Responses of Ten Weed Species to Microwave Radiation Exposure as Affected by Plant Size[1]

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Abstract

There is interest in alternative weed control methods to herbicide use, especially among those interested in organic approaches. The use of microwave radiation as a weed control method appears to be a good alternative because it does not produce chemical residues in the environment. A study was conducted to determine the impact of plant age on weed control using microwave radiation. Ten weed species, representing monocots and dicots, were selected for this study: southern crabgrass (*Digitaria ciliaris* (Retz.) Koeler), dallisgrass (*Paspalum dilatatum* Poir.), false green kyllinga (*Kyllinga gracillima* Miquel), fragrant flatsedge (*Cyperus odoratus* L.), yellow nutsedge (*Cyperus esculentus* L.) common ragweed (*Ambrosia artemisiifolia* L.), white clover (*Trifolium repens* L.), pitted morningglory (*Ipomoea lacunosa* L.), henbit (*Lamium amplexicaule* L.) and field bindweed (*Convolvulus arvensis* L.). In general, weed species become more tolerant of microwave treatments as they increased in size, as 8 to 10 week-old plants were injured less than 4 to 6 week-old plants. Most grass species regrew when treated at 90 and 180 joules·cm^{-2} of microwave radiation. Pitted morningglory and common ragweed showed the highest susceptibility to microwave radiation among all treated weed species. The increase in a weed's biomass over time probably increases the amount of microwave radiation necessary for heating samples to the thermal threshold required for control.

Index words: Nonchemical control, microwave, weed age, weed maturity, thermal weed control.

Species used in this study: southern crabgrass (*Digitaria ciliaris* (Retz.) Koeler); dallisgrass (*Paspalum dilatatum* Poir.); false green kyllinga (*Kyllinga gracillima* Miquel); fragrant flatsedge (*Cyperus odoratus* L.); yellow nutsedge (*Cyperus esculentus* L.); common ragweed (*Ambrosia artemisiifolia* L.); white clover (*Trifolium repens* L.); pitted morningglory (*Ipomoea lacunosa* L.); henbit (*Lamium amplexicaule* L.); field bindweed (*Convolvulus arvensis* L.).

Significance to the Horticulture Industry

Microwave radiations are a potential means of non-chemical weed control as a substitute for herbicides. Information is needed on the optimum plant size for effective control. More energy was needed to control older, larger plants in comparison to younger plants. Therefore, plant size will play a significant role when microwave radiation is used for weed control. Treatment of weeds less than 15 cm (6 in) tall using microwave radiation should be a more economical and viable option for farmers than treating taller weeds.

Introduction

The main objective of weed control in cropping systems is to prevent competition with the crop being produced (Brown et al. 1957, Davis et al. 1971, Menges and Wayland 1974). Controlling undesirable weed populations lowers the risk of crop production losses in terms of both quantity and quality. Chemical control has been the primary method to control weeds in the last 50 years due to its high efficiency (Nelson 1996). Herbicides have the biggest share (68%) in the pesticide market followed by fungicides (9%) and insecticides (3.2%) [NASS 2006]. Approximately 113.4 million kilograms (250 million lb) of herbicides are sold yearly in the United States. The use of pesticides has raised questions on potential adverse impacts to the environment. Chemical control practices can cause environmental concerns related to human health and to sustainability, especially in undeveloped and developing countries where the regulatory system is impaired. For example, paraquat, a quaternary ammonium herbicide, produces degenerative lesions in the lung after systemic administration to animals (Bus and Gibson 1984). The potential for herbicide carryover injury to rotational or replant crops is another concern. These problems occur because some chemicals leave residues with long persistence (Morozov et al. 1999) that can injure subsequent crops.

Interest in nonchemical weed control has been increasing with the spread of herbicide-resistant biotypes (Heap 1997) and because of environmental concerns over herbicide use (Sartorato et al. 2006). There is a demand for alternatives to chemical control, especially among those interested in organic approaches. The search for alternatives to chemical weed control is an important challenge for research and has led to the development of diverse methods of elimination. The use of thermal methods appears to be a good alternative because they do not produce chemical residues in the environment (Nelson 1985, Olsen and Hammer 1982).

Weed control using microwave radiation is a thermal method. Thermal weed control methods generate heat to kill weed seed 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

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al. 1984), γ-irradiation (Suss and Bacthaler 1968), lasers (Couch and Gangstad 1974), and ultraviolet light (Andreasen et al. 1999). Thermal control methods can be divided into two groups according to their mode of action: (a) direct heating methods using flame, infrared, hot water, steaming, or hot air and (b) indirect heating methods which includes electrocution, microwaves, laser radiation and ultraviolet radiation. All thermal weed control methods denature proteins (Parish 1990) and cause intracellular water expansion (Lague et al. 2001), resulting in loss of cell function and rupturing of membranes (Morelle 1993, Pelletier et al. 1995) to ultimately render death to emerged weeds or weed seed (Heiniger 1999, Rahkonen and Jokela 2003, Rifai et al. 1996).

Microwaves radiations are electromagnetic waves with frequencies ranging from approximately 300 MHz to 300 GHz and corresponding wavelengths from 0.001 to 1 m (Decareau 1985). Microwave heating is based on the transformation of electromagnetic field energy into thermal energy by affecting polar molecules of a material. Microwave radiation is in the central portion of the non-ionizing region of the electromagnetic spectrum. The ability of microwave radiation to penetrate and couple with polar molecules such as water provides an excellent means of obtaining controlled and precise heating of undesired plants. Absorption of microwave radiation causes water molecules within the tissue to oscillate, thereby converting electromagnetic energy into heat. This technique is rapid, versatile and effective, as the electromagnetic waves heat the plant tissue and destroys cellular integrity. This dielectric heating has been exploited to kill weeds and weed seed (Barker and Craker 1991, Davis et al. 1971, Sartorato et al. 2006). The most important characteristic of microwave heating is that materials absorb microwave energy directly and internally and convert it into heat (Mullin 1995). Since this heating depends upon the dielectric properties of the plant tissues, there is a possibility of advantageous selective heating in mixtures of different plant species based on anatomy and age.

Few researchers have investigated the effects of microwave radiation on weed seed, plants and soil organisms. Heating from microwave radiation depends on the power density of the radiation. Factors such as size of seed and plants, shape, and moisture content are important, as are the properties of the soil (Kaleita et al. 2005). A few studies have considered the efficacy of microwave treatments (Ascard 1994, Kolberg and Wiles 2002), focusing on optimization of microwave radiation use (Ascard 1995, 1997, Hansson and Ascard 2002, Hansson and Mattsson 2002, 2003), or comparing different methods of microwave radiation applications (Ascard 1998). Several related studies indicate plant developmental stage at the time of treatment is an important factor for weed control (Ascard 1994, Ascard 1998, Casini et al. 1993, Daar 1994, Hansson and Ascard 2002, Parish 1989, Parish 1990).

Treatment at an early developmental stage should reduce input energy requirements and lower the operational cost. There is a continuous dry mass accumulation and reduction in water content as plants mature, so more microwave energy is needed to control weeds as they grow. However, leaf surface area also increases as plants grow, thus potentially increasing the interception of microwave radiation. An increase in surface area should improve irradiation interception and thus control but an increase in biomass should adversely affect weed control using microwave radiation. The objectives of this investigation were to determine the impact of plant size on weed control using microwave radiation and to compare the sensitivities of grasses, sedges, and broadleaf weeds. A prototype running belt system was developed to more accurately assess the required amount of microwave radiations required for control of individual weed species.

Materials and Methods

Studies were conducted in a greenhouse at the Hampton Road Agricultural Research and Extension Center in Virginia Beach, using a conveyer system for microwave application to weeds either 4 to 6 or 8 to10 weeks old. The same mobile microwave radiation applicator reported by Rana and Derr (2017) was used.

Ten weed species representing monocots and dicots selected for this study were southern crabgrass, dallisgrass, false green kyllinga, fragrant flatsedge, yellow nutsedge, common ragweed, white clover, pitted morningglory, henbit, and field bindweed. These weeds were selected based on their anatomical diversity. The angle of inclination of microwave radiation on the canopy would be different for upright versus prostrate weeds. The assumption was that older plants having a wider canopy would require more microwave energy for its control. All weeds were grown from seed, or in the case of yellow nutsedge from tubers, in flats containing a peat-based growing medium (Promix BX, Griffin Greenhouse Supplies, Inc., Tewksbury, MA 01876) in a greenhouse for 3 to 4 weeks. After 4 to 6 weeks, uniformly-sized weeds were transplanted to 10 by 10 cm pots (4 by 4 in) containing the same peat-based growing medium listed above. Grasses and sedges were 12 to 15 cm (4.7 to 5.9 in) tall at the time of treatment for the early growth stage. Common ragweed plants were 12 to 18 cm (4.9 to 7.0 in) tall. Pitted morningglory and field bindweed were in the first true leaf stage. White clover and henbit were 8 to 12 cm (3.1 to 4.9 in) tall. For the later growth stage, 8 to 12 week old plants were treated. Grasses and sedges were 20 to 25 cm (7.9 to 9.8 in) tall at the time of treatment for the later growth stage. Common ragweed plants were 25 to 28 cm (9.8 to 11.0 in) tall. Pitted morningglory and field bindweed were in the 5 to 8 leaf stage. White clover and henbit were 10 to 15 cm (4 to 6 in) tall. Plants were irrigated daily and fertilized with Osmocote (14-14-14, Everris, P.O Box 40 4190 CA, Geldermalsen, The Netherland), a polymer-coated fertilizer. A randomized complete block design with four replications for each treatment was used for each study. There were two microwave energy doses, 5 seconds irradiation delivering 90 joules$\cdot$cm^{-2} and 10 seconds irradiation delivering 180 joules$\cdot$cm^{-2}, plus a nontreated control. In general, a magnetron needs a critical temperature to produce microwave radiation optimally. Magnetrons were preheated for one minute before treatment

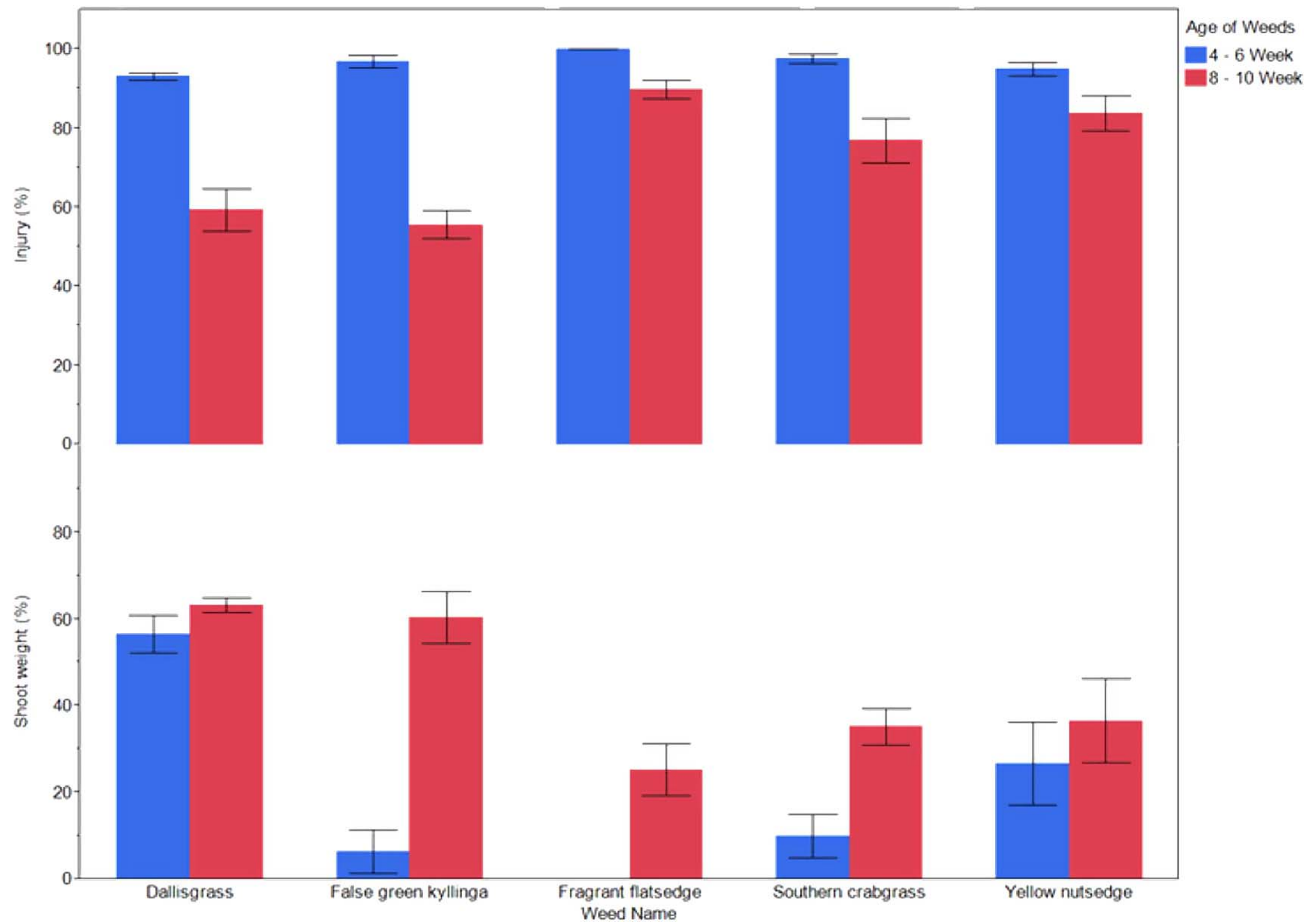

Fig. 1. Effect of 90 joules cm^{-2} microwave radiation on percent injury at 1 WAT and shoot weight at 4 WAT, expressed as percent of nontreated plants, to monocot weed species at two plant ages in a greenhouse trial. Error bars represents standard error.

started to ensure efficient operation. Greenhouse temperature was approximately 32 to 35 C (89.6 to 95 F) during each experiment. A microwave-radiation leakage detector (CEM, Model no. DT-2G, Matthews, NC) with a sensitivity range of 0 to 9.99 $mW{\cdot}cm^{-2}$ and warning value set at 5.0 mW cm^{-2} was used to find any microwave radiation leakage during operations as well as to determine a safe distance for human operators.

After microwave treatment, these weeds were transferred to greenhouse benches and irrigated daily. Injury was evaluated visually on a weekly basis for four weeks. Shoot fresh weight was recorded at 4 weeks after treatment (WAT). Since the species varied in their shoot weight, data was converted into percent of nontreated plants for that species. Collected data were analyzed and graphs were developed using statistical software (JMP 10, SAS, 100 SAS Campus Drive Building T Cary, NC). Student's t test was used for mean separation. Each study was repeated twice and there was no significant trial by treatment interaction. Therefore, presented results were averaged across both trials. There were three way interactions between microwave dose, weed species and plant age. Therefore, results are reported for this interaction.

Results and Discussion

Control of monocots at 90 joules${\cdot}cm^{-2}$. There was a significant effect of weed age on injury caused by microwave radiation at 90 joules${\cdot}cm^{-2}$ (Fig. 1). False-green kyllinga showed the highest decline in injury as plants grew larger, with 97% injury to 4 to 6 week-old weed plants compared to 56% for 8 to 10 week-old weed plants. A similar response to plant size was seen for dallisgrass (93% versus 59%) and southern crabgrass (97% to 77%) at 1 WAT for plants treated at the 4 to 6 and 8 to 10 week age groups, respectively. A lesser effect of plant size was observed in fragrant flatsedge (100% versus 90%) and yellow nutsedge (95% versus 84%), respectively, one week after application for plants treated at the 4 to 6 and 8 to 10 week age groups.

Similar results were seen in shoot fresh weight, where 93% reduction in weight was seen with 4 to 6 week-old plants compared to 40% reduction in 8 to 10 week-old false-green kyllinga plants (Fig. 1) . Four to six week old fragrant flatsedge plants did not show any regrowth but 8 to 10 week old plants did, although shoot weight was only 25% of the weight of nontreated plants. Greater reduction in shoot weight of southern crabgrass plants was observed for 4 to 6 week old plants compared to 8 to 10 week old

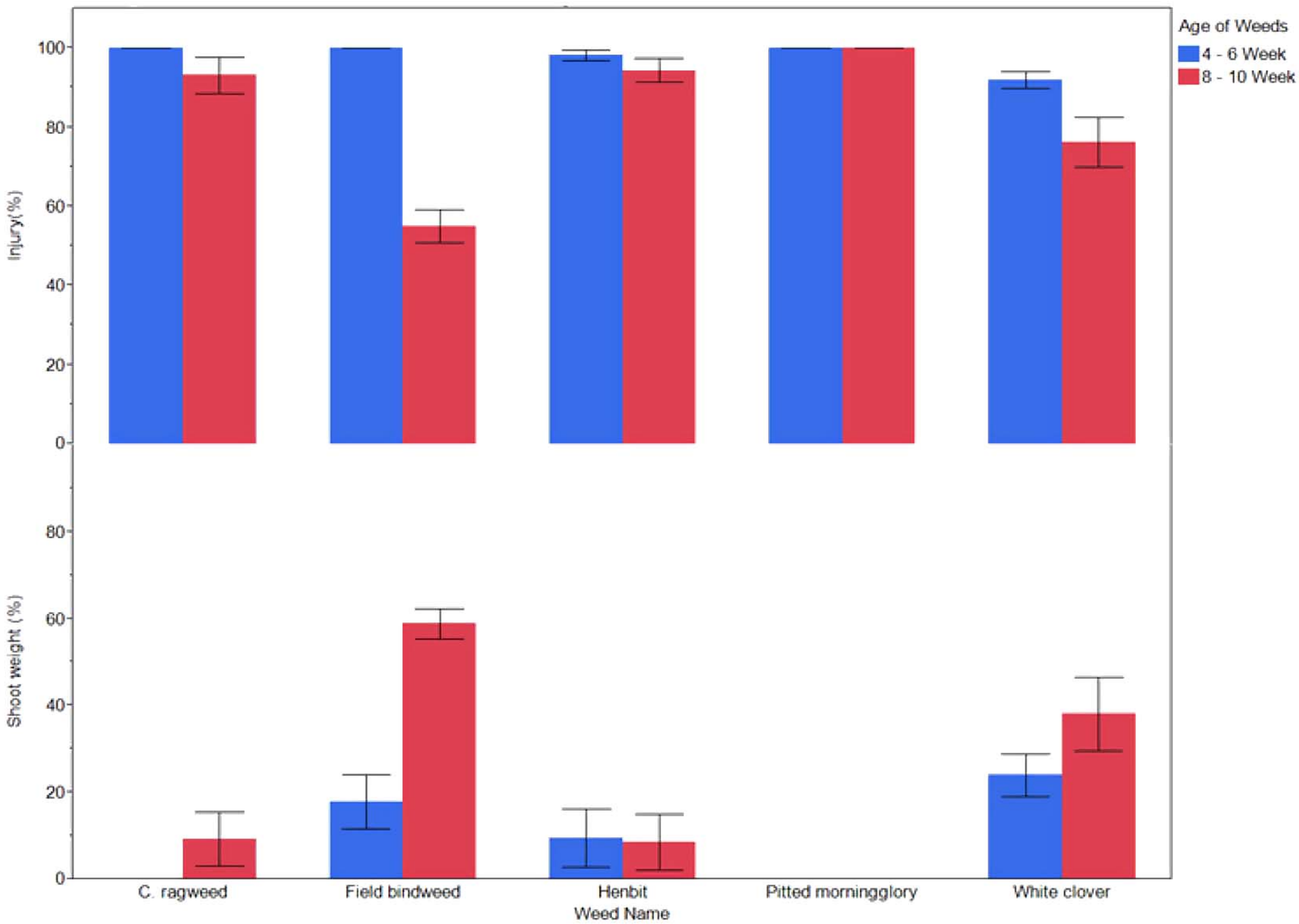

Fig. 2. Effect of 90 joules cm^{-2} microwave radiation on percent injury at 1 WAT and shoot weight at 4 WAT, expressed as percent of the weight of nontreated plants, to dicot weed species at two plant ages in a greenhouse trial. Error bars represents standard error.

ones. Shoot weight for 4 to 6 and 8 to 10 week old yellow nutsedge plants was 27% and 37% of nontreated plants, respectively. Of the species treated, dallisgrass had the lowest percent reduction in shoot weight after application of 90 joules·cm^{-2} regardless of plant age.

Control of dicots at 90 joules·cm^{-2}. Four to six week old pitted morningglory, common ragweed and field bindweed plants were injured 100% one week after the microwave treatment, with 98% injury seen in henbit and 92% injury to white clover (Fig. 2). Lower injuries were reported in 8 to 10 week old broadleaf weeds except for pitted morningglory, where no differences in injury were seen with respect to age. The decline in injury seen in 8 to 10 week old plants compared to 4-6 week old plants was lower in henbit and common ragweed, with a greater decline seen in field bindweed and white clover. Similar results were seen in shoot weight at 4 WAT. Four to six week old pitted morningglory and common ragweed did not show any regrowth. A low shoot fresh weight, ranging from 10 to 24% of nontreated plants, was seen in 4 to 6 week old common ragweed, white clover, field bindweed, and henbit. Highest shoot weight for 4 to 6 week old treated plants was observed in field bindweed (59% of nontreated plants) followed by white clover (38% of nontreated plants).

Control of monocots at 180 joules·cm^{-2}. A higher dose (180 joules cm^{-2}) of microwave radiation was sufficient for controlling both 4 to 6 week old and 8 to 10 week old monocots (Fig. 3). Four to six week old plants of false-green kyllinga, fragrant flatsedge, yellow nutsedge, dallisgrass, and southern crabgrass were injured 97 to 100% while 8 to 10 week old plants were injured 98% and 97% at 1 WAT. Injury did not decline below 94% for 8 to 10 week old treated plants regardless of weed species.

Control of dicots at 180 joules·cm^{-2}. All 4 to 6 week old broadleaf weeds treated with 180 joules cm^{-2} of microwave radiation showed at least 97% injury (Fig. 4). However, injury was approximately 85% for 8 to10 week old field bindweed and white clover plants treated with 180 joules cm^{-2} of microwave treatment. Common ragweed, henbit and pitted morningglory did not show any decline in control with respect to plants age at the higher dose. The 4 to 6 week old broadleaf plants showed little to no regrowth. However, significant regrowth was seen when 8 to 10 week old plants of field bindweed and white clover were treated.

Mature plants showed more tolerance to microwave treatment in comparison to young plants regardless of species. More biomass accumulates as plants grow. The root system of plants becomes more robust to protect plants from biotic and abiotic stresses. More energy is therefore

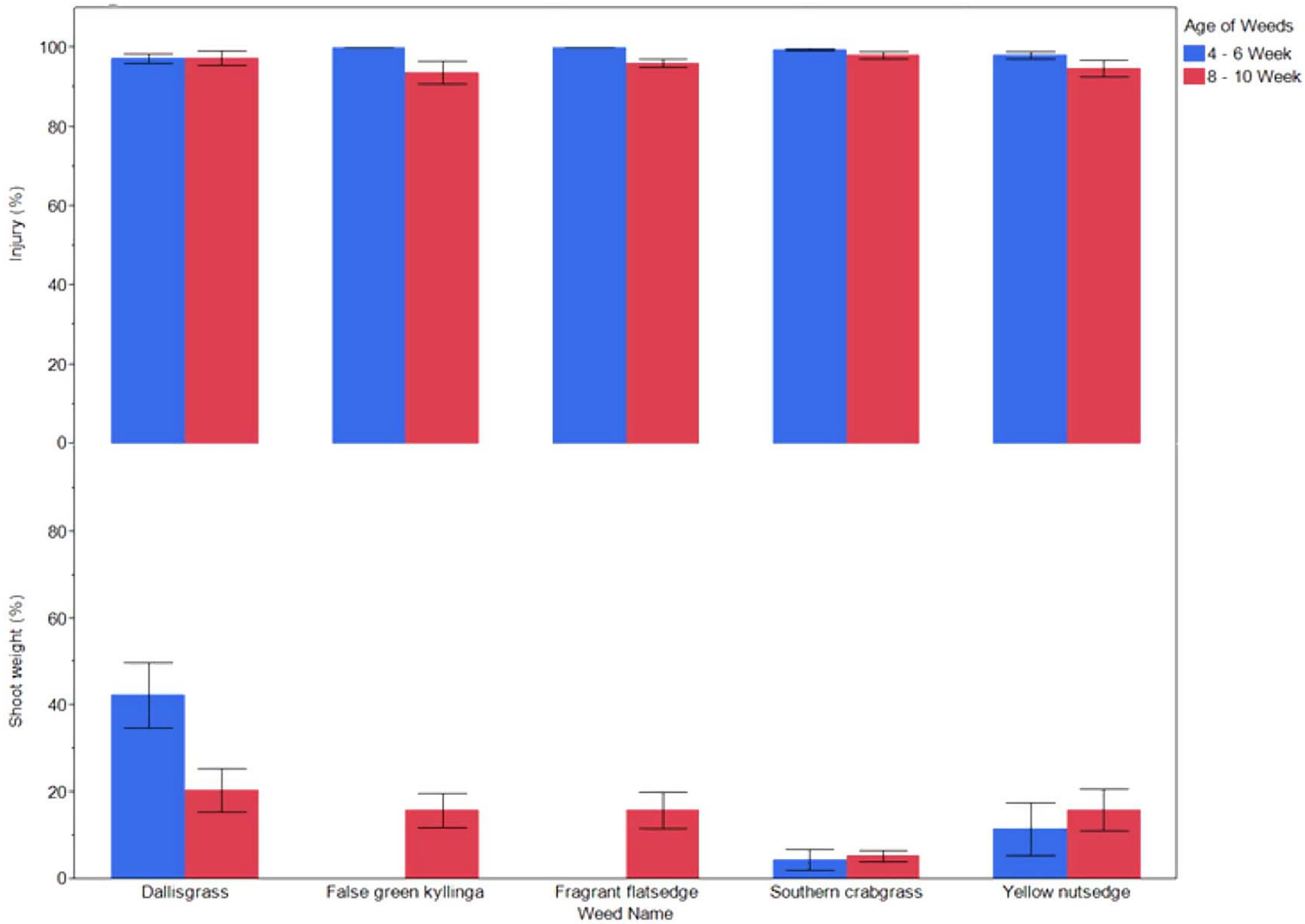

Fig. 3. Effect of 180 joules cm^{-2} microwave radiation on percent injury at 1 WAT and shoot weight at 4 WAT, expressed as percent of nontreated plants, to monocot weed species at two plant ages in a greenhouse trial. Error bars represents standard error.

needed to control older plants in comparison to young plants. Davis et al. (1971) reported similar results when they found snap bean (*Phaseolus vulgaris* L.) and honey mesquite (*Prosopis glandulosa* Torr.) injured more when younger plants were treated with microwave radiation. Snap bean plants were several times more susceptible to microwave treatment than honey mesquite plants. Wayland et al. (1975) field tested a mobile microwave apparatus and found grasses were more tolerant than broadleaf species. This might be due to the comparatively narrower leaf blade of grasses in comparison to broadleaf plants, thus affecting the amount of energy absorbed. The growing point of grasses is more protected than that of broadleaf plants, also potentially causing less sensitivity in grasses.

The effect of a microwave treatment in field conditions depends not only on the total energy of the microwave flux, but also, on plant size and the orientation of the electrical field of the flux in relation to the soil surface and plant morphology. This provides researchers an opportunity to look further for selective weed control using microwave technology. Preemergence weed control requires a huge amount of energy due to the high microwave attenuation of the soil (Gracia-López and Velázquez-Martí 2002, Velázquez-Martí et al. 2005). But the radiation energy necessary for elimination of emerged vegetation can be less due to the high water content in their structures. Also, no attenuation exists in the radiation path from the magnetron to the leaves of emerged weeds.

Others have reported lower control of monocots than dicots with other forms of thermal heating. Sivesind et al. (2009) studied the response of barnyardgrass, [*Echinochloa crus-galli* (L.) Beauv.]; common lambsquarters, (*Chenopodium album* L. CHEAL); redroot pigweed, (*Amaranthus retroflexus* L.); shepherd's-purse, [*Capsella bursa-pastoris* (L.) Medik.]; and yellow foxtail, [*Setaria pumila* (Poir.) Roemer and J.A. Schultes] to flame weeding at different developmental stages. Dose-response curves generated by species and growth stage showed dicot species were more effectively controlled than monocot species. Common lambsquarters was susceptible to flame treatment with doses required for 95% control (LD_{95}) ranging from 0.9 to 3.3 kg·km^{-1} (3.2 to 11.7 lb·A^{-1}) of propane with increasing maturity stage. Comparable levels of control in redroot pigweed required higher doses than common lambsquarters, but adequate control was still achieved. Flaming effectively controlled shepherd's-purse at the cotyledon stage ($LD_{95} = 1.2$ kg·km^{-1}). However, the LD_{95} for weeds with two to five leaves increased to 2.5 kg·km^{-1}, likely due to the rosette stage of growth, which allowed treated weeds to avoid thermal injury. Control of barnyardgrass and

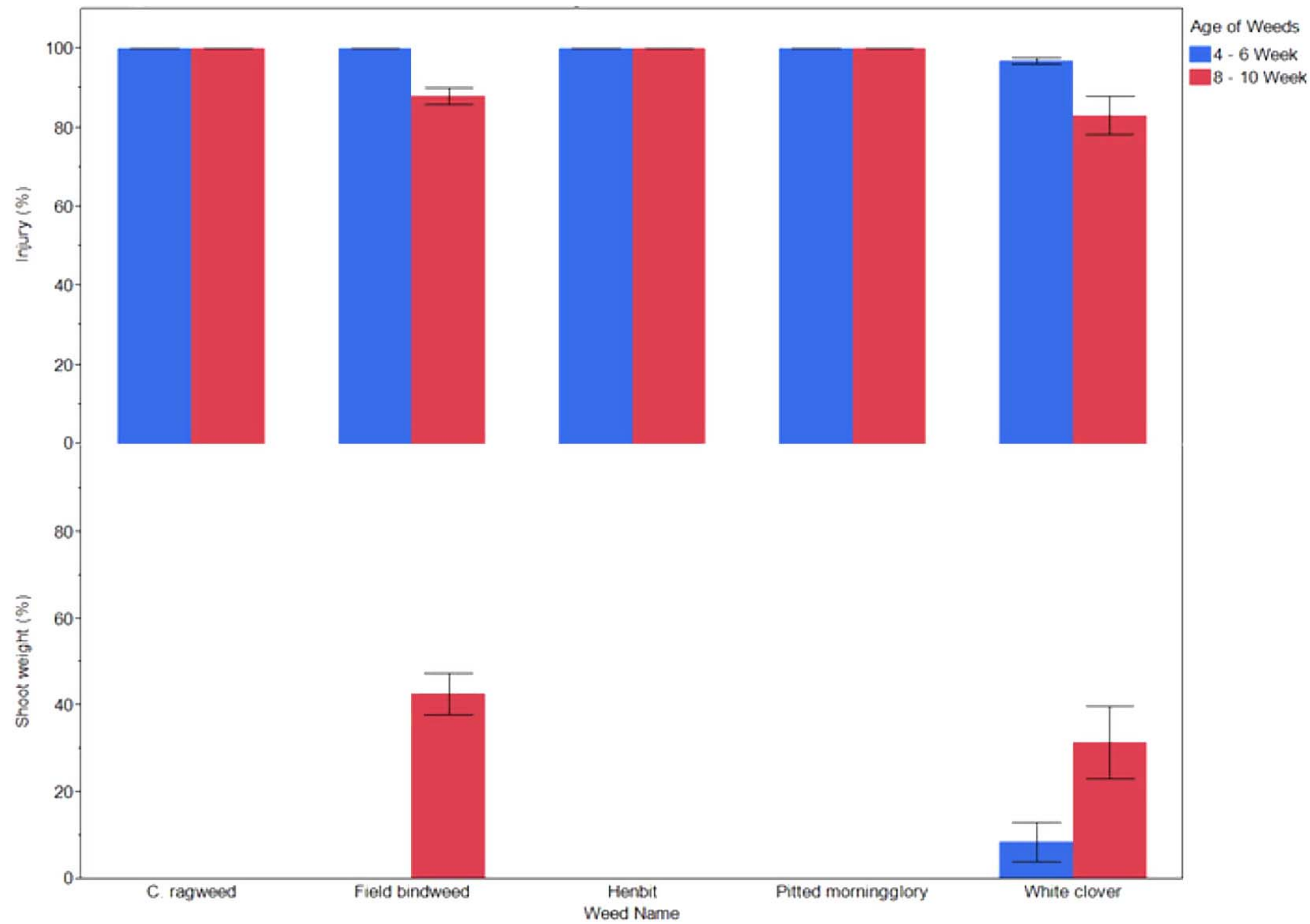

Fig. 4. Effect of 180 joules cm^{-2} microwave radiation on percent injury at 1 WAT and shoot weight at 4 WAT, expressed as percent of the weight of nontreated plants, to dicot weed species at two plant ages in a greenhouse trial. Error bars represents standard error.

yellow foxtail was poor, with weed survival >50% for all maturity stages and flaming doses tested. Leon and Ferreira (2008) recorded injury caused by steam treatment to leaves of bermudagrass, [*Cynodon dactylon* (L.) Pers.], common purslane, (*Portulaca oleracea* L.), English daisy, (*Bellis perennis* L.), and perennial ryegrass, (*Lolium perenne* L.), species that differ in leaf morphology. They also determined injury to plants at different stages of plant development. Plants were exposed to steaming at 400 C (752 F) for 0.36s, equivalent to a steaming speed of 2 km·h^{-1}. They found plants with greater leaf thickness had less injury. For broadleaf species only, species with wider leaves were injured more than species with narrower leaves. Injury was greatest when plants had fewer than six true leaves and when their shoots were less than 10 cm (4 in) long. Brett et al. (2013) reported similar results with dogfennel (*Eupatorium capillifolium* L), as its height was a limiting factor in its control using triclopyr plus fluroxypyr.

Microwave application for weed management has the potential to be competitive compared to alternative methods of control if applied at earlier growth stages of weeds. Several patents dealing with microwave treatment of weeds and their seed have been registered (Clark and Kissell 2003, Grigorov 2003, Haller 2002); however none of these systems appear to have been commercially developed due to concerns about the energy requirements of microwave energy applicator. This hurdle perhaps could be solved using an appropriate design of the microwave applicator and thus is a needed area of research.

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