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Organic Weed Management in Field Crops with a Propane Flamer and Rotary Hoe

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The weed management needs of organic producers are unique because they rely primarily on cultural and physical management strategies. Recommendations regarding commonly used tools for weed management could benefit this sector of agriculture. The objectives of this research were to (1) determine the optimum time of day for propane flaming to achieve maximum weed reductions while minimizing corn damage; (2) assess whether flaming, rotary hoeing, or a combination of the two tools best manages early-season weeds without injuring dry beans; and (3) evaluate the use of growing degree days (GDD) to optimize rotary hoe timing. Experiments were carried out between 2006 and 2009 in Hickory Corners and East Lansing, MI. Flaming reduced broadleaf weed densities by at least 82% when done in the morning to midafternoon but only reduced densities by 58% when weeds were flamed in the evening. Common lambsquarters, redroot pigweed, and velvetleaf were easier to control by flaming than common ragweed and common purslane. Flaming did not reduce grass weed densities. When comparing flaming and rotary hoeing, the two treatments that achieved the highest level of weed control and highest dry bean yields were flaming prior to bean emergence followed by two rotary hoeings and rotary hoeing three times (no flaming). However, the added cost of the flamer may only be justified when wet conditions make rotary hoeing ineffective. Flaming dry beans POST resulted in significant injury and yield reductions of 60%; therefore this practice is not recommended. Timing rotary hoe passes every 300 GDD (base 3.3 C) from the time of soybean or dry bean planting resulted in fewer passes compared with the 7-d or 150 GDD treatments, while maintaining similar levels of weed control and yields similar to the weed-free treatment in 1 of 2 yr for each crop.
Nomenclature: Common lambsquarters, *Chenopodium album* L. CHEAL; common purslane, *Portulaca oleracea* L. POROL; common ragweed, *Ambrosia artemisiifolia* L. AMBEL; redroot pigweed, *Amaranthus retroflexus* L. AMARE; velvetleaf, *Abutilon theophrasti* Medik. ABUTH; corn, *Zea mays* L.; dry bean, *Phaseolus vulgaris* L.; soybean, *Glycine max* (L.) Merr.
Key words: Growing degree days, thermal weed control.

Las necesidades de manejo de malezas de los productores orgánicos son únicas porque ellos dependen primordialmente de estrategias culturales y físicas. Las recomendaciones que consideren herramientas comúnmente utilizadas para el manejo de malezas podrían beneficiar a este sector de la agricultura. Los objetivos de esta investigación fueron: (1) determinar el momento óptimo del día para quemar con llamas de propano y alcanzar reducciones máximas en las poblaciones de malezas al tiempo que se minimiza el daño al maíz; (2) evaluar si las llamas, el cultivador rotativo, o la combinación de estas dos herramientas brinda el mejor manejo de malezas en la etapa temprana del cultivo sin dañar al frijol común; y (3) evaluar el uso de grados días de crecimiento (GDD) para optimizar el momento de uso del cultivador rotativo. Entre 2006 y 2009, se realizaron experimentos en Hickory Corners y East Lansing, MI. La quema con llamas realizada entre la mañana y media tarde redujo las densidades de malezas de hoja ancha en al menos 82%, pero solamente redujo las densidad en 58% cuando las malezas fueron quemadas en la noche. El control con llamas de *Chenopodium album*, *Amaranthus retroflexus y Abutilon theophrasti* fue más sencillo que el control de *Ambrosia artemisiifolia y Portulaca oleracea*. La quema con llamas no redujo las densidades de malezas gramíneas. Al comparar la quema con llamas con el cultivador rotativo, los dos tratamientos que alcanzaron el mayor nivel de control de malezas y el mayor rendimiento del frijol común fueron: quema con llamas antes de la emergencia del frijol seguida por dos pases del cultivador rotativo y tres pases del cultivador rotativo (sin quema). Sin embargo, el costo extra del quemador de llamas se justificaríÚa solamente cuando condiciones húmedas limitan la efectividad del cultivador rotativo. El exponer el frijol común a las llamas POST resultó en daños significativos y reducciones en el rendimiento de 60%; por esta razón esta práctica no es recomendada. El realizar los pases del cultivador rotativo cada 300 GDD (base 3.3 C) desde el momento de la siembra de la soya o el frijol común resultó en menos pases en comparaciín con los tratamientos de 7 días o 150 GDD, al mismo tiempo que se mantuvieron niveles de control de malezas y de rendimiento similares al tratamiento libre de malezas en 1 de los 2 años de cada cultivo.

Weed management is one of the highest input costs in crop production systems. This is especially true in organic systems, where growers must rely largely on physical, cultural, and biological methods of weed control. Bond and Grundy (2001) reviewed nonchemical weed control methods in organic cropping systems, including thermal and mechanical control as well as cover crops and mulches for weed control. Recent areas of weed management research in the north-central United States include using a propane flamer (Knezevic and Ulloa 2007) and new cultivation tools, and improving the

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Table 1. Environmental conditions at the time of each flaming for objective 1: flaming time of day.

	2007				2008			
Time 24 h	Temp[a]	Rel. h	Soil wetness[b]	Dew[c]	Temp	Rel. h	Soil wetness	Dew
	C	%			C	%		
8:00 A.M.	23	64	2	Y	23	68	2	Y
12:00 P.M.	26	43	3	N	29	57	3	N
4:00 P.M.	34	40	3	N	29	54	4	N
8:00 P.M.	33	43	3	N	27	63	4	N

[a] Abbreviations: Temp, temperature; Rel. h, relative humidity.

[b] Soil wetness was ranked on a scale of 1 to 5 (1 = wet, 5 = dry).

[c] Dew presence at the time of flaming (Y = yes; N = no).

timing of weed management based on environmental cues (Dale and Renner 2005).

Using fire to control weeds in field crops is a practice that has been around for nearly 100 yr. Initially kerosene and diesel flamers were drawn by horses (Cramer 1990). In the 1940s and 1950s, use of flaming for weed control had increased, using propane, butane, and kerosene as fuels. By the mid-1960s, 25,000 flamers were in use nationwide (Heiniger 1998). Since that peak, however, flaming has drastically decreased in popularity due to the increased efficiency and affordability of herbicides. With the current demand, both nationally (USDA-ERS 2009) and abroad (Willer and Kilcher 2011), for organically produced goods, there has been a renewed interest in using flaming as a tool for weed control. The high heat of propane flaming effectively controls small weeds in field crop and vegetable production systems (Ascard 1995; Johnson and Mullinix 2008; Knezevic and Ulloa 2007; Parish et al. 1997; Wszelaki et al. 2007). Propane flaming can be timed prior to (Diver 2002) or after crop emergence, when weeds are quite small (Parish et al. 1997; Ulloa et al. 2010b). Propane flaming has two advantages over mechanical weed control. Weeds can be managed when soil conditions are moist, which renders mechanical means less effective, and the soil surface is not disturbed, which can encourage new weed emergence.

Crop and weed susceptibility to propane flaming has been studied by numerous researchers (Ascard 1994, 1995; Cisneros and Zandstra 2008; Ulloa et al. 2010a) and has been found to differ by species. The propane dose used for flaming combines the factors of tractor speed with burner output and spacing, and is one way to quantify differences in susceptibility among species (Knezevic and Ulloa 2007; Ulloa et al. 2010a). Grasses are more difficult to control than broadleaf weeds (Cisneros and Zandstra 2008; Parish et al. 1997; Ulloa et al. 2010a; Wszelaki et al. 2007). Broadleaf weeds in vegetative growth stages require propane doses ranging from 30 to 60 kg ha^{-1}, whereas a vegetative grass such as barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] can require up to 79 kg ha^{-1} to achieve the same level of control (Ulloa et al. 2010a). Weed sensitivity to flaming also varies by weed size; larger or more succulent weeds are less susceptible to flaming (Wszelaki et al. 2007). Finally, environmental conditions, such as the presence of dew, may reduce the effectiveness of propane flaming (Parish et al. 1997).

One of the popular ways of mechanically managing weeds in organic systems is with a rotary hoe. Rotary hoes have been manufactured since the mid-1800s and were widely used starting in the early 1900s to control weeds and improve soil aeration by breaking the soil crust (Lovely et al. 1958; Peters et al. 1959). The rotary hoe is one of the preferred tools for early-season weed management in organic soybean and dry bean prior to interrow cultivation (Amador-Ramirez et al. 2002; Corp et al. 2010; Frye 2011; Kluchinski and Singer 2005; VanGessel et al. 1995, 1998). Rotary hoes, used prior to or following crop emergence, uproot small weeds both within and between the planted crop rows while leaving well-rooted crop plants intact; they have been shown to be as effective as tined weeding (Mohler et al. 1997). Delaying rotary hoeing 12 to 14 d after planting did not reduce soybean populations (Kluchinski and Singer 2005; Renner and Woods 1999); however, soybean populations were reduced by 9 to 15% when rotary hoeing occurred 4 to 6 d after planting (cotyledon stage) (Leblanc and Cloutier 2001b; Renner and Woods 1999). The more established root systems of older soybean were not uprooted by the rotary hoe. Reductions in dry bean populations following rotary hoeing have been reported by some studies (Burnside et al. 1994; Leblanc and Cloutier 2001a), but not others (Burnside et al. 1993; VanGessel at al. 1995).

Many growers base the timing of rotary hoeing events on calendar days or when they first observe weeds emerging in the field. It has been proposed that the ideal time for rotary hoeing would take place when weeds are at the white-thread stage, which is when germinated seedlings are just below the soil surface (Pullen and Cowell 1997). One problem with relying on a rotary hoe for early-season weed control is the potential for overuse. Frequent rotary hoeing may cause crop injury and yield loss while increasing fuel and labor costs; however, delayed or too few rotary hoeings may result in poor weed control and reduced crop yields (Kluchinski and Singer 2005, Leblanc and Cloutier 2001b; Lovely et al. 1958; Mohler et al. 1997). Delaying rotary hoeing until weeds have emerged and have one to three true leaves has been shown to reduce rotary hoeing effectiveness by nearly 60% (dry biomass reduction) compared with hoeing when weeds are in the white thread stage (Lovely et al. 1958). Increasing the number of rotary hoe passes from one to two during the first 2 wk after soybean planting increased control of common lambsquarters (*Chenopodium album* L.) by 41 to 62% and giant foxtail (*Setaria faberi* Herrm.) and pigweed species (i.e. redroot pigweed [*Amaranthus retroflexus* L.] and Palmer amaranth [*Amaranthus powellii* S. Wats.]) control by 34 to 45% (Buhler et al. 1992). Considering environmental factors, such as GDD, that are known to trigger weed seed germination while taking into consideration the crop growth stage could help optimize the timing of rotary hoe operations. The baseline germination temperatures for many weed species are known and could be incorporated into developing a decision tool for timing rotary hoeing based on GDD and the prediction of weed emergence (Amador-Ramirez et al. 2002; Dale and Renner 2005; Steinmaus et al. 2000).

The objectives of this research were to (1) determine the time of day for propane flaming that maximizes weed

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management and minimizes corn injury; (2) assess whether propane flaming, rotary hoeing, or a combination of the two techniques best manages early-season weeds without reducing edible dry bean yields; and (3) determine if using GDD to time rotary hoeing improves weed control in soybean and edible dry bean without reducing yields. Each objective was addressed by a separate field experiment.

Materials and Methods

Flaming Based on Time of Day. Following chisel plowing and cultivation with a soil finisher, field corn was planted on May 22, 2007 (Blue River Hybrids '26K21′, Blue River Hybrids Organic Seed, Kelly, IA), and May 23, 2008 (Blue River Hybrids '25M90′, Blue River Hybrids Organic Seed) at 69,000 seeds ha^{-1} at the Kellogg Biological Station in Hickory Corners, MI, to determine the effect of time of day of propane flaming on weed control in organic corn. Corn was flamed at the V3 stage (3 visible collars), when weeds were less than 5 cm in height. The trial consisted of six treatments: an untreated control; a rotary hoe–only control; and propane flaming at 8:00 A.M., 12:00 P.M., 4:00 P.M., or 8:00 P.M.. The untreated control received no early-season weed management and the rotary hoe control was hoed the same day as flaming and again 1 wk later. At each flaming time, air temperature, humidity, soil wetness (ranked on a scale of 1 to 5, 1 = wet, 5 = dry), and the presence or absence of dew were recorded (Table 1). All treatments received uniform interrow cultivation once a week for 2 wk, beginning 2 wk after flaming. The study was organized in a randomized complete block design with four replicates. Plots consisted of six rows of corn 21.3 m long, spaced 76 cm apart. The propane flamer used was a six-row model from Flame Engineering, Inc. (LaCrosse, KS) with two burners (LT 2 × 8) per row mounted at a 45° angle relative to the ground. The flamer was operated at 6.4 km h^{-1} at a pressure of 207 kPa, providing an estimated propane dose of 25 kg ha^{-1}.

Three permanent weed sampling stations were established in each plot to record the change in weed density over time. Each sampling station was 15 cm wide by 72 cm long, centered on the corn row. Weed densities were measured immediately prior to flaming, 5 to 6 d after flaming, and 1 mo after flaming (2 wk after cultivation). Corn yields were not taken because of deer damage.

Flaming vs. Rotary Hoeing. On June 22, 2009, and June 29, 2010, 'Jaguar' black beans (Michigan Crop Improvement Association, Okemos, MI) were planted at 262,000 seeds ha^{-1} into a freshly prepared seedbed at the Kellogg Biological Station to determine the effects of flaming and rotary hoeing combinations on dry bean response and weed control. There were four early-season weed control treatments: (1) flaming once (PRE), (2) flaming twice (once PRE and again at the cotyledon stage), (3) flaming once (PRE) followed by rotary hoeing (cotyledon and again before two trifoliates had unfolded), and (4) rotary hoeing three times (PRE, cotyledon, and before two trifoliates had unfolded) (Table 2). A treatment was also included which received no early-season weed control. Following early-season treatments, all plots

Table 2. Weed control treatments for objective 2: flaming vs. rotary hoeing.

	Timing[a]			
Treatment	PRE	VC	VC–V1	V2 and beyond
Flame (1×)	Flame	—	—	Cultivate
Flame (2×)	Flame	Flame	—	Cultivate
Flame + rotary hoe (2×)	Flame	Rotary hoe	Rotary hoe	Cultivate
Rotary hoe (3×)	Rotary hoe	Rotary hoe	Rotary hoe	Cultivate
Cultivation only	—	—	—	Cultivate

[a] Timings are based on dry bean stage of development.

[b] Abbreviations: VC, cotyledons unfolded; VC–V1, between unfolded cotyledons and the first unfolded trifoliate leaf; V2 and beyond, from two unfolded trifoliate leaves until the canopy closed.

were cultivated weekly (interrow) until canopy closure. The study was organized in a randomized complete block design with four replicates. Plots consisted of six rows of dry beans 21.3 m long, spaced 76 cm apart.

Four days after planting, prior to dry bean emergence, the first weed control treatments were implemented. The same flamer was used as described previously. The tractor speed for flaming was 6.4 km h^{-1} and the propane pressure was set to 207 kPa, providing an estimated propane dose of 25 kg ha^{-1}. The rotary hoe used was a 4.56-m single-unit model built by Yetter (Colchester, IL). The tractor speed for rotary hoeing was 14 to 16 km h^{-1}.

Weed densities and dry bean populations were measured after all early-season treatments were complete, and again 1 mo following the last interrow cultivation. Weed densities were determined by setting up three permanent weed sampling stations in each plot. Each sampling station was 15 cm wide by 72 cm long, centered on the bean row. Dry bean populations were recorded at each weed sampling time by counting the number of plants in 6.1 m of row. Dry bean populations and yields were recorded at harvest. Two dry bean rows 6.1 m in length were harvested by hand and threshed using a stationary thresher. Yields were adjusted to 18% moisture.

Rotary Hoeing by GDD. To examine the effect of timing rotary hoe operations based on GDD $\{(temp_{max} + temp_{min})/2] - temp_{base}\}$, a field experiment was conducted at the Michigan State University Agronomy Farm in East Lansing, MI, from 2007 to 2009. On May 29, 2007, and May 28, 2008, following final seedbed preparation with a soil finisher, soybean ('Pioneer 91M91′, Pioneer Hi-Bred International Inc., Johnston, IA) were planted at 494,210 seeds ha^{-1} and on May 28, 2008, and June 12, 2009, Jaguar black beans were planted at a population of 296,500 seeds ha^{-1}. The rotary hoe timing treatments were as follows: every 7 calendar days, every 150 GDD (± 25), and every 300 GDD (± 50). GDD were calculated with a base of 3.3 C using data from the Enviro-weather station (Enviro-weather, Web site: http://www.enviroweather.msu.edu) located at the Hancock Turf Center, 0.5 km from the research site. The rotary hoe used was a 3-m single-unit model built by Case International (Racine, WI). The tractor speed for rotary hoeing was 14 to 16 km h^{-1}. In addition to these treatments there were weed-free and nontreated controls. The weed-free treatments were main-

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Table 3. Broadleaf weed species susceptibility to flaming for objective 1: flaming time of day.

Weed species	2007 Density at flaming	2007 Height at flaming[a]	2007 Density reduction 6 DAF[b,c]	2008 Density at flaming	2008 Height at flaming	2008 Density reduction 6 DAF
	plants m^{-2}	cm	%	plants m^{-2}	cm	%
Velvetleaf	5	3	97	2	2	100
Redroot pigweed	5	5	87	6	2	87
Common ragweed	—	—	—	10	2	64
Common lambsquarters	10	3	99	52	1	95
Common purslane	12	1	63	3	0.5	33
Red clover	—	—	—	11	1	81
LSD (0.05)			14			34

[a] Maximum height of weed species at the time of flaming.

[b] Abbreviation: DAF, days after flaming.

[c] Densities were recorded in permanent quadrats immediately before flaming and again 6 DAF and are averaged across all flaming time of day treatments.

tained using PRE and POST herbicide applications in both crops. Once the beans had two trifoliates (V2 stage) all plots were cultivated (interrow) uniformly once a week until canopy closure (three times total). Each plot consisted of four 61-m-long rows spaced 76 cm apart. Plots were arranged in a randomized complete block design with four replicates.

Weed densities were recorded, using three 1-m^2 quadrats placed over the center two rows, after the final rotary hoeing (i.e., beans had reached the V2 stage) and again after cultivations were complete (i.e., bean canopy closure). Also, bean populations were recorded at V2 in two 4.6-m-long rows per plot. Soybeans were harvested from the two center rows with a two-row plot combine and yields were adjusted to 13% moisture. Dry beans were harvested by hand from 4.6 m of the two center rows and threshed using a stationary thresher; yields were adjusted to 18% moisture.

For each of the three experiments, weed densities, crop population, and yield data (no yield data for objective 1) were subject to analysis of variance and mean separation with Fisher's Protected LSD ($p < 0.05$) using Proc Mixed in SAS version 9.2 (SAS Institute, Cary, NC). In the event of interactions across years data were analyzed separately. In most cases weed densities were combined across species into broadleaves or grasses due to site-year variability in species present.

Results and Discussion

Flaming Based on Time of Day. Grass and broadleaf weeds responded differently to the time of day when they were flamed. In both years the dominate grass species present at the time of flaming were large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and giant foxtail (173 plants m^{-2} in 2007 and 148 plants m^{-2} in 2008). Common purslane (*Portulaca oleracea* L.), common lambsquarters, redroot pigweed, and velvetleaf (*Abutilon theophrasti* Medik.) were the dominant broadleaf species in 2007; and in 2008 red clover (*Trifolium pratense* L.) and common ragweed (*Ambrosia artemisiifolia* L.) were also present (broadleaf weed densities are listed in Table 3). Grass weed densities were not affected by flaming 6 d after flaming (DAF), regardless of the treatment time (Table 4). Grasses exhibited some necrosis but the growing point was not affected. In most cases grass emergence appeared to be stimulated by flaming when evaluated 6 DAF (Table 4). However, 1 mo after flaming (MAF), grass densities in flamed treatments were similar to those in the rotary hoe treatment, with the exception of the 8:00 A.M. timing in 2008 which had fewer grasses than the rotary hoe treatment (Table 4). Other studies have also shown poor grass control (Ulloa et al. 2010a,c; Wszelaki et al. 2007) and an increase in grass weed densities after flaming (Cisneros and Zandstra 2008). Several factors may account for this phenomenon, including increased seed germination, or reduced seed dormancy, due to exposure to high temperatures or increased sunlight reaching the soil surface after other weeds are killed (Ascard 1995).

Flaming in the early morning (8:00 A.M.), at noon (12:00 P.M.), or in the midafternoon (4:00 P.M.) reduced the total number of broadleaf weeds by 82% or more 6 DAF (Table 4). Flaming in the evening is a common practice as it is much easier to see when a propane burner goes out (Parish et al. 1997). However, flaming in the evening (8:00 P.M.) reduced broadleaf weed density by only 58% 6 DAF and it did not appear to be the result of a particular temperature or relative humidity (Tables 1 and 4). One MAF broadleaf weed

Table 4. Reduction in weeds 6 DAF[a] and weed density 1 MAF when weeds were flamed at different times of day for objective 1: flaming time of day.

Time 24 h	6 DAF Broadleaves	6 DAF Grasses	1 MAF Broadleaves	1 MAF Grasses[b] 2007	1 MAF Grasses[b] 2008
	— % reduction[c,d] —		——— weeds m^{-1} ———		
8:00 A.M.	91	−3	11	54	19
12:00 P.M.	87	−5	4	58	41
4:00 P.M.	82	−32	8	33	70
8:00 P.M.	58	1	12	66	37
Rotary hoe	—	—	15	43	66
Cultivated only	—	—	39	34	104
LSD (0.05)	19	NS	15	NS	41

[a] Abbreviations: DAF, days after flaming; MAF, month after flaming.

[b] Because of a treatment-by-year interaction data are presented by year.

[c] Densities were recorded in permanent quadrats immediately before flaming and again 6 DAF.

[d] Negative numbers indicate an increase in weed densities.

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Table 5. Weed densities, dry bean populations, and yields compared among five early-season weed control treatments for objective 2: flaming vs. rotary hoeing.

Treatment[a,b]	Weed density			Dry bean population		
		After cult[c]				
	After EST	2009	2010	After EST	After cult[d]	Yield
	weeds m^{-2}			plants ha^{-1}		kg ha^{-1}
Flame (1×)	254	11	71	163,000	133,000	3,760
Flame (2×)	169	25	175	93,000	68,000	1,960
Flame (1×) + Rotary hoe (2×)	17	3	15	165,000	124,000	4,810
Rotary hoe (3×)	15	1	17	162,000	123,000	4,440
Cultivation only	119	16	84	168,000	124,000	3,920
LSD (0.05)	155	11	36	17,000	18,000	700

[a] Abbreviations: EST, early-season weed control treatments; cult, cultivation; VC, cotyledons unfolded; VC-V1, between unfolded cotyledons and the first unfolded trifoliate leaf; V2, two unfolded trifoliate leaves.

[b] Treatments: flame (1×), flamed once prior to bean emergence; flame (2×), flamed prior to bean emergence and again at VC; fame (1×) + rotary hoe (2×), flamed PRE then rotary hoed at VC and again at VC-V1; rotary hoe (3×), rotary hoed PRE and at VC and VC-V1; cultivation only, no early-season weed control treatment. All treatments were cultivated uniformly from V2 until canopy closure.

[c] Because of a year by treatment interaction weed densities following cultivation are presented by year.

[d] One month after final interrow cultivation.

densities in the flamed treatments were similar to the rotary hoe treatment, and were lower in comparison with the cultivated-only treatment (Table 4). Dew was only present at the 8:00 A.M. flame timing (Table 1) and did not reduce flaming efficacy, contradictory to previous research (Parish et al. 1997). Furthermore, differences in flaming effectiveness were not explained by relative humidity and temperature since the greatest changes in relative humidity and temperature did not produce distinguishable weed control differences with the exception of improved annual grass control with propane flaming at 8:00 A.M. in 2008. Our findings regarding timing are consistent with those of Wszelaki et al. (2007), who found flaming in the morning (10:30 A.M.) to be more effective than the evening (5:00 P.M.) in cabbage (*Brassica oleracea* L.) and tomato [*Lycopersicon lycopersium* (L.) H. Karst.]. Recently, results from Ulloa et al. (2012) stated that larger weeds, five-leaf velvetleaf and six-leaf green foxtail [*Setaria viridis* (L.) Beauv.], are most susceptible to flaming in the afternoon under greenhouse conditions. They found that 90% control was achieved 7 DAF at timings of 3:00 P.M. and 4:00 P.M. for velvetleaf and green foxtail, respectively (29 kg ha^{-1} propane dose). Weeds have also been shown to be more susceptible to a midday herbicide application (Mohr et al. 2007; Stewart et al. 2009). Andersen and Koukkari (1979) found leaf orientation of different broadleaf species varied throughout the day. This suggests that optimum weed control timing using herbicides would also be species dependent as the timing of maximum leaf exposure would differ. However, the orientation of leaves due to time of day may be less important when propane flamers are used compared with herbicides, because the growing point of broadleaf weeds would be exposed to the propane flame, regardless of leaf orientation. Ulloa et al. (2012) have suggested that sensitivity to flaming may be related to the relative water content of the leaves, with lower relative water content leading to increased injury from flaming.

Regardless of flaming time of day, common purslane was more difficult to control than common lambsquarters, redroot pigweed, and velvetleaf 6 DAF in both 2007 and 2008. In 2008, when common ragweed was present, it was present in 2008, it was more difficult to control than velvetleaf (Table 3). This supports previous research by Wszelaki et al. (2007), in which succulent weeds such as common purslane were more difficult to control than other broadleaf weeds.

Flaming vs. Rotary Hoeing. At the time of the initial weed control treatments (before bean emergence), the dominant weed species present were annual grasses (giant foxtail and large crabgrass) at 8.6 and 9.5 plants m^{-2} for 2009 and 2010, respectively; redroot pigweed (1.8 and 0.5 plants m^{-2} for 2009 and 2010, respectively); velvetleaf (0.6 plants m^{-2} for 2009 only); and common lambsquarters (2.5 plants m^{-2} for 2010 only). In 2009 and 2010, the flaming plus rotary hoeing–twice treatment and the three-pass rotary hoeing treatment resulted in the fewest weeds, both after early-season treatments and 1 mo after cultivation, and the highest yields (Table 5). Weeds remaining in the flaming-only and cultivation-only treatments were predominantly giant foxtail and large crabgrass (data not shown). Black beans were not tolerant of propane flaming following emergence, resulting in bean population and yield reductions of 45 and 53%, respectively, compared with the average of all other treatments (Table 5). Using water shields or placing metal shields over the row to protect the black bean growing points would reduce crop injury, but also weed control, in the row (Diver 2002; Parish et al. 1997). Black bean yields in the flaming plus rotary hoeing–twice and the rotary hoeing–three times treatments were not significantly different (Table 5), and

Table 6. Weed densities in the untreated plots immediately prior to cultivation for objective 3: rotary hoeing by growing degree days.

Crop	Year	Giant foxtail	Powell amaranth	Common lambsquarters	Common purslane
		weeds m^{-2}			
Soybean	2007	24.1	15.5	8.4	51.8
	2008	3.4	10.1	3.0	2.6
Dry bean	2008	258.0	183.7	8.7	141.7
	2009	156.6	280.1	5.3	68.7

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Table 7. Weed density and bean yields for rotary hoe timing treatments based on GDD[a] for objective 3: rotary hoeing by GDD.

				Soybean			Dry bean			
	Number of rotary hoe passes			Weed density[c]	Yield		Weed density		Yield	
Rotary hoe timing	2007	2008	2009	2007 and 2008	2007	2008	2008	2009	2008	2009
				weeds m^{-2}	— kg ha^{-1} —		— weeds m^{-2} —		— kg ha^{-1} —	
150 GDD	4	4	4	7	3,568	1,352	12	15	2,643	2,066
300 GDD	3	2	2	15	3,435	1,191	19	22	2,388	2,888
7 days	3	3	3	15	3,294	1,325	24	25	2,141	1,902
Cult only[b]	—	—	—	35	3,122	493	89	35	733	2,263
Weed free	—	—	—	1	3,098	2,334	0	1	3,746	3,700
LSD (0.05)				7	NS	503	18	12	1,005	1,073

[a] Abbreviations: GDD, growing degree days; cult, cultivation.

[b] Cult only, interrow cultivated only (i.e., no early-season weed control before beans reached two fully expanded trifoliates).

[c] Weed densities were measured 2 wk after the final cultivation.

although flaming did effectively control weeds when used in combination with rotary hoeing it would not be as economical as rotary hoeing three times and not flaming (Taylor et al. 2008). However, having the option of using a propane flamer could provide an economic benefit to organic growers in the event that wet weather prevented timely mechanical weed control measures and hand labor for weeding was in short supply.

Rotary Hoeing by GDD. Prior to cultivation in all years for both soybean and dry bean, the dominant weed species were giant foxtail, Powell amaranth (*Amaranthus powellii* S. Wats.), common lambsquarters, and common purslane (Table 6). The number of rotary hoe passes for the 7-d treatment and the 150- and 300-GDD treatments ranged from two to four passes during the first 3 wk following planting (Table 7). Timing rotary hoeing every 150 GDD provided weed control similar to the weed-free treatment in both soybean and dry bean before and after cultivation, with one exception after cultivation in the 2009 dry beans. Timing rotary hoeing every 7 d or every 300 GDD provided weed control similar to the weed-free treatment in 1 of 2 yr for both soybean and dry bean before cultivation (data not shown), but not after (Table 7). When comparing among the three timing treatments, weed densities did not differ, with the exception of the 150-GDD treatment providing better weed control 2 wk after final cultivation in soybean. All rotary hoe timing treatments had significantly less weeds than the cultivated-only treatments at both V2 and canopy closure for both crops. These findings are consistent with those of Amador-Ramirez et al. (2002), who found that weed densities were 44% lower in plots that were rotary hoed followed by cultivation, compared with plots that were cultivated only in 1 of 2 yr in Nebraska.

Soybean populations (284,000 plants ha^{-1}) were not affected by the early-season weed management operations. However, rotary hoeing, regardless of the frequency, reduced dry bean populations by an average of 20% (209,000 plants ha^{-1}) when compared with the weed-free and untreated treatments (260,000 plants ha^{-1}). There were no differences in soybean or dry bean yield among the rotary hoe timing treatments (Table 7). For both soybean and dry bean, the cultivated-only treatment yielded lower than all other treatments in 1 of 2 yr. One way to assess differences in weed pressure between site years is to determine the competitive load, which provides an assessment of the competitiveness of the weed population in the field, based on weed species and weed density (Wilkerson et al. 1991). In both crops, the competitive load following all weed management was three times higher in 2008 than in the other years. Reduced competitive load in the 2007 soybean and 2009 dry bean seasons may have prevented yield differences among the weed control treatments (Hock et al. 2006; Sprague et al. 2006). In 2008, the weed-free treatment in soybean and dry bean had a higher yield compared with all other treatments; in 2009, dry bean yield was similar in the weed-free and 300-GDD (two rotary hoeing) treatments.

By timing rotary hoeing every 300 GDD throughout the early growing season we were able to reduce the frequency of rotary hoeing during periods of cool weather when weed seed germination and seedling emergence were slower. The reduced number of passes in the 300-GDD treatment may be what led to yields similar to the weed-free treatment in 1 of 2 yr for both soybean and dry bean. This is a similar finding to microrate herbicide applications in sugarbeet (*Beta vulgaris* L.), where timing of the first and sequential applications at 152 GDD (base 1.1 C) reduced unnecessary herbicide applications and crop injury during cool weather (Dale and Renner 2005).

In summation, considering this research and that of Ulloa et al. 2012, the best results for weed management and reduced crop injury occur when flaming is in the afternoon as opposed to the evening. Flaming could replace a rotary hoeing early in the growing season (PRE for dry beans) when followed by two subsequent rotary hoeings. However, in the absence of wet soils, utilizing a rotary hoe alone for early-season weed management appears to be effective and the most economical choice. Efficiency with a rotary hoe (i.e., achieving acceptable weed control while reducing labor and fuel costs) is further increased by timing passes every 300 GDD from the time of planting until plants are large enough to cultivate.

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Literature Cited

Amador-Ramirez, M. D., R. G. Wilson, and A. R. Martin. 2002. Effect of in-row cultivation, herbicides, and dry bean canopy on weed seedling emergence. Weed Sci. 50:370–377.

Andersen, R. N. and W. L. Koukkari. 1979. Rhythmic leaf movements of some common weeds. Weed Sci. 27:401–415.

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 developmental stages. Weed Res. 35:397–411.

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

Buhler, D. D., J. L. Gunsolus, and D. F. Ralston. 1992. Integrated weed management techniques to reduce herbicide inputs in soybean. Agron. J. 84:973–978.

Burnside, O. C., W. H. Ahrens, B. J. Holder, M. J. Wiens, M. M. Johnson, and E. A. Ristau. 1994. Efficacy and economics of various mechanical plus chemical weed control systems in dry beans (*Phaseolus vulgaris*). Weed Technol. 8:238–244.

Burnside, O. C., N. H. Krause, J. J. Wiens, M. M. Johnson, and E. A. Ristau. 1993. Alternative weed management systems for the production of kidney beans (*Phaseolus vulgaris*). Weed Technol. 7:940–945.

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

Corp, M. K., S. Machado, L. Pritchard, and C. Luttrell. 2010. Weed Control in Organic Small Grains Production. Oregon State University Extension Service: Organic Dry Land Small Grains Fact Sheet 1002. http://extension.oregonstate.edu/umatilla/sites/default/files/100726_organic_small_grains_weed_control_0.pdf. Accessed: May 2, 2012.

Cramer, C. 1990. Turbocharge your cultivator: flame weeding is cheap, effective—and safe. The New Farm by The Rodale Institute. 12:27–35.

Dale, T. M. and K. A. Renner. 2005. Timing of postemergence micro-rate applications based on growing degree days in sugar beet. J. Sugar Beet Res. 42:87–100.

Diver, S. 2002. Flame Weeding for Vegetable Crops. ATTRA-National Sustainable Agriculture Information Service. https://attra.ncat.org/attra-pub/summaries/summary.php?pub=110. Accessed: May 1, 2012.

Frye, D. L. 2011. Management Challenges of Running Parallel Organic and Conventional Systems. http://www.soils.wisc.edu/extension/wcmc/proc/2011_wcmc_proc.pdf#page=193. Accessed on: May 2, 2012.

Heiniger, R. W. 1998. Controlling weeds in organic crops through the use of flame weeders. Organic Farming Research Foundation Final Project Report. http://ofrf.org/funded/reports/heiniger_94-43.pdf. Accessed: October 21, 2011.

Hock, S. M., S. Z. Knezevic, and A. R. Martin. 2006. Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. Weed Sci. 54:38–46.

Johnson, W. C. III, and B. G. Mullinix, Jr. 2008. Potential weed management systems for organic peanut production. Peanut Sci. 35:67–72.

Kluchinski, D. and J. W. Singer. 2005. Evaluation of Weed Control Strategies in Organic Soybean Production. Plant Management Network. http://www.plantmanagementnetwork.org/pub/cm/research/2005/organic/. Accessed: May 1, 2012.

Knezevic, S. Z. and S. M. Ulloa. 2007. Flaming: potential new tool for weed control in organically grown agronomic crops. J. Agr. Sci. 52:95–104.

Leblanc, M. L. and D. C. Cloutier. 2001a. Susceptibility of dry edible bean (*Phaseolus vulgaris*, cranberry bean) to the rotary hoe. Weed Technol. 15:224–228.

Leblanc, M. L. and D. C. Cloutier. 2001b. Susceptibility of row-planted soybean (*Glycine max*) to the rotary hoe. J. Sustain. Agr. 18:53–61.

Lovely, W. G., C. R. Weber, and D. W. Staniforth. 1958. Effectiveness of the rotary hoe for weed control in soybeans. Agron. J. 50:621–625.

Mohler, C. L., J. C. Frisch, and J. Mt. Pleasant. 1997. Evaluation of mechanical weed management programs for corn (*Zea mays*). Weed Technol. 11:123–131.

Mohr, K., B. A. Sellers, and R. J. Smeda. 2007. Application time of day influences glyphosate efficacy. Weed Technol. 21:7–13.

Parish, R. L., W. C. Porter, and P. R. Vidrine. 1997. Flame cultivation as a complement to mechanical and herbicidal control of weeds. J. Veg. Crop Prod. 3:65–83.

Peters, E. J., D. L. Klingman, and R. E. Larson. 1959. Rotary hoeing in combination with herbicides and other cultivations for weed control in soybeans. Weeds 7:449–458.

Pullen, D.W.M. and P. A. Cowell. 1997. An evaluation of the performance of mechanical weeding mechanisms for use in high speed inter-row weeding of arable crops. J. Agr. Eng. Res. 67:27–34.

Renner, K. A. and J. J. Woods. 1999. Influence of cultural practices on weed management in soybean. J. Prod. Agric. 12:48–53.

Sprague, C. L., J. J. Kells, and K. Schirmacher. 2006. WeedSOFT® 2006. Weed Management Support System. Michigan Version 11.0.

Steinmaus, S. J., T. S. Prather, and J. S. Holt. 2000. Estimation of base temperatures for nine weed species. J. Exp. Bot. 51:275–286.

Stewart, C. L., R. E. Nurse, and P. H. Sikkema. 2009. Time of day impacts postemergence weed control in corn. Weed Technol. 23:346–355.

Taylor, E., K. Renner, and C. Sprague. 2008. Integrated Weed Management: Fine Tuning the System. East Lansing, MI.: Michigan State University Extension Bulletin E-3065. 132p.

Ulloa, S. M., A. Datta, and S. Z. Knezevic. 2010a. Tolerance of selected weed species to broadcast flaming at different growth stages. Crop Prot. 29:1381–1388.

Ulloa, S. M., A. Datta, G. Malidza, R. Leskovsek, and S. Knezevic. 2010b. Yield and yield components of soybean [*Glycine max* (L.) Merr.] are influenced by the timing of broadcast flaming. Field Crop. Res. 119:348–354.

Ulloa, S. M., A. Datta, and S. Z. Knezevic. 2010c. Growth stage-influenced differential response of foxtail and pigweed species to broadcast flaming. Weed Technol. 24:319–325.

Ulloa, S. M., A. Datta, C. Bruening, G. Gogos, T. J. Arkebauer, and S. Z. Knezevic. 2012. Weed control and crop tolerance to propane flaming as influenced by the time of day. Crop Prot. 31:1–7.

[USDA-ERS] U.S. Department of Agriculture–Economic Research Service. 2009. Organic Agriculture: Organic Market Overview. http://www.ers.usda.gov/briefing/organic/demand.htm. Accessed: October 21, 2011.

VanGessel, M. J., L. J. Wiles, E. E. Schweizer, and P. Westra. 1995. Weed control efficacy and pinto bean (*Phaseolus vulgaris*) tolerance to early season mechanical weeding. Weed Technol. 9:531–534.

VanGessel, J. J., E. E. Schweizer, R. G. Wilson, L. J. Wiles, and P. Westra. 1998. Impact of timing and frequency of in-row cultivation for weed control in dry bean (*Phaseolus vulgaris*). Weed Technol. 12:548–553.

Wilkerson, G. G., S. A. Modena, and H. D. Coble. 1991. HERB: decision model for postemergence weed control in soybean. Agron. J. 83:413–417.

Willer, H. and L. Kilcher, eds.2011. The Work of Organic Agriculture—Statistics and Emerging Trends 2011. Bonn, Germany, and Frick, Switzerland: International Federation of Organic Agriculture Movements and Research Institute of Organic Agriculture. 286 p.

Wszelaki, A. L., D. J. Doohan, and A. Alexandrou. 2007. Weed control and crop quality in cabbage (*Brassica oleracea* (capitata group)) and tomato (*Lycopersican lycopersicum*) using a propane flamer. Crop Prot. 26:134–144.

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