experimental runs and seeded turfgrass species. Control of weed species by thermal weed-control methods is presented in Table 3. Thermal weed-control methods and dazomet resulted in various percentages of control relative to the control treatment. At 6 WAS, greatest carpetweed control was achieved by solarization (92%). Previous research also

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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 and install solarization plastic	Dazomet application[c]		Till soil	Till soil and install germination cloth	
1	Remove solarization plastic		Till soil and flame application	Flame application	Remove germination cloth and flame application	Till soil
0	Turfgrass establishment	Turfgrass establishment	Turfgrass establishment	Turfgrass establishment	Turfgrass establishment	Turfgrass establishment

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

[b] Days before establishing turfgrass species.

[c] Dazomet (389 kg ha^{-1}).

reported excellent (100%) broadleaf weed control, including *Mollugo* spp., by solarization (McSorley et al. 2009). The 2×CEWF treatment controlled carpetweed 90%. All other weed-control methods resulted in < 80% carpetweed control. Dazomet controlled carpetweed the least (52%) at 6 WAS (9 wk 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.

The covered, emerged, weed-flaming treatments also effectively controlled another small-seeded, summer, annual. broadleaf weed—spotted surge (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 for spotted spurge control (38% control).

Two Rubiaceae species, Virginia buttonweed and old world diamond flower, were common in the research areas. Solarization and dazomet controlled Virginia buttonweed 95 and 94%, respectively (Table 3). Virginia buttonweed control was < 75% by all other thermal weed-control methods. Old world diamond-flower control (93%) was greatest by 2×CEWF. Solarization provided 57% old world diamond-flower control.

Solarization was an effective treatment on evaluated grass weed species (Table 3). Solarization controlled large crabgrass and goosegrass, 95 and 89%, respectively. Our findings are in contrast to Rosskopf et al. (2010) who reported that solarization treatment increased goosegrass populations. Although previous results demonstrate that emerged flaming, with an unshielded, thermal-treatment apparatus, is less effective on grassy weeds than it is on broadleaf weeds (Ascard 1994), we found excellent control of large crabgrass and goosegrass by emerged, weed-flaming treatments, with an enclosed thermal-treatment unit. Large crabgrass control was 94 and 95% with double, emerged, weed-flaming and covered, emerged, weed-flaming treatments, respectively. 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 cocks-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 (Egley 1983; Stapleton and DeVay 1986). Cocks-comb kyllinga and yellow nutsedge control by solarization was greatest, 72 and 67%, respectively, even though reports show that yellow nutsedge or purple nutsedge (*Cyperus rotundus* L.) cannot be controlled by solarization (Elmore 1983). Tolerance of yellow and purple nutsedge to thermal heat treatments is likely due to underground reproductive tubers. Dazomet controlled yellow nutsedge 61%, similar to what Unruh et al. (2002) found,

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

Treatment	Weed control[b]							
	MOLVE	DIQVI	EPHMA	DIGSA	ELEIN	OLDCO	KYSQ	CYPES
	%							
1. Dazomet[c]	52 bc	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: MOLVE, carpetweed; DIQVI, Virginia buttonweed; EPHMA, spotted spurge; DIGSA, large crabgrass; ELEIN, goosegrass; OLDCO, old world diamond-flower; KYSQ, cocks-comb kyllinga; CYPES, yellow nutsedge; 2 ×, conducted twice.

[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 (389 kg ha^{-1}).

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

Treatment[c]	Weed control							
	MOLVE	DIQVI	EPHMA	DIGSA	ELEIN	OLDCO	KYSQ	CYPES
Contrast	%							
Dazomet[d] (1) vs. thermal (2, 3, 4, 5, 6, 7)	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. emerged 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. emerged 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 $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively.

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

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

[d] Dazomet (389 kg ha^{-1}).

reporting 57 % sedge (*Cyperus* spp.) control. Yellow nutsedge and cocks-comb kyllinga control was minimal 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 ($P = 0.033$), spotted spurge ($P = 0.001$), and goosegrass ($P = 0.040$). All other weed species were similar in weed control at $P = 0.05$ significance level, concluding that thermal-treatment methods controlled the evaluated weed species just as well or better than dazomet.

Solarization controlled (70% or greater) all the evaluated weed species, except cocks-comb kyllinga and yellow nutsedge. Contrasts confirm effective weed control by solarization when compared with flame treatments (DSF, EWF, CEWF, 2×EWF, 2×CEWF), DSF, or emerged, weed-flaming treatments (EWF, CEWF, 2×EWF, 2×CEWF) for all evaluated weed species, except old world diamond-flower. Old world diamond-flower control by solarization was approximately 20% less than it was by flame treatments, DSF, and emerged, flaming treatments.

Within all the flame treatments, emerged, weed-flaming treatments controlled all evaluated weed species greater than approximately 70%, except cocks-comb kyllinga and yellow nutsedge (Table 4). Emerged, weed-flaming treatments controlled carpetweed, spotted spurge, large crabgrass, and cocks-comb kyllinga better 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 treatments.

Emerged, covered, flaming treatments (CEWF, 2×CEWF) vs. emerged, uncovered, flaming treatments (EWF, 2×EWF) resulted in increased spotted spurge control (91 compared with 69%). No other differences were observed for other evaluated weed species in pairwise contrasts between coverings. Single, emerged, flaming (EWF, CEWF) vs. double, emerged, flaming treatments (2×EWF, 2×CEWF) also resulted in 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 before tall fescue establishment than at summer timings (Table 5). Direct soil flaming and covered weed flaming were top-performing weed control treatments before tall fescue establishment. All fall-timing treatments controlled carpetweed and old world diamond-flower > 86% (Table 5). Covered, emerged, weed flaming controlled carpetweed and old world diamond-flower 100% 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, emerged flaming (EWF, CEWF); DSF vs. pooled, emerged flaming; and EWF vs. CEWF pairwise comparisons. Pooled thermal treatments (SOL, DSF, EWF, CEWF) outperformed dazomet. Pooled thermal treatments controlled carpetweed and old world diamond-flower 99 and 98%, respectively, which was 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, dazomet.

Fall-timing, thermal weed-control applications were observed to have increased control of evaluated weeds compared with summer timing. Increased control is likely due to many summer, annual weeds completing their life cycle as well as their inability to establish at the fall timing. Furthermore, a shift of the competitive advantage from the weed species to turfgrass species could also have occurred. Cool-season turfgrasses are known to establish quicker than do warm-season turfgrass species (Turgeon 2002). Therefore, during

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

Treatment	Control[b] MOLVE	OLDCO
	%	
1. Dazomet[c]	94 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[d]	% control	
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: MOLVE, carpetweed; OLDCO, old world diamond-flower.

[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 (389 kg ha^{-1}).

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

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

establishment, tall fescue could have possibly outcompeted initial weed infestations. These findings propose that the 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: < 18% turfgrass cover for all species (data not shown). During turfgrass seeding, soil disturbance was minimal because soil agitation increases the total number of weed seedlings emerged (Froud-Williams et al. 1984). Therefore, the most likely cause of the lack of establishment was not having sufficient seed-to-soil contact. Successful seeded turfgrass establishment requires firm contact between seeds and soil particles (Turgeon 2002).

For fall-timing trials, tall fescue resulted in > 60% turfgrass cover for all treatments, including the control treatment (Table 6). Dazomet resulted in the highest tall fescue cover (86%). Direct soil-flaming treatment resulted in 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 also confirmed by contrast, comparing turfgrass cover of dazomet vs. all other thermal weed control methods (SOL, DSF, EWF, CEWF)($P = 0.045$). Contrasts also resulted in a difference between solarization and direct soil flaming ($P = 0.046$). Solarization and direct soil flaming obtaining 70 and 81% turfgrass cover, respectively, at 6 WAS. No other contrasts were significant. In conclusion, dazomet and all other thermal weed-control methods did not inhibit tall fescue establishment and resulted in successful turfgrass establishment.

Potential Future Use. From current and past research, thermal treatment appears to be a viable method for weed control before turfgrass establishment. Desjardins et al. (1997) tested an open-flame, thermal-treatment apparatus on annual bluegrass control in bentgrass (*Agrostis stolonifera* L.) fairways. Adequate annual bluegrass control was achieved but unacceptable turf quality resulted due to turfgrass dehydration and chlorosis (Desjardins et al. 1997). One month after treatment, the bentgrass fairway completely recovered (Desjardins et al. 1997).

Our research demonstrates that an enclosed thermal-treatment unit used before turfgrass establishment can effectively control weeds without restricting tall fescue establishment. Therefore, use of a covered thermal treatment unit may be an effective option for weed control before

Table 6. Effects of thermal weed control methods on turfgrass cover (%) 6 wk after seeding (WAS) pooled over fall timing trials in 2009 and 2010.

Treatment	Fescue cover[a,b,c]
	%
1. Dazomet[d]	86 a
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	
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. emerged flaming (4, 5)	70 vs. 78
Direct soil flaming (3) vs. emerged flaming (4, 5)	81 vs. 78
Emerged, uncovered flaming (4) vs. emerged, covered flaming (5)	79 vs. 76

[a] 'Rebel IV' tall fescue.

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

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

[d] Dazomet (389 kg ha^{-1}).

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turfgrass establishment. Future research on application timing of a contained thermal treatment unit can better refine application and increase efficacy.

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Literature Cited

Abu-Irmaileh, B. E. 1991. Weed control in squash and tomato fields by soil solarization in the Jordan Valley. Weed Res. 31:125–133.

Al-Masson, A. A., A.-R. Saghir, and S. Itani. 1993. Soil solarization for weed management. Weed Technol. 7:507–510.

Andreasen, C., L. Hansen, and J. C. Streibig. 1999. The effect of ultraviolet radiation on the fresh weight of some weeds and crops. Weed Technol. 13:554–560.

Anonymous. 1999. Something for strawberry growers to get steamed up about. Fruit Grower. April:11–12.

Ascard, J. 1994. Dose–response models for flame weeding in relation to plant size and density. Weed Res. 34:377–385.

Ascard, J. 1995. Effects of flame weeding on weed species at different development stages. Weed Res. 34:397–385.

Ascard, J. 1997. Flame weeding: effects of fuel pressure and tandem burners. Weed Res. 37:77–86.

Ascard, J. 1998. Comparison of flaming and infrared radiation techniques for thermal weed control. Weed Res. 38:69–76.

Ascard, J., P. E. Hatcher, B. Melander, and M. K. Upadhyaya. 2007. 10 Thermal Weed Control. Pages 155–175 *in* Upadhyaya M.K. R. E. Blackshaw, eds. Non-Chemical Weed Management: Principles, Concepts and Technology. Wallingford, UK: CAB International.

Barberi, P., A. C. Moonen, A. Peruzzi, M. Fontanelli, and M. Raffaelli. 2009. Weed suppression by soil steaming in combination with activating compounds. Weed Res. 49:55–66.

Bell, C. E., C. L. Elmore, and A. Durazo, III. 1988. Soil solarization for weed management in vegetable. Pages 475–479 *in* P. Allen and D. Van Dusen, eds. Proceedings of the 6th International Conference of the International Federation of Organic Agriculture Movements. Bonn, Germany: IFOAM.

Bell, C. E. and F. F. Laemmlen. 1991. Weed control by solarization. Chapter 18. *in* J. Kattan and J. E. DeVay, eds. Soil Solarization. Boca Raton: CRC Press.

Benvenuti, S., M. Macchia, and S. Miele. 2001. Quantitative analysis of emergence of seedlings from buried weed seeds with increasing planting depth. Weed Sci. 49:528–535.

Bertram, A. and J. Meyer. 1996. Optimization of thermal weed control. *Z. Pflanzenkr. Pflanzenschutz* 15:407–416. [In German]

Bond, W., G. Davies, and R. J. Turner. 2007. A review of thermal weed control. Technical Report. HDRA. Coventry, UK: Ryton Organic Gardens.

Bond, W. and A. C. Grundy. 2001. Non-chemical weed management in organic farming systems. Weed Res. 41:383–405.

Bowers, S. A. and R. J. Hanks. 1962. Specific heat capacity of soils and minerals as determined with a radiation calorimeter. Soil Sci. 94:392–396.

Cisneros, J. J. and B. H. Zandstra. 2008. Flame weeding effects on several weed species. Weed Technol. 22:290–295.

Couch, R. and E. O. Gangstad. 1974. Response of water hyacinth to laser radiation. Weed Sci. 22:450–453.

Dahlquist, R. M., T. S. Prather, and J. J. Stapleton. 2007. Time and temperature requirements for weed seed thermal death. Weed Sci. 55:619–625.

Desjardins, Y., M. Tardif, J. Gill, and C. Lagüe. 1997. *Poa annua* war calls for scorched-earth policy. Golf Course Manag. 65:49–54.

Diprose, M. F., F. A. Benson, and A. J. Willis. 1984. The effect of externally applied electrostatic fields, microwave radiation and electric currents on plants and other organisms with special reference to weed control. Bot. Rev. 50:171–223.

Egley, G. H. 1983. Weed seed and seedling reduction by soil solarization with transparent polyethylene sheets. Weed Sci. 31:404–409.

Egley, G. H. 1990. High-temperature effects on germination and survival of weed seeds in soil. Weed Sci. 38:429–435.

Elmore, C. L. 1983. Solarization for weed control in vegetable crops. Abstr. Weed Sci. Soc. Am. 23:32.

Elmore, C. L. 1991. Weed control by solarization. Chapter 5 *in* J. Katan and J. E. DeVay, eds. Soil Solarization. Boca Raton, FL: CRC Press.

Froud-Williams, R. J., R. J. Chancellor, and D. S. H. Drennan. 1984. The effects of seed burial and soil disturbance on emergence and survival of arable weeds in relation to minimal cultivation. J. Appl. Ecol. 21:629–641.

Hatcher, P. E. and B. Melander. 2003. Combining physical, cultural and biological methods: prospects for integrated non-chemical weed management strategies. Weed Res. 43:303–322.

Heiniger, R. W. 1999. Controlling weeds in organic crops with flame weeders. Santa Cruz, CA: Organic Farming Research Foundation, Information Bulletin 6. pp. 17–19.

Heisel, T., J. Schou, C. Andreasen, and S. Christensen. 2002. Using laser to measure stem thickness and cut weed stems. Weed Res. 42:242–248.

Hopkins, C. Y. 1936. Thermal death point of certain weed seeds. Can J. Res. 14:178–183.

Horowitz, M. 1980. Weed research in Israel. Weed Sci. 28:457–460.

Horowitz, M., Y. Regev, and G. Herzlinger. 1983. Solarization for weed control. Weed Sci. 31:170–179.

Katan, J., A. Greenberger, H. Alon, and A. Grinstein. 1976. Solar heating by polyethylene mulching for the control of diseases caused by soil-borne pathogens. Phytopathology 76:683–688.

Lague, C., J. Gill, and G. Peloquin. 2001. Thermal control in plant protection. Pages 35–46 *in* C. Vincet, B. Panneton, and F. Fleurant-Lessard, eds. Physical Control Methods in Plant Protection. Berlin, Germany: Springer-Verlag.

Lang, C. 1878. Über Wärmekapazität der Bodenkonstituieren. Fortschr. Geb. Agric. Phys. 1:109–147.

Mathiassen, S. K., T. Bak, S. Christensen, and P. Kudsk. 2006. The effect of laser treatment as a weed control method. Biosys. Eng. 95:497–505.

McSorley, R., K. –H. E. Wang, N. Rosskopf, N. H. N. Kokalis-Burelle, Hans Petersen, H. K. Grill, and R. Krueger. 2009. Nonfumigant alternatives to methyl bromide for management of nematodes, soil-borne disease, and weeds in production of snapdragon (*Antirrhinum majus*). Int. J. Pest. Manag. 55:265–273.

Melander, B. and G. Rasmussen. 2001. Effects of cultural methods and physical weed control on intrarow weed numbers, manual weeding and marketable yield in direct-sown leek and bulb onion. Weed Res. 41:491–508.

Morelle, B. 1993. Thermal weed control and its applications in agriculture and horticulture. Pages 111–116 *in* Communications of the 4th International Conference International Federation of Organic Agriculture Movements—Nonchemical Weed Control; Dijon, France. Bonn, Germany: IFOAM.

Ochsner, T. E., R. Horton, and T. Ren. 2001. Simultaneous water content, air-filled porosity, and bulk density measurements with thermal-time domain reflectometry. Soil Sci. Am. J. 65:1618–1622.

Parish, S. 1990. A review of non-chemical weed control techniques. Biol. Agric. Hortic. 7:117–137.

Patten, H. E. 1909. Heat Transfer in Soils. Washington, DC. U.S. Department of Agriculture. Bureau of Soils Bulletin 59.

Peachey, R. E., J. N. Pinkerton, K. L. Ivors, M. L. Miller, and L. W. Moore. 2001. Effect of soil solarization, cover crops, and metham on field emergence and survival of buried annual bluegrass (*Poa annua*) seeds. Weed Technol. 15:81–88.

Pelletier, Y., C. D. McLeod, and G. Bernard. 1995. Description of sub-lethal injuries caused to Colorado potato beetle by propane flamer treatment. J. Econ. Entomol. 88:1203–1205.

Rahkonen, J. and H. Jokela. 2003. Infrared radiometry for measuring plant leaf temperature during thermal weed control treatment. Biosys. Eng. 86:257–266.

Rifai, M. N., M. Lacko-Bartosova, and V. Puskarova. 1996. Weed control for organic vegetable farming. Rostl. Vyroba 42:463–466.

Rosskopf, E. N., N. Kokalis-Burelle, D. Butler, and S. Fennimore. 2010. Evaluation of stem for nematode and weed control in cut flower production in Florida. Pages 83-1–83-3 in Proceedings of the Annual International Research Conference on Methyl bromide Alternatives and Emissions Reductions; Orlando, FL. Fresno, CA: Methyl Bromide Alternatives Outreach.

Rubin, B. and A. Benjamin. 1983. Solar-heating the soil: effect on weed control and on soil incorporated herbicides. Weed Sci. 31:819–825.

https://doi.org/10.1614/WT-D-12-00057.1 Published online by Cambridge University Press

Rubin, B. and A. Benjamin. 1984. Solar heating of the soil: involvement of environmental factors in the weed control process. Weed Sci. 32:138–142.
Sivesind, E. C., M. L. Leblac, D. C. Cloutier, P. Seguin, and K. A. Stewart. 2009. Weed response to flame weeding at different development stages. Weed Technol. 23:438–443.
Smith, W. O. 1942. The thermal conductivity of dry soil. Soil Sci. 53:435–450.
Standifer, L. C., P. W. Wilson, and R. Poorche-Sorbet. 1984. Effects of solarization on soil weed seed populations. Weed Sci. 32:569–573.
Stapleton, J. J. and J. E. DeVay. 1986. Soil solarization: a non-chemical approach for management of plant pathogens and pests. Crop Prot. 5:190–198.
Suss, A. and G. Bacthaler. 1968. Preliminary experiments on γ-irradiation of weed seeds. Pages 20–24 *in* Proceedings of the 9th British Weed Control Conference; Brighton, UK. Alton, UK: British Crop Production Council.
Trotter, K. 1991. Sidlesham steamers. Grower Nexus Hortic. 116:24–25.
Turgeon, A. J. 2002. Turfgrass Management. 6th ed. Englewood Cliffs, NJ: Prentice Hall. Pp. 100–101.
Ulrich, R. 1894. Untersuchungen Fiber die Wärmekapazität der Bodenkonstituieren. Fortschr. Geb. Agric. Phys. 17:1–31.
Unruh, J. B., B. J. Brecke, J. A. Dusky, and J. S. Godbehere. 2002. Fumigant alternatives for methyl bromide prior to turfgrass establishment. Weed Technol. 16:379–387.
Van Duin, R.H.A. 1963. The Influence of Soil Management on the Temperature Wave Near the Surface. Wageningen, The Netherlands: Institute for Land and Water Management Research Technical Bulletin 29.
Van Rooyen, M. and H. F. Winkerton. 1959. Structural and textural influences on thermal conductivity of soils. Highway Res. Bd. Proc. 38:576–621.
Vigneault, C. and Benoit. D. L. and N. B. McLaughlin. 1990. Energy aspects of weed electrocution. Reviews of Weed Sci. 5:15–26.

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