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Weed Response to Flame Weeding at Different Developmental Stages

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Flame weeding is often used for weed control in organic production and other situations where use of herbicides is prohibited or undesirable. Response to cross-flaming was evaluated on five common weed species: common lambsquarters, redroot pigweed, shepherd's-purse, barnyardgrass, and yellow foxtail. Dose-response curves were generated according to species and growth stage. 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 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). However, the LD_{95} for weeds with two to five leaves increased to 2.5 kg/km, likely due to the rosette stage of growth, which allowed treated weeds to avoid thermal injury. Control of barnyardgrass and yellow foxtail was poor, with weed survival > 50% for all maturity stages and flaming doses tested. Flame weeding can be an effective and labor-saving weed control method, the extent of which is partially dependent on the weed flora present. Knowledge of the local weed flora and their susceptibility to flame weeding is vital for the effective use of this method.

Nomenclature: Barnyardgrass, *Echinochloa crus-galli* (L.) Beauv. ECHCG; common lambsquarters, *Chenopodium album* L. CHEAL; redroot pigweed, *Amaranthus retroflexus* L. AMARE; shepherd's-purse, *Capsella bursa-pastoris* (L.) Medik. CAPBP; yellow foxtail, *Setaria pumila* (Poir.) Roemer and J.A. Schultes SETLU.

Key words: Dose-response, flaming, growth stage, organic agriculture, weed control, weed management.

Producers cite weed control as the most difficult problem they face when transitioning to organic production (Walz 1999). Conventional agriculture makes widespread use of effective synthetic herbicides, which are prohibited under the rules of organic agriculture. Organic producers are forced to turn to other measures such as mechanical cultivation, which often is supplemented with laborious and costly hand weeding. In less competitive crops such as onions, this added labor cost can be significant (Mojžiš 2002). One way producers can attempt to reduce costs and labor requirements is through the use of flame weeding. Flame weeding is an allowed weed control option in organic production systems, often utilized prior to sowing as a stale seedbed technique or before crop emergence (Bond and Grundy 2001). The latter method is often used with small-seeded, slow-germinating crops such as onion and carrot (Ascard et al. 2007).

Directed flame weeding controls weeds in the crop row, as interrow weeds can be effectively controlled through conventional mechanical methods (Melander 1998). Intra-row weeds are more difficult to control as mechanical methods are ineffective or cause too much damage to the crop plants, especially early in the growing season. Many producers therefore are forced to rely on sometimes large amounts of hand weeding. Hand weeding can require a ready supply of field workers, and can be expensive for large areas or for less competitive crops that require multiple hand weedings. The labor requirement for weeding the crop row by hand is considerable and can take as many as 200 to 300 h/ha in seeded onions (Ascard and Fogelberg 2008). Flame weeding provides organic producers effective weed control in the crop row where cultivation is difficult and reduces the amount of costly hand weeding.

Ascard (1994, 1995, 1997, 1998) conducted a comprehensive series of trials on the effectiveness of flame weeding. These studies evaluated the role of different biological factors on weed flora susceptibility, as well as technical aspects of the burner apparatus that had an effect on flame weeding efficacy. These studies utilized the type of system used for preemergent flaming; namely, covered burners oriented parallel to the crop row. Cisneros and Zandstra (2008) evaluated the response of six weed species (three monocots and three dicots) to a covered flamer in a laboratory setting. These previous studies found that weed susceptibility to flaming varied among species and seedling size. In general, dicot species are reported to be controlled more effectively with flaming than monocot species. Ascard (1994) constructed dose-response curves of various weed species according to plant size and density that demonstrated differences in susceptibility between species tested.

Flaming can alternatively be used after crop emergence or planting in tolerant species. Flaming with crop plants present requires a different system, where uncovered, angled burners are staggered and set perpendicular to the crop row. Many of the recent studies on flame weeding have utilized a covered, parallel burner system, as is used in preemergent flaming. It is unknown how well the results of those studies translate to the uncovered, cross-flaming burners required for application with crop plants present.

Studies were designed to test the efficacy of flame weeding under field conditions on a variety of weed species common to horticultural fields in southwestern Québec. A broad range of flaming intensities were tested on a variety of weeds of differing maturity stages. A cross-flaming system such as is

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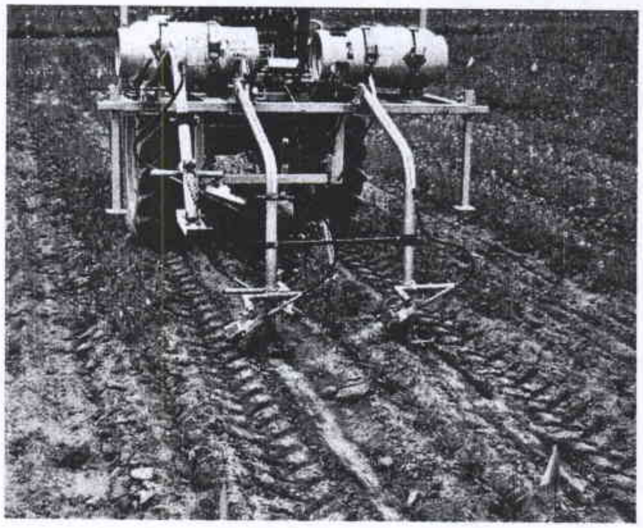

Figure 1. Photo showing two burner–tractor mounted flame weeders used for all treatments.

used in selective postemergence flaming was used for flame treatments. Dose-response curves were then constructed in order to determine the correct dose to apply based on the weed flora present. Dose-response curves for weeds are important so that the lowest effective dose can be applied, which saves energy and results in lower production costs for the producer.

Materials and Methods

Field Management. Experiments were conducted at the Institut de recherche et de développement en agroenvironment (IRDA) in Saint-Hyacinthe, QC, Canada (45°38′N, 72°57′W) in 2005 and 2006. The soil types of the fields employed were a Duravin loam and a St-Damase sandy loam. Experiments were conducted as randomized complete block designs (RCBD) with four replications and repeated in two successive years. Treatments took place in fields planted with one of four crops: transplanted Spanish onion (*Allium cepa* L. 'Vaquero'), transplanted broccoli (*Brassica oleracea* L. var. *Italica* 'Everest'), direct seeded common beet (*Beta vulgaris* L. 'Rosette'), and direct seeded spinach (*Spinacia oleracea* L. 'Unipack 151'). Sixty-day-old onion transplants were planted May 18, 2005, and May 28, 2006, with 15-cm spacing. Sixty-day-old broccoli transplants were planted May 25, 2005, and May 30, 2006, with 30-cm spacing. Spinach was direct-seeded at a rate of 2.5 kg/ha with 4.5-cm spacing on June 1, 2005, and May 5, 2006. Common beet was direct-seeded at 5 kg/ha with 2.5-cm spacing on June 1, 2005, and May 8, 2006. Onion was flamed at five stages: 15, 21, 33, 40, or 49 d after transplanting (DAT) in 2005, and 9, 20, 34, 51, or 60 DAT in 2006. Broccoli received flame treatments at five stages: 14, 26, 33, 41, or 49 DAT in 2005, and 10, 20, 30, 41, or 50 DAT in 2006. Spinach and common beet were each flamed at three stages: one preemergence and two postemergence at the four- and six-leaf stages. Quadrats (20 by 50 cm) were placed along the center of each plot before flame treatments and weeds were recorded, according to species and maturity stage. Between 1 and 3 d following flame treatment, quadrats were reassessed for weed mortality. To eliminate difficulties in assessment and to control for contamination of the data by post-treatment weed germination, in 2006, quadrats were replaced with tagging of individual weeds. Weeds along the crop row were marked by placing a metal marker around, but at a distance from, the base of the plant so as not to affect the response. Surrounding weed flora was then removed. In order to ensure sufficient weed numbers for accurate data, in 2006, each of the four blocks was seeded with one of four weed species: redroot pigweed, common lambsquarters, barnyardgrass, or yellow foxtail. Crop response data will appear in a subsequent publication.

Table 1. Parameters used to calculate flaming rates used in experimental treatments. Flaming doses measured in mass of propane consumed.

2005	2006				
Pressure	Pressure	Speed	Rate	Dose	Dose
kPa	kPa	km/h	kg/h	kg/ha[a]	kg/km
138	117	5	2.7	27.0	0.54
138	117	4	2.7	33.8	0.68
241	214	5	4.3	43.0	0.86
138	117	3	2.7	45.0	0.90
241	214	4	4.3	53.8	1.08
345	310	5	5.9	59.0	1.18
138	117	2	2.7	67.5	1.35
241	214	3	4.3	71.7	1.43
345	310	4	5.9	73.8	1.48
345	310	3	5.9	98.3	1.97
241	214	2	4.3	107.5	2.15
345	310	2	5.9	147.5	2.95

[a] Flaming dose in kg/ha on broadcast basis using a flamed width of 20 cm; included to facilitate comparison with flaming rates presented on broadcast basis in other studies.

Flaming Specifications. Flame treatments were performed using a tractor-mounted, unshielded two burner system[1] directed perpendicularly to the crop row (Figure 1). Burners were staggered to avoid flames intersecting and deflecting upwards. Burners were set at an angle of 30° with respect to horizontal 18 cm from the row measured along the angle. Flame treatments consisted of all combinations of three fuel pressures (138, 241, and 345 kPa in 2005; 117, 214, and 310 kPa in 2006) and four driving speeds (2, 3, 4, and 5 km/h) resulting in 12 different flaming intensity treatments. Flaming doses were converted into a linear scale based upon the fuel burned/hour (Table 1). Due to a replaced fuel regulator, fuel pressures were adjusted in 2006 in order to maintain equal flaming rates.

Flaming Dose Calculation. Flame weeding doses are often given in terms of mass of fuel used per area of coverage (e.g., kg/ha). In situations utilizing nonselective systems using covered burners oriented parallel to crop row, the width of coverage is assumed to be the width of the burner cover. The flaming dose/area can then either be represented as coverage of the entire field area, or else as the actual fuel usage/ha flamed. Presenting doses on a broadcast basis is difficult when using noncovered cross-flamers, as the width of coverage would be somewhat arbitrarily decided, as coverage would decrease gradually with distance from the crop row. Care must be taken with the latter approach as well, as any dosage given is dependent upon row spacing and must be converted if row spacing is not consistent. For this reason, we have decided to present the flaming doses used in this study as propane burned per unit row length (i.e., kg propane/km). We feel this is prudent as it accurately represents the fuel used, and would be simple to accurately compare dosages used in separate studies by authors using different equipment. Also, this avoids the problem of determining exact width of coverage for uncovered cross-flamers. In order to determine the actual amount of fuel required for a given field, all that is required is to multiply the linear rate by 10 and divide by the row width in meters. For example, in this study we used a row spacing of 0.90 m, so a dose of 0.9 kg/km would be equal to 10 kg/ha. For a row spacing of 0.60 m, this same example would be equal to 15 kg/ha. This approach simplifies the comparison of rates used by different parties, and makes it easy to calculate the actual amount of fuel that is required for any given field. Flaming rates used in this study were converted into kg/ha (broadcast basis) in order to facilitate comparison with other studies that present rates in this manner. To arrive at these rates, 20 cm was used as the width of coverage.

Modeling Weed Response. Data from all four experiments over 2 yr were combined for analysis. Dose-response curves were generated in order to evaluate the effect of a range of flaming doses on weed mortality. Response curves were independently generated for each weed species and maturity stage tested. The dependent variable y is defined as the percentage of weeds of a particular species and maturity stage that remain viable following flame treatment. The independent variable x is the flaming dose measured as kilograms of propane burned per kilometer of row length treated.

The model used to describe weed response was the following four-parameter logistic equation (Ascard 1994; Streibig et al. 1993):

$$y = C + \frac{(D - C)}{1 + \left(\frac{x}{a}\right)^b} \qquad [1]$$

where C is the lower asymptote, D is the upper asymptote, a is the point of inflection around which this model is symmetrical on a log-dose scale as well as the dose that gives a response halfway between the upper and lower asymptotes (Ascard 1994), and b is the slope of the curve at a. Because y is the percent survival rate, D will be equal to 100. For weeds where complete kill is achieved at high doses, C will be equal to zero and can thus be dropped from the model (Ascard 1995). In these cases, a is also equal to the LD_{50} value, the point at which 50% of weeds survive. Once the values for the other parameters are known, the dose (x) at which 95% control is achieved (LD_{95}) can be obtained by substituting the corresponding weed survival percentage (5) for y. For species that were not found to be controlled effectively with flame treatments and whose responses were not accurately described by the above model, the standard linear model

$$y = mx + b \qquad [2]$$

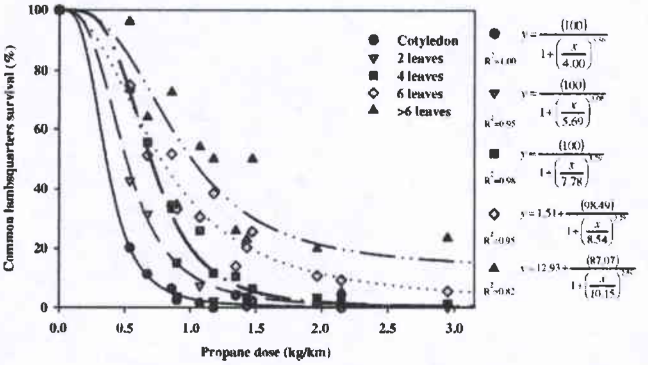

Figure 2. Response of common lambsquarters seedlings of differing sizes to a range of flame treatments.

where m is the slope and b is the y-intercept, was used to illustrate trends. Models were fit to data and R^2 values generated using SigmaPlot graphing software.[2]

Results and Discussion

Weed response to flaming varied and was dependent upon species and maturity stage. The logistic model described the response of the dicotyledonous weeds with R^2 values for most stages of weeds exceeding 0.90 (Figures 2–4). The doses used in this study were in the appropriate range with weed survival, depending on species and growth stage, varying from 100% to complete kill. The logistic model with the lower asymptote set to zero (representing situations where complete kill can be achieved) was the best descriptor of the response of all stages of shepherd's-purse, and common lambsquarters and redroot pigweed until the six-leaf stage. For the six-leaf stage in redroot pigweed and the six- and greater than six-leaf stages in common lambsquarters, 100% control was not realized at any dose tested. For these weeds, the logistic model that retained a variable for the lower asymptote proved the best fit (Figures 2 and 3).

The logistic models were very accurate in describing the response of common lambsquarters to flame treatments, with R^2 values above 0.95 through the six-leaf stage (Figure 2). In the cotyledon stage, 50% weed control was achieved when flamed at 0.4 kg/km, compared to 95% control at 0.9 kg/km (Table 2). As weed size increased, regressions indicated that higher flaming rates were necessary to achieve comparable levels of control. For example, the LD_{50} values for common lambsquarters from the cotyledon to the greater than six-leaf stages progressively increase from 0.4 to 1.0 kg/km. With the six-leaf and greater than six-leaf stages, the model that retained the lower asymptote variable C best described the response of the weeds to flaming, as complete kill was not achieved at any of the rates tested for these stages. Doses required for 95% control trended upwards, ranging from 0.9 kg/km for the cotyledon stage up to 3.3 kg/km for weeds with six leaves. The R^2 value for the greater than six-leaf stage was lower than that of the other stages evaluated due to the greater variability of weeds in this category.

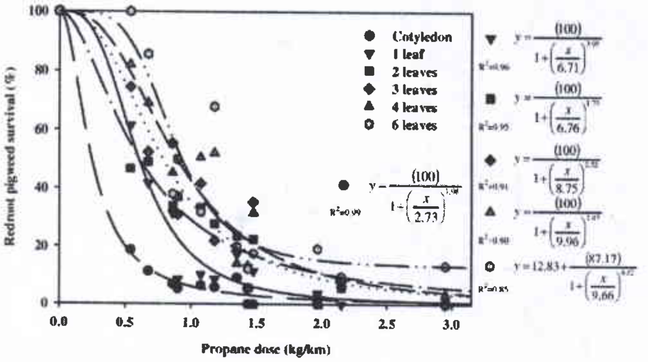

Figure 3. Response of redroot pigweed seedlings of differing sizes to a range of flame treatments.

Overall, the response of redroot pigweed mirrored that of common lambsquarters. The logistic model accurately described the response up to the six-leaf stage (Figure 3). As expected, weed response to flaming shifted as weeds matured, although some overlap was observed due to changes in the slope of the curves in some stages. Weeds at the cotyledon stage were controlled with moderate doses (LD_{50} = 0.3 kg/km), and successively higher doses were required for similar levels of control in more advanced stages (Table 2). As observed in common lambsquarters, LD_{50} values for redroot pigweed increased from the cotyledon (0.3 kg/km) to the six-leaf stage (0.9 kg/km). However, in general, higher flaming doses were required for comparable treatment levels in redroot pigweed as compared to common lambsquarters. This was especially true when achieving high levels of control in weeds with two or more leaves. The reasons for these differences are unclear. Variation in morphology (level of pubescence, cuticle thickness, etc.) may play a role in this difference. However, this is merely speculation as these characteristics were not investigated in this study.

Shepherd's-purse had a higher LD_{50} value at the cotyledon stage (0.6 kg/km) than common lambsquarters (0.4 kg/km) and redroot pigweed (0.3 kg/km) (Table 2). This is likely due at least in part to shepherd's-purse being in rosette form at this point in its growth, as opposed to the upright growth habit of common lambsquarters and redroot pigweed. Evaluation of other species with similar growth forms is necessary to support this possibility. The lower R^2 value for the two- to five-leaf stages (Figure 4) is likely due to the greater variation of plants included in this category. Despite this, shepherd's-purse is still controlled with flaming, although higher rates are required than for the other dicot weeds evaluated.

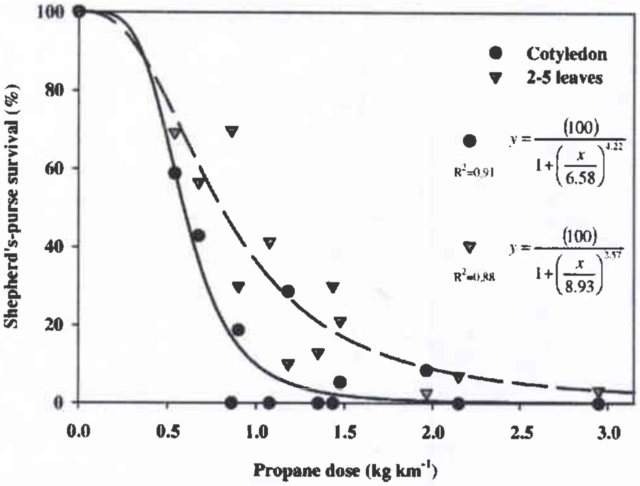

Figure 4. Response of shepherd's-purse seedlings of differing sizes to a range of flame treatments.

Table 2. Flaming doses required for 50 and 95% control of dicot weeds at different developmental stages.

	Stage	LD_{50}	LD_{95}
Redroot pigweed	Cotyledon	0.2	1.1
	1 leaf	0.6	1.6
	2 leaves	0.6	3.1
	3 leaves	0.8	2.5
	4 leaves	0.9	2.7
	6 leaves	0.9	-------
Shepherd's-purse	Cotyledon	0.6	1.2
	2–5 leaves	0.8	2.5
Common lambsquarters	Cotyledon	0.4	0.9
	2 leaves	0.5	1.3
	4 leaves	0.7	1.5
	6 leaves	0.8	3.2
	> 6 leaves	1.0	-------

The response of the two monocot species examined in this study to flame weeding was in stark contrast to what was observed in the dicot species. Neither barnyardgrass nor yellow foxtail was able to be effectively controlled at any flaming rate tested. For barnyardgrass, all stages had greater than 75% survival at all flaming doses tested (Figure 5). Yellow foxtail was controlled somewhat more effectively, but control was still unacceptable and never exceeded 50% for any stage or treatment level (Figure 6). The low levels of control observed in the two monocot species studied were not due to tolerance to the flame treatment. Rather, the high survival rate was due to these species' much greater ability to recover following flaming. In earlier maturity stages (e.g., one to two leaves), higher flaming rates killed nearly all aboveground tissue. However, after 2 to 3 d, visible regrowth would occur. This was due to the meristem in monocots being located near or below ground level, protecting it from flame damage. Additionally, the growing point is surrounded by a protective sheath of leaves, further protecting it from damage. These phenomena can result in an increased percentage of weed flora being monocot species in the weeks following flame treatment, as dicots are largely killed and monocots survive.

The results of this study largely agree with data previously reported in the literature. Wszelaki et al. (2007) reported that monocots and weeds with fleshy leaves were more difficult to control with flaming than most dicot species. Ascard (1995) divided weed species into four groups based on susceptibility to flame weeding. The most susceptible species were those with unprotected meristems and thin leaves, such as common lambsquarters and common chickweed [*Stellaria media* (L.) Vill.]. Redroot pigweed and common lambsquarters would be placed in this category, and in this study were able to be effectively controlled until the four- and six-leaf stages,

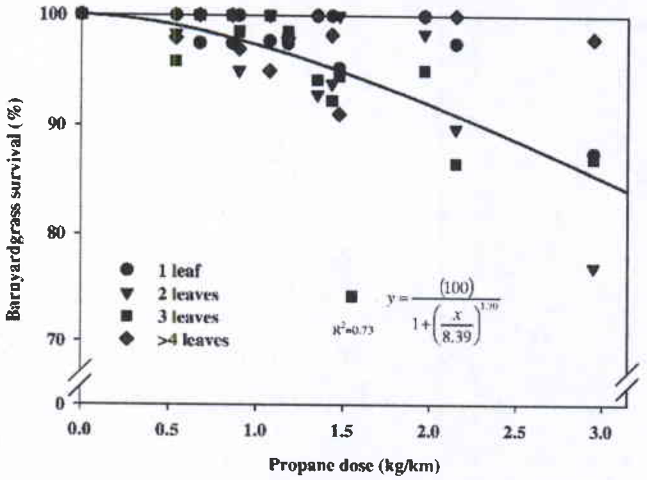

Figure 5. Response of barnyardgrass seedlings of differing sizes to a range of flame treatments. Sample regression made using Equation 1 included simply to illustrate overall trends.

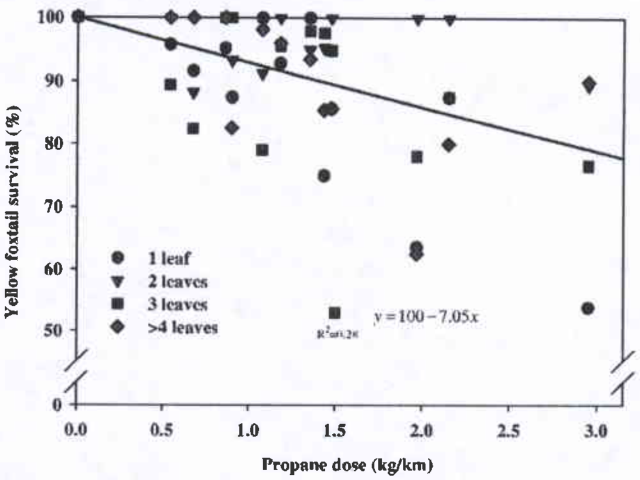

Figure 6. Response of yellow foxtail seedlings of differing sizes to a range of flame treatments. Sample regression made using Equation 2 included simply to illustrate overall trends.

respectively. The final group contained the least susceptible species, which were not able to be controlled with a single flame treatment. The only species in Ascard's study that was included in this final group was annual bluegrass (*Poa annua* L.), though the author noted that other monocot species may be expected to belong to this group as well. The results presented here suggest that the monocot species tested, barnyardgrass and yellow foxtail, do in fact belong in this grouping. The results of the current study support the observations of these earlier studies.

Dose-response curves of weeds to flame weeding had previously been explored in a series of experiments carried out by Ascard (1994, 1995). This study was designed in part to confirm and expand on the results of those studies. Weeds were flamed at a greater number of specific growth stages in order to achieve a more exact picture of the dose-response relationship. In this study, rates required to achieve 95% control were found to be 1.3 kg/km for common lambsquarters at the two-leaf stage, and 2.5 kg/km for shepherd's-purse in the two- to five-leaf stage. Ascard (1995) was able to achieve 95% control of common lambsquarters and shepherd's-purse at rates of 0.4 and 0.7 kg/km, respectively, for seedlings at the two-leaf stage (using a 20-cm width of coverage for both studies). The considerably lower flaming rates required for equivalent control in the latter study are likely due to the use if an insulated cover, which retained heat and improved efficiency. Although the rates cannot be directly compared due to differences in methodological and technical aspects of these experiments (e.g., uncovered cross-flaming system in the current study compared to a parallel, covered apparatus used by Ascard [1995]), the trends present between species in both studies are similar. Monocot species were not effectively controlled in either study. Ascard (1995) noted that 100% control of annual bluegrass was not achieved at either the one- to two-leaf stage or the greater than six-leaf stage. The lower limit of survival of annual bluegrass was found to be 31%. In addition, increased emergence of annual bluegrass was observed after treatment with higher flaming doses. In the current study, barnyardgrass survival was greater than 75% at all doses and maturity stages, and control of yellow foxtail never exceeded 50%. Any changes in emergence patterns were not recorded, as we evaluated only weeds that were present prior to flame treatments.

Cisneros and Zandstra (2008) evaluated the effectiveness of flame weeding on several weed species in a laboratory setting using a parallel mounted, covered flaming system. They reported greater variability in response between monocot species than was found in our study. The authors reported little control in numbers of barnyardgrass at either the zero- to two-leaf or the two- to four-leaf stages (indeed, an increase in numbers was reported in all treatments), regardless of flaming intensity. However, a substantial reduction in plant biomass 14 d after treatment was observed in all treatments. Although control was somewhat better in our study, these results are largely in agreement with the results of our study, where satisfactory control of barnyardgrass was never attained. Substantially better control was observed with green foxtail [*Setaria viridis* (L.) Beauv.], where stand reductions of 70 to 99% were observed at the zero- to two-leaf stage depending upon flaming dose. Though no differences were seen between treatments, all were significantly lower than the control. At the two- to four-leaf stage, reductions of 14 to 77% as compared to the nonflamed control were observed depending upon flaming dose. A significant reduction in plant numbers of large crabgrass [*Digitaria sanguinalis* (L.) Scop.] at both the zero- to two- and two- to four-leaf stages was only achieved with the highest dose tested (49 and 32% reductions, respectively). All treatments resulted in reduced fresh weights 14 d after treatment in the zero- to two-leaf stage. At the two- to four-leaf stage, no significant reductions in fresh weight were observed in any treatment. Much greater differences were seen in responses to flaming between monocot species in their study than we found in ours. The reason for this discrepancy needs to be explored. The authors also examined three dicot weeds: redroot pigweed, common ragweed (*Ambrosia artemisiifolia* L.), and common lambsquarters. At the zero- to two-leaf stage, the authors reported no differences between treatments in reductions of plant stands, but all were significant from the untreated control (92, 82, and 93%, respectively, averaged over treatments). At the two- to four-leaf stage, reductions of 95, 93, and 99% were observed, respectively, when averaged over treatments. Of note is the fact that for common lambsquarters, and to a greater extent common ragweed, flaming was more effective on plants with two- to four-leaves than those with zero- to two-leaves, whereas in redroot pigweed, flaming was approximately of equal effectiveness with either stage in three of the four treatment levels tested. The authors speculated that the reason for this could be a larger surface area of the more mature seedlings for the flame to contact. This observation contradicts the results of our study, which found, with few exceptions, a steady decrease in the effectiveness level of a particular flaming dose on dicot weeds of increasing maturity. It should be noted, however, that Cisneros and Zandstra (2008) found this phenomenon to be most pronounced in common ragweed, which we did not evaluate.

Our study was designed to construct dose-response curves of a number of weeds common to horticultural fields to a cross-flame weeding system in a field setting. The data generated overall agree with the information available in the literature. The information provided in this study should further the understanding of weed response to flame weeding and help producers to more effectively utilize this weed control tool.

Sources of Materials

[1] Liquid phase burners, Model LT 1 ½ × 6 Liquid Torch, Flame Engineering, Inc., LaCrosse, KS 67548.

[2] SigmaPlot for Windows, version 6.10. Systat Software, Inc., San Jose, CA 95110.

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