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DESIGN AND FIELD TESTING OF A COMBINED FLAMING AND CULTIVATION IMPLEMENT FOR EFFECTIVE WEED CONTROL

B. D. Neilson, C. A. Bruening, S. Stepanovic, A. Datta, S. Knezevic, G. Gogos

ABSTRACT. *Flaming is a thermal weed control method that uses heat to control weeds within or between crop rows. Mechanical cultivation is another weed control method which undercuts weeds between crop rows, while leaving a strip of weeds within the crop row. A combination flamer/cultivator implement was designed to take advantage of the good qualities of both flaming and cultivation methods to provide a more consistent weed control than using either flaming or mechanical cultivation alone. Flaming hoods were designed in the spring of 2010 and retrofitted on an existing row crop cultivator. The flaming hoods were redesigned in the spring of 2011 for easier manufacturing. They were tested in field studies in corn (*Zea mays *L.*) and soybean [*Glycine max *(L.) Merr.] during the summers of 2010 and 2011. Of the seven treatments tested, a treatment of flaming combined with cultivation applied twice during a season produced the highest weed control and crop yield, while maintaining low crop injury and weed dry matter.*

Keywords. Cultivation, Cultivators, Flame cultivators, Organic farming, Weed control.

Controlling weeds using flaming dates back over a century and a half to 1852 when John A. Craig of Arkansas patented and used a flaming machine (Edwards, 1964). Several patents were granted in the early and mid-1940's on schemes of flaming (Edwards, 1964). By the early 1940's, flaming had begun to be used in cotton and other crops (Edwards, 1964). The first hooded burner designed to flame the crop inter-row space came in 1962 (Edwards, 1964). By 1963, there were at least 20 states in which some research was being done by public and private research groups (Edwards, 1964). In 1964, an estimated 15,000 row crop flamers were in use.

The tractor-mounted cultivator was developed in the early 1920's (Timmons, 2005). Flaming was combined with cultivation as early as 1900, when S. B. Jones of Illinois was granted a patent for an attachment to be mounted on a one-row cultivator (Edwards, 1964). It consisted of a fuel tank and two burners, one on each side of the row. The principal use of this machine was for insect control (Edwards, 1964).

The number of herbicides in general use in the United States and Canada increased from 15 in 1940 to 25 in 1950, and to 100 in 1969 (Timmons, 2005). Seifert and Snipes (1996) and Laguë et al. (1997) suggested that flaming use declined in the 1970s due to both rising LPG prices and the widespread introduction of efficient, less expensive herbicides. Concerns due to the environmental effects of herbicides, higher worker protection standards, elevated herbicide prices, and the increased prevalence of herbicide-resistant weeds renewed interest in flaming practice (Seifert and Snipes, 1996).

CURRENT FLAMING AND CULTIVATION TECHNOLOGY

During flaming, the heat from the flame causes rupturing of the cell walls, which leads to water loss and plant death (Parish, 1990). Weeds are not ignited during a flaming treatment. Thomas (1964) states that exposure times between 0.065 and 0.130 s were sufficient to control weeds. The temperature Thomas used was believed to be between 800°C and 900°C (Kang, 2001).

Many successful studies have been conducted that used some sort of flaming technique to control weeds without herbicides. Netland et al. (1994) reported that two selective flame weeding treatments with 50 kg propane ha⁻¹ provided as good weed control in cabbage as two applications of propachlor herbicide. Mutch et al. (2008) also reported similar yields of organic corn (*Zea mays* L.) when using flaming or rotary hoe for weed control. Flaming also has an advantage over cultivation during springs when the fields are too wet for mechanical weeding. Although flamers can control weeds as well as or better than mechanical implements if properly designed, currently flamers are

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usually slower than chemical weed control (Ascard et al., 2007).

Flaming effectiveness varies with weed species. Weeds with protected growing points, such as grasses and perennials, are stunted by flaming but eventually recover (Wszelaki et al., 2007). Ulloa et al. (2010a) also reported that foxtail species were more tolerant to flaming, in general, than pigweed species. However, large broadleaf species, such as smooth pigweed (*Amaranthus hybridus* L.), are the bigger threat to crop productivity, as they were shown to be more competitive in general than most grasses and smaller broadleaf weeds, in crops such as peanut (*Arachis hypogaea* L.), soybean [(*Glycine max* (L.) Merr.], and corn (Canner et al., 2002).

Flaming torches can either be oriented to direct flames at an angle to the crop row, known as cross-flaming, or parallel to the row. The main disadvantages of cross-flaming are that it only provides weed control in the intra-row space (Stepanovic, 2013), and it is not compatible with hooded torches. Ascard (1995) reported hooded torches to be 40% more energy-efficient than open torches, while Bruening (2009) reported hooded torches to be 50% more energy-efficient than open torches. Carter et al. (1960) reported that vertical or sloping ridges on the sides of the crop row, created by tillage, have an adverse effect when the torches are set up in the cross-flaming orientation; the flame is deflected upward by the ridge, thus increasing crop injury and reducing effectiveness of weed control. Raffaelli et al. (2013) used a self-propelled flaming machine in their study that can be adjusted for either parallel or cross-flaming.

In addition to increasing the energy efficiency of a flaming operation, hoods also provide safety and more consistent treatments. The hoods provide safety by keeping the flames and heat down on the ground and away from the tractor operator. The hoods provide more consistent treatments by blocking much of the effect of wind during a treatment. Storeheier (1994) suggested that hooded torches are far more effective than open ones and reported that torches under a shield are more tolerant to variations in torch angle with the ground.

The key dimensions of the Bruening hood (2009) are explained in figure 1. The overall length, d1, was 120 cm. Bruening (2009) reported that the length of the secondary treatment zone, d4, must be at least 13.4 cm long when driving 4.8 km h^{-1} to satisfy the exposure time benchmark of 800°C for 0.1 s recommended by Thomas (1964). The secondary treatment zone length, d4, was 89 cm on this hood (not to scale). The hood width (into the page) was 30.5 cm. The horizontal distance from the torch housing to the hood inlet, d3, was 15 cm. It was optimized so that the combustion characteristics of the open torch and flame shape remain unaffected, yet all the hot gases still entered the hood (Bruening, 2009). The height of the hood at its inlet was 30 cm, with a 30° sloping section, and leveled off at an 11.4 cm outlet height, d2. This design was consistent with the recommendations of Storeheier (1994), who reported the optimum shield height to be 10 cm, and that a backwards-sloping shield keeps sufficient oxygen supply up front while forcing hot gases downwards at the rear end.

Row crop cultivators work by cutting weeds at the soil surface and displacing soil towards the crop row to cover weeds close to the crop. Jones et al. (1995) reported that burial to 1 cm depth and cutting weeds at the surface to be most effective. Gunsolus (1990) reported that standard row crop cultivators are most effective on weeds that are 15 cm tall or less.

COMBINING FLAMING AND CULTIVATION

Traditional mechanical cultivation methods control weeds satisfactorily in the inter-row space, but a strip of weeds remains within the crop row after cultivation. Schweizer et al. (1994) said that if herbicide use is to be reduced, better methods of in-row cultivation must be developed. The weeds nearest the crop row present the greatest challenge in mechanical cultivation, as they directly influence crop performance (Mulder and Doll, 1993).

Flaming has the potential to remove weeds within the crop row without significantly damaging the crop. Wszelaki et al. (2007) proposed that "combining flaming with mechanical cultivation and hand-weeding may be an effective integration to optimize weed control."
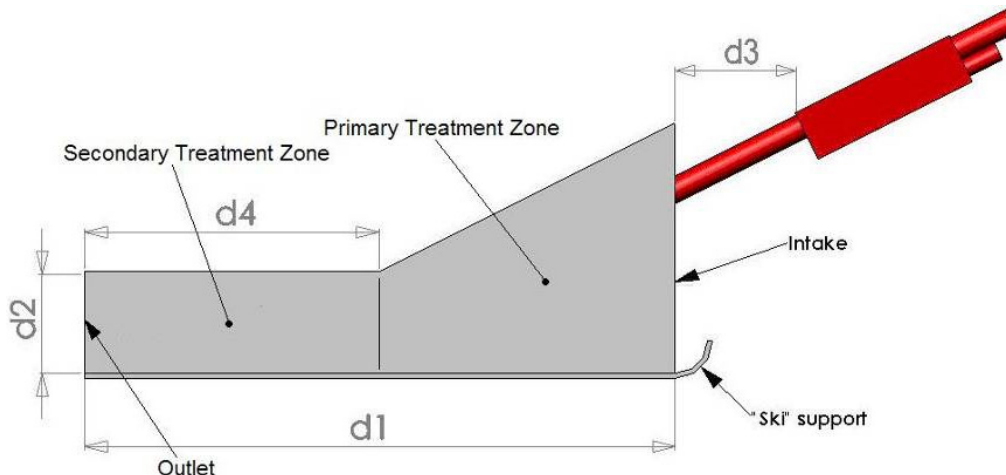

Figure 1. Key dimensions of flaming hood used in Bruening (2009) field studies.
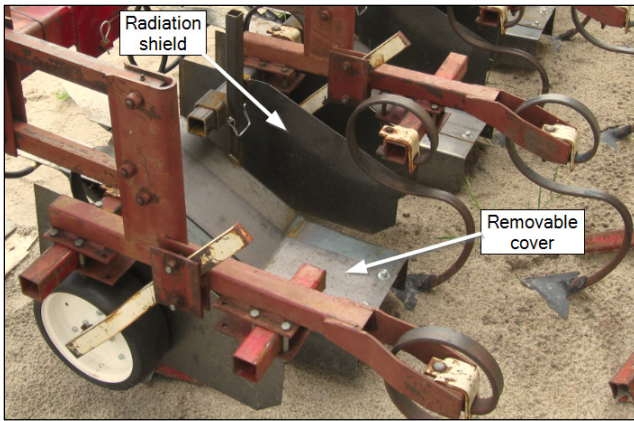
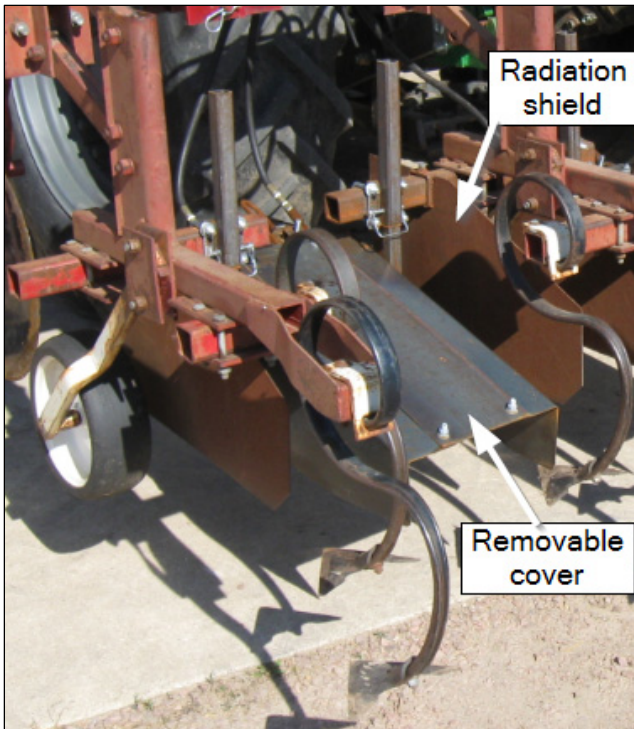**Figure 2. Flamer/cultivator Prototype 1, used in the 2010 field studies.**

Figure 3. Flamer/cultivator Prototype 2, used in the 2011 field studies.

OBJECTIVE

The objective of this work was to design a combination flamer/cultivator (figs. 2 and 3) and validate its effective- ness in weed control through field studies. Such an implement could provide better organic weed control than either flaming or mechanical cultivation alone, with lower propane usage than flaming the entire row width (full flaming). Treatments with full flaming alone (using a full flamer implement) and cultivation alone were included in these field studies to validate this hypothesis.

MATERIALS AND METHODS
DESIGN OF FLAMER/CULTIVATOR PROTOTYPE 1

Flaming needs to be the first operation applied to the weeds, before the cultivator sweeps pass through. If the cultivation was conducted before flaming, the weeds would be partially covered by soil, thus insulated from the heat produced by the torches. The weeds could then grow back through the loose soil, making the treatment less effective. Two flamer/cultivator prototypes are discussed in this article. Prototype 1 was utilized for the 2010 field studies, and Prototype 2 was utilized for the 2011 field studies.

A Noble™ brand Row-Runner model cultivator (Gibbsville Implement Inc., Waldo, Wisconsin, USA) was utilized in this project. The cultivator originally had five narrow sweeps per gang (fig. 4). It was fitted with new 191 mm wide sweeps, three per gang (fig. 5).

The operating depth of the cultivator sweeps was approximately 2.5 cm, as recommended by Bowman (2002). Increasing the working depth does little to improve weed kill (Bond and Grundy, 2001). The Noble™ cultivator was a four-row model, and was set up for a row width of 76 cm.

Torches

The torches were 7.6 cm wide cylindrical LT 3-12 T torches purchased from Flame Engineering, Inc. (Flame Engineering, 2012). The torches were at a 30° angle with the ground, parallel to the slope of the hood. This fell within the 22.5°-45° range recommended by Storeheier (1994), who also mentioned that torch angle does significantly influence performance for cylindrical torches when used without a hood. The torches were spaced 7.6 cm from the crop row on Prototype 1. The propane flow rates of these torches, as well as all other torches used, were characterized at different
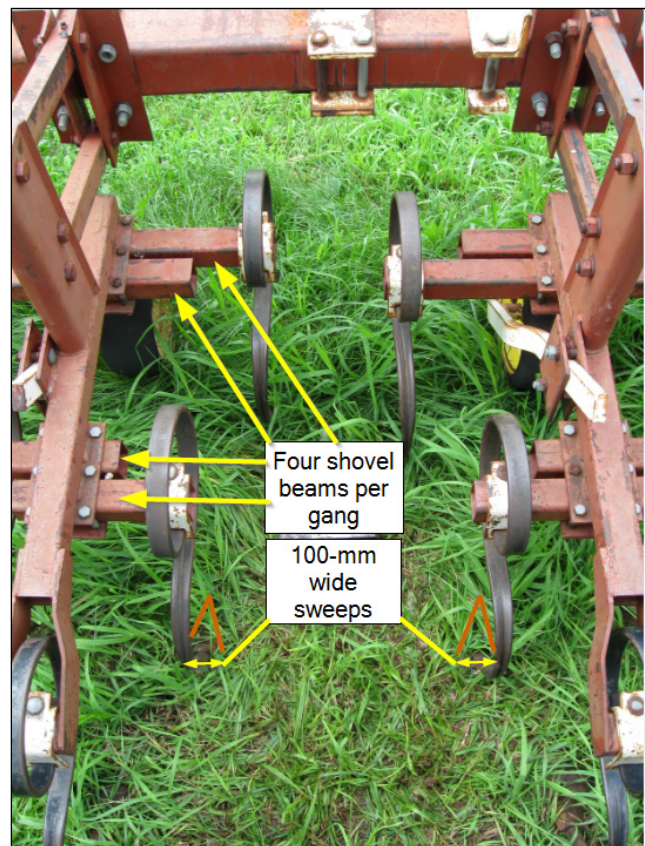

Figure 4. Two cultivator gangs before modification, with five narrow sweeps per gang.
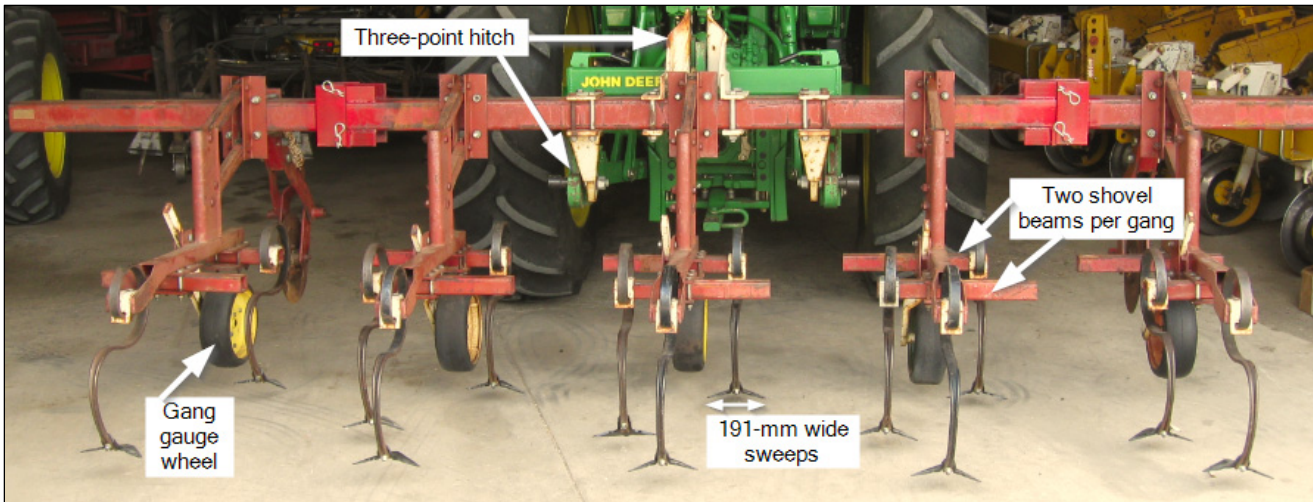
Figure 5. Modified row crop cultivator with three wide sweeps per gang.

operating pressures, using the propane tank on a scale and a stopwatch. For example, the cylindrical torch used an operating pressure of 103 kPa (gauge pressure) during the 2010 field studies, which provided a propane flow rate of 4.0 kg h^{-1}.

The tractor speed of the flamer/cultivator during the field studies was 4.8 km h^{-1}. Considering only the treated band width of 15 cm, the intra-row biological propane application rate of both flamer/cultivator prototypes was 52 kg ha^{-1}. However, in actual practice, a user of the flamer/cultivator would consider the propane used over the entire width of the row. Considering that two torches (together with the sweeps) provide weed control to an entire row that is 76 cm wide, or 38 cm per torch, then the effective propane application rate is 20 kg ha^{-1}. This effective propane application rate is the fraction 15/38 of the intra-row biological rate and is the rate that is used in subsequent discussion in this article.

Hood Design

The hood used on Prototype 1 was based on that of Bruening (2009) (fig. 1). The dimension d4 was changed from 89 cm to 28 cm, so the overall length d1 was 60 cm. The resulting hood was mounted on the cultivator (fig. 2). During final assembly, both of the sweeps were mounted on the rear shovel beam, near the hood outlet (fig. 6). Mounting one sweep on the forward shovel beam would have interfered with the hood and radiation shield (described later).

The hood mount, which slid back and forth on the shovel beams, allowed the hood position to be adjusted horizontally with a set-screw and vertically with a pin (fig. 7).

To allow the flamer/cultivator to be used on both early crop growth stages (VC for soybean, V3 for corn) and late growth stages (V5 for soybean, V7 for corn), the hood was designed as three separate parts: two side parts (fig. 6) and a removable cover (fig. 2). During late-season flaming, the crop was tall and needed to pass through an opening between the two side parts. Removing the cover created this opening. Each side part of the hood covered one torch and passed next to the crop row. During early-season flaming, the crop was either pre-emergent or slightly

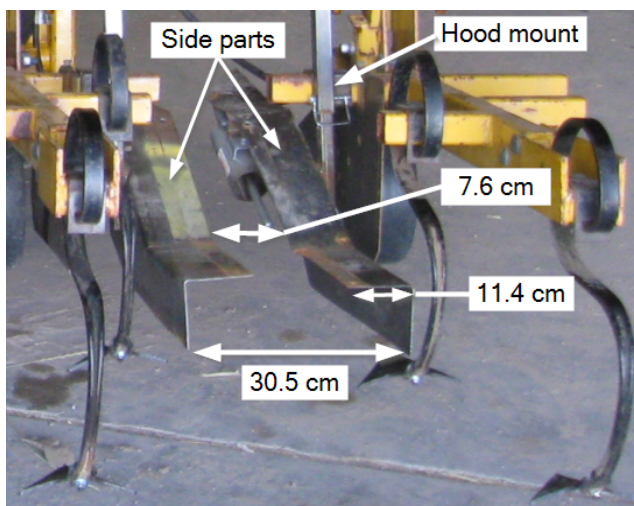**Figure 6. Prototype 1 hood assembly for late-season flaming, with a 7.6 cm gap between side parts for late growth stage crops.**
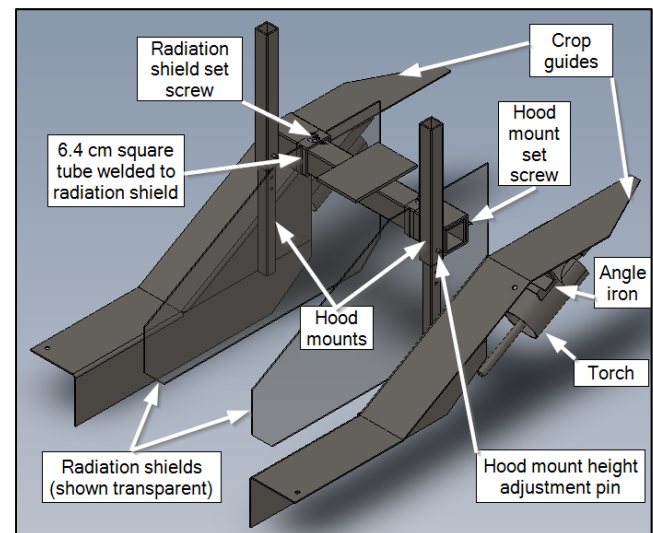

Figure 7. Rendering of two hood side parts and two radiation shields mounted on a cultivator gang shovel beam.

emerged. At this point, the entire hood could pass over the crop without knocking it down. Because Ascard (1995) and Bruening (2009) reported flaming with hoods to be 40% and 50% more energy-efficient, respectively, than open torches, the removable cover for full flaming was designed to enclose the two side parts of the hood. The gap between the hoods for late-season flaming was designed to be 7.6 cm (fig. 6). The shape of the side parts at their inlets were designed to guide the crop into the gap between the hoods and allow for the operator to drive at a moderate speed even with the narrow 7.6 cm gap (fig. 7). With a total hood width of 30.5 cm (fig. 6), each side part of the hood then had a width of 11.4 cm.

Radiation Shields

The highest hood temperature, found in subsequent lab measurements, was 645°C. This heat would transfer by radiation, potentially damaging the gauge wheels or their bearings. To prevent this failure mode, radiation shields were installed approximately midway between the hood and the gauge wheel. The shield was a sheet of steel welded to a piece of 6.4 cm square tube, able to slide back and forth like the hood mount (fig. 7). It was held in place by a set-screw. The shields can be seen hanging on the shovel beam between the hood mounts and the gauge wheels (fig. 2).

DESIGN OF FLAMER/CULTIVATOR PROTOTYPE 2

Prototype 1 was used during the 2010 field studies. During spring 2011, the flamer/cultivator hood and torch mounting system was redesigned to address shortcomings of the original design, ease of manufacture, and new torches which were also developed that spring.

New Torches

Prototype 1 had its LT 3-12 T torch bolted to a short length of angle iron under the crop guide (fig. 7). New torches were designed in 2011 by the authors at the University of Nebraska-Lincoln (UNL) for Prototype 2 (fig. 8). They were box-shaped, utilized a U-shaped vaporizer tube, and had one nozzle. A single LT 3-12 T torch, used on Prototype 1, had tandem nozzles (two total). To eliminate the angle iron used for fastening the torches on Prototype 1, the new torches had bolts welded to the side and were directly bolted to the side wall of the flamer/cultivator hood (fig. 9). These torches were spaced 10 cm from the crop row on Prototype 2. Due to a smaller nozzle orifice, this torch used a higher operating pressure of 172 kPa (gauge) to deliver the same propane flowrate as the LT 3-12 T torch used on Prototype 1.

U-bolt Mounting System and New Crop Guides

Prototype 1 had a set-screw holding the hood mount in place on the gangs. It was determined that these mounts were not secure enough for the high-vibration application and required periodic adjustments and tightening. Prototype 2 replaced the set-screws with two square U-bolts that more securely clamp each hood mount in place (fig. 9). The height adjustment uses the same pin as before.

Figure 8. New torch designed in 2011 for Prototype 2.

The crop guides on Prototype 1 (fig. 7) were flat pieces of sheet steel above each of the torches, parallel to the ground, which funneled the crop between the two side parts of the hood during flaming at late growth stages. There were two major problems with this design. First, the Prototype 1 crop guides extended 36.8 cm behind the hood inlet, sometimes interfering with the three-point hitch. Second, limited room between the top of the Prototype 1 torches and the crop guide made maintenance difficult, and the new torches designed in 2011 did not fit underneath the Prototype 1 crop guide. The crop guide design for Prototype 2 was a 6 mm thick steel strap that bends around the torch, making maintenance much easier (fig. 9). Also, the crop guide on Prototype 2 extends only 31.8 cm behind the hood inlet (fig. 10), decreasing the chance of interference with the three-point hitch.

Hood Improvements

The roof of the Prototype 1 hoods had two portions (fig. 2). One portion sloped down at a 30° angle from the
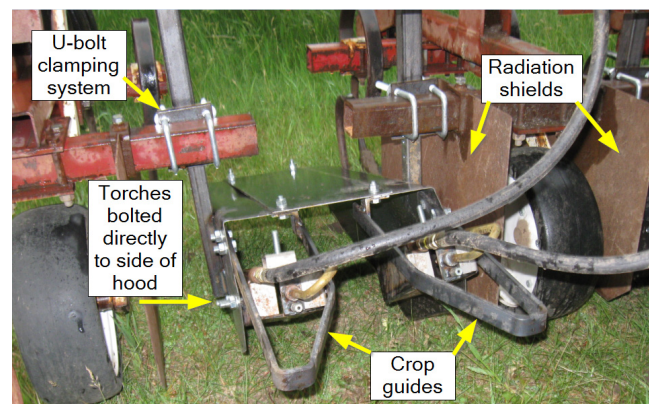

Figure 9. Prototype 2 flamer/cultivator hood and torch mounting system.
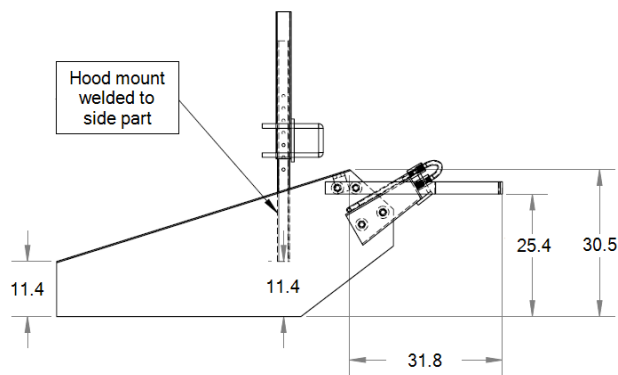
Figure 10. Side dimensions of Prototype 2 hood (units are in cm).

hood inlet, and the other was a horizontal portion at 11.4 cm above the bottom of the hood that led to the hood exit. The Prototype 2 hood design (fig. 10) had just one flat piece of sheet steel, and it sloped continuously from the top of the hood inlet, 30.5 cm from the bottom, to the hood exit, 11.4 cm from the bottom. Thus the new hood roof sloped at a 17° angle. Having one flat piece for the roof made manufacturing and assembly easier.

The Prototype 2 hoods each had a cover (fig. 11a) that could be removed during flaming at late growth stages (V7 for corn, V5 for soybean). The Prototype 1 hood design had a 7.6 cm gap, which was problematic when flaming on side hills; the crop always grows vertically and the hoods interfere with the crop due to a reduced effective gap. The new hood design had a wider gap of 10 cm (fig. 11b). The complete flamer/cultivator Prototype 2 is shown in figure 3.

DESIGN OF FULL FLAMER

The full flamer (fig. 12), another type of flaming implement previously designed by the authors at UNL, was used in the field studies. It has two torches per crop row, one on each side of the row, similar to the flamer/cultivator. The torch orientation is parallel to the crop row, as was discussed earlier. The weeds were exposed to the entire flame length in the direction of travel. The torches were spaced 19 cm from the crop row, farther from the crop row
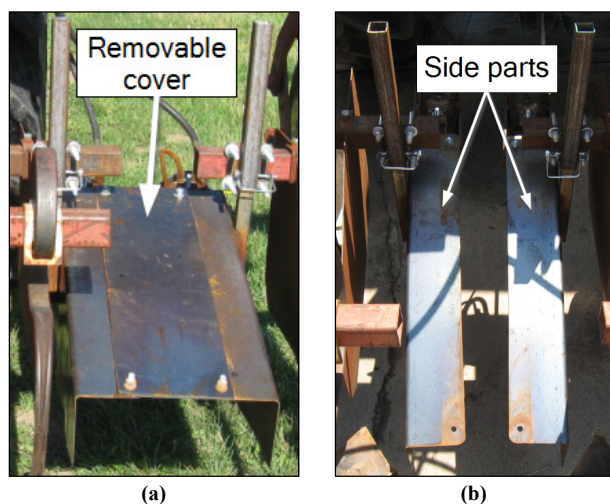

Figure 11. (a) New hood in early season setup. (b) New hood in late season setup.

than on the flamer/cultivator (7.6 cm on Prototype 1 and 10 cm on Prototype 2), because their flame coverage area was much wider. The torches were angled down 30°. In 2010, the torches used were the larger, cowbell-shaped LT 2×8 torches (Flame Engineering, 2012). For the 2011 study, new cowbell-shaped torches were developed at UNL incorporating new vaporizers and nozzles (Neilson, 2012). The larger hoods were closed for the early-growth-stage treatment (fig. 12a). The individual hoods slid left and right by 7.5 cm, and so could be opened to a 15 cm gap for the late-growth-stage treatments, allowing the tall crop to pass through (fig. 12b).

In 2010, it was determined that operation at 310 kPa (gauge pressure) provides a propane flow rate of 7.9 kg h^{-1}. The tractor speed of the full flamer during the field studies was 4.8 km h^{-1}. Considering that two torches cover an entire row width of 76 cm, then the effective propane application rate is 45 kg ha^{-1}. The new torches developed in 2011 use a higher operating pressure of 448 kPa to deliver the same propane application rate, due to a smaller nozzle orifice. Full flaming or flaming/cultivation treatments were not conducted for the field studies considered here if the wind was blowing more than 16 km h^{-1}.

FIELD STUDIES

Two similar field studies were conducted in organic corn and soybean during the summers of 2010 and 2011 to test the flamer/cultivator prototypes at the UNL Haskell Agricultural Laboratory in Concord, Nebraska (42°37′N, 96°68′W). The field preparations included one disking and one field cultivation. Corn was grown in rotation with soybean. Nitrogen fertilizer was applied at 123 kg ha^{-1} prior to planting. The organic corn hybrid was Blue River Hybrids 56M30, while the organic soybean hybrid was Blue River Hybrids 2612034 in 2010 and 56M30 in 2011. Information on the planting dates and rates, as well as treatment dates, can be found in table 1. The plots were 13.7 m long by 3.05 m wide consisting of four rows in each plot, at 0.76 m spacing. Different fields were used for the two years of the study.

The historical weather data recorded at Concord, Nebraska, during the years of the study are shown in table 2.

Corn Treatments

In corn, eight weed-control treatments were compared that involved cultivation, flaming, and a combination of the two, as well as weed-free and weedy-season-long control plots (table 3). The treatments were arranged in a randomized complete block design (RCBD) with four replications. The treatments were conducted either once or twice during a season, and were applied at either one or two particular growth stages (V3-V4 and V6-V7) of corn. Growth stages of corn were determined by counting the number of fully developed leaves that have a visible collar, e.g., V3: the collar of the third leaf is visible, and is designated as the 3-leaf stage (Ritchie et al., 2008). In the authors' experience in Nebraska, the number of cultivations per season varies widely among organic producers. Treatments with one or two applications per season were

Figure 12. Full flamer in the (a) early flaming setup and (b) late flaming setup.

Table 1. Planting and treatment information for the field studies.[a]

		Corn		
Year	Planting Date	Planting Rate (seeds ha^{-1})	V3-V4 Treatment Date	V6-V7 Treatment Date
2010	19 May	60,911	9 June	24 June
2011	1 June	63,449	19 June	4 July
		Soybean		
Year	Planting Date	Planting Rate (seeds ha^{-1})	VC Treatment Date	V4-V5 Treatment Date
2010	19 May	444,143	15 June	7 July
2011	11 June	368,187	19 June	18 July

[a] For corn, the growth stages listed represent the number of fully developed leaves (i.e., V3 = 3-leaf). For soybean, the VC growth stage represents unfolded cotyledons, and the others represent the number of trifoliate leaves (i.e., V4 = 4-trifoliate).

Table 2. Mean monthly temperature and rainfall recorded at Concord, Neb., during the growing seasons of 2010 and 2011.

	2010				2011			
	Temperature (°C)			Rainfall	Temperature (°C)			Rainfall
Month	Min.	Max.	Mean	(mm)	Min.	Max.	Mean	(mm)
May	7.5	21.1	14.3	53	8.2	20.5	14.4	225
June	15	27	21	326	14.7	26	20.3	131
July	17	28.4	22.7	264	20.2	30.5	25.3	59
August	16.8	28.5	22.7	127	16.3	27.7	22	148
September	9.8	23	16.4	66	8.1	22.1	15.1	19
October	3.5	19.5	11.5	13	4.1	19.1	11.6	40

chosen for this study to maximize yield while keeping the number of plots limited.

Plots in the WFC treatment were maintained by hand weeding. No weed control treatments were conducted in the WSL plots. The equipment used for treatments involving cultivation was the flamer/cultivator (figs. 2 and 3), pulled by a tractor using a three-point hitch. For treatments FC1 and FC2, the torches were running. This is a banded treatment, such that 0.30 m of the space centered on the crop was flamed and 0.48 m of the inter-row space was cultivated, with approximately 2.5 cm of overlap between the two operations. For treatments C1 and C2, the

torches were not running. Approximately 0.48 m of the inter-row space was cultivated in these treatments. Prototype 1 was used in 2010 and Prototype 2 was used in 2011. The equipment used for FF1 and FF2 was the full flamer (fig. 12).

Soybean Treatments

In soybean, seven treatments were compared that involved cultivation, flaming, and a combination of the two, as well as weed-free and weedy-season-long control plots (table 4). The treatments were arranged in an RCBD with four replications. The treatments were conducted either once or twice during a season, and were applied at either one or two particular growth stages (VC and V4-V5) of soybean. Growth stages of soybean were based on leaf number that included VC (unfolded cotyledons) and V4-V5 (4-trifoliate–5-trifoliate). Early flaming was completed at VC stage. Ulloa et al. (2010b) reported the unifoliate stage (VU) to be the most susceptible stage for flaming, and that flaming at growth stages from VU to V2-V3 will cause high crop injury and yield loss.

Data Collection

The treatments were evaluated based on four metrics: weed control, weed dry matter, crop injury, and crop yield.

Table 3. List of treatments in corn with corresponding growth stages in field studies at Concord, Neb. in 2010 and 2011.

Treatment Abbreviation	Treatment Performed	Growth Stage(s)[a]
WFC	Weed-free control	-
WSL	Weedy season-long	-
FC1	Flaming + cultivation once	V3-V4
FC2	Flaming + cultivation twice	V3-V4 & V6-V7
FF1	Full flaming once	V3-V4
FF2	Full flaming twice	V3-V4 & V6-V7
C1	Cultivation once	V3-V4
C2	Cultivation twice	V3-V4 & V6-V7

[a] For corn, the growth stages listed represent the number of fully developed leaves (i.e., V3 = 3-leaf).

Table 4. List of treatments in soybean with corresponding growth stages in field studies at Concord, Neb. in 2010 and 2011.

Treatment Abbreviation	Treatment Performed	Growth Stage(s)[a]
WFC	Weed-free control	-
WSL	Weedy season-long	-
FC1	Flaming + cultivation once	VC
FC2	Flaming + cultivation twice	VC & V4-V5
FF1	Full flaming once	VC
FF2	Full flaming twice	VC & V4-V5
F1C1	Full Flaming once at VC, followed by cultivation once at V4-V5	VC, V4-V5

[a] For soybean, the VC growth stage represents unfolded cotyledons, and the others represent the number of trifoliate leaves (i.e., V4 = 4-trifoliate).

Visual ratings of weed control and crop injury were taken at 7 and 28 days after treatment (DAT). Visual estimates of percent weed control are one of the most common ways of presenting data in the weed science literature (Knezevic et al., 2007). The ratings used a scale of 0-100%, where 0% means no weed control or crop injury, and 100% means weed or crop death. Several of the authors were trained in this visual rating system, used in numerous other papers on flame weeding at UNL (Ulloa, et al., 2011; Stepanovic et al., 2016a, 2016b). Weed dry matter was collected for the two studies on a single day each year, from two 0.25 m^2 quadrats placed approximately 2 m inside the top and bottom edges of the plot, at approximately 60 days after the final treatment applications in the study. Weeds were collected using clippers at ground level, and then dried at 50°C for two weeks before shoot dry mass was recorded. The dry matter was classified by weed species. Hand harvesting of the crop was done from 4 m lengths in each of the two middle rows in each plot, near the center of the plot length, for a total of 6.08 m^2 harvested. Harvested

samples were shelled, weighed, and adjusted to 15.5% moisture content for corn and 13% moisture content for soybean to obtain yield data.

Data Analysis

All response variables (weed control, weed dry matter, crop injury, and yield) were subjected to analysis of variance (ANOVA) using the PROC GLIMMIX procedure of the Statistical Analysis Systems (SAS) software (SAS, 2005) to test for significance ($P<0.05$) of years and treatments. Means for the significant treatment effects were compared using Fisher's protected least significant difference (LSD) procedure at $P < 0.05$. Prior to performing the analysis, the four data points in each treatment per year were subjected to the Tukey robust outlier test (Shoemaker, 1999). The data were significantly different between the two years ($P<0.05$) and could not be pooled.

RESULTS AND DISCUSSION

The changes in the hood design made in 2011 provided benefits to manufacturability and durability. In particular, the U-bolt clamping system provided a secure hold that did not require periodic adjustments. An issue that was not anticipated was warping of the hood sidewalls due to the heat of torches being mounted directly onto them, causing the torches to point slightly to the side. It is unknown if this had an effect on the results of the 2011 study.

CORN

Weed Control and Weed Dry Matter

The effective dose to obtain 90% weed control (ED90) is a standard parameter widely utilized to describe weed

Table 5. 2010 corn injury (7 and 28 DAT), weed control (7 and 28 DAT), and weed dry matter (60 DAT) as affected by treatments in field studies at Concord, Neb. (mean values of four replications).[a]

Treatment Abbreviation	Treatment Name[b]	Crop Injury (%) 7 DAT	28 DAT	Weed Control (%)[c] 7 DAT	28 DAT	Weed Dry Matter (g m^{-2})
WFC	Weed-free control					
WSL	Weedy season-long					201 a
FC1	Flaming + cultivation once (V3-V4)	17 ab	5 b	90 a	32 b	71 cd
FC2	Flaming + cultivation twice (V3-V4 & V6-V7)	10 c	5 b	96 a	98 a	2 e
FF1	Full flaming once (V3-V4)	19 a	10 a	89 a	30 b	54 cde
FF2	Full flaming twice (V3-V4 & V6-V7)	11 bc	3 b	90 a	85 a	13 de
C1	Cultivation once (V3-V4)	-	-	73 b	21 b	155 ab
C2	Cultivation twice (V3-V4 & V6-V7)	-	-	50 c	43 b	114 bc

[a] Different letters refer to statistically significant differences following Fisher's protected LSD procedure at p < 0.05.
[b] For corn, the growth stages listed represent the number of fully developed leaves (i.e., V3 = 3-leaf).
[c] Weed control is defined as the percentage decrease in weeds over weedy season-long.

Table 6. 2011 corn injury (7 and 28 DAT), weed control (7 and 28 DAT), and weed dry matter (60 DAT) as affected by treatments in field studies at Concord, Neb. (mean values of four replications).[a]

Treatment Abbreviation	Treatment Name[b]	Crop Injury (%) 7 DAT	28 DAT	Weed Control (%)[c] 7 DAT	28 DAT	Weed Dry Matter (g m^{-2})
WFC	Weed-free control					
WSL	Weedy season-long					179 abc
FC1	Flaming + cultivation once (V3-V4)	38 a	19 a	54 b	26 c	245 a
FC2	Flaming + cultivation twice (V3-V4 & V6-V7)	33 a	14 a	88 a	75 a	39 c
FF1	Full flaming once (V3-V4)	43 a	16 a	69 ab	34 bc	114 abc
FF2	Full flaming twice (V3-V4 & V6-V7)	35 a	15 a	58 b	34 bc	156 abc
C1	Cultivation once (V3-V4)	-	-	87 a	56 ab	72 bc
C2	Cultivation twice (V3-V4 & V6-V7)	-	-	56 b	44 bc	217 ab

[a] Different letters refer to statistically significant differences following Fisher's protected LSD procedure at p < 0.05.
[b] For corn, the growth stages listed represent the number of fully developed leaves (i.e., V3 = 3-leaf).
[c] Weed control is defined as the percentage decrease in weeds over weedy season-long.

response to herbicides (Knezevic et al., 2007). Knezevic and Ulloa (2007) reported that in organic cropping systems a goal of 90% control might be challenging to achieve, so presented values of 80% control (ED80) in addition to ED90. Therefore 80% weed control at 28 DAT was the criteria used for acceptable weed control in this study. The acceptable treatments in terms of weed control in 2010 were FC2 and FF2 (table 5), with values of 98% and 85% weed control, respectively, at 28 DAT. In 2011, none of the treatments maintained 80% weed control at 28 DAT (table 6). Even at 7 DAT, only two treatments, C1 and FC2, had greater than 80% weed control (table 6).

In 2010, treatment FC2 (2 g m^{-2}) had significantly less weed dry matter at 60 DAT than the other treatments (table 5), except FF1 and FF2. The WSL treatment (201 g m^{-2}) had significantly more weed dry matter at 60 DAT (table 5) than the other treatments, except C1. In 2011, there were no treatments with significantly less weed dry matter at 60 DAT (table 6) than WSL (179 g m^{-2}). FC2 (39 g m^{-2}) was the only treatment with significantly less weed dry matter than C2 and FC1 (table 6). In 2010, the weed dry matter at 60 DAT in corn was predominantly from broadleaf species (table 7), whereas in 2011 grass weed species were predominant.

The cultivation treatments were conducted differently than how many farmers conduct them. Farmers often use a cultivator with large sweeps that displace generous amounts of soil toward the intra-row space to cover the weeds. Due to the use of only one cultivator for both the cultivation-only and flaming + cultivation treatments, not as much soil was thrown with this unit. Such an "aggressive" cultivation treatment with generous amounts of soil displaced toward the crop row may be more effective than the method used in this study. Stepanovic et al. (2016b) reported banded flaming followed by "aggressive" cultivation, applied twice in the season, to have better weed control and crop yields than the flamer/cultivator tested here.

Crop Injury

Treatments WFC, WSL, C1, and C2 do not produce corn injury, so only the remaining four were considered for this metric. In 2010, three treatments (FC1, FC2, and FF2) maintained the least corn injury (5%, 5%, and 3%, respectively) at 28 DAT (table 5). Only FF1 produced significantly more (10%). In 2011, the corn injury at 28 DAT (table 6) was similar among these four treatments (14%-19%).

There could be many reasons for the significant difference between 2010 and 2011 results. A few factors include the following:

The torches used on flamer/cultivator Prototype 1 in 2010 had an operating pressure of 103 kPa, whereas the new torches designed and used on Prototype 2 in 2011 had an operating pressure of 172 kPa for the same propane flowrate. Likewise, the full flamer torches used in 2010 had

an operating pressure of 310 kPa, whereas the torches used in 2011 had an operating pressure of 448 kPa. The higher pressures were used to compensate for the smaller nozzle orifices in the torches used in 2011. Laguë et al. (1997) noted that operating pressure affects the flame geometry and its temperature distribution. They showed that for a given burner, increasing the operating pressure yields a wider and longer high temperature zone within the flame. However, the relationship between maximum flame temperature and operating pressure was not conclusive in their work. Measurements of flame temperature in the flamer/cultivator setup should be conducted to identify causes for the differences in results between the two years.

The weed composition at 60 DAT was also dramatically different between 2010 and 2011 (table 7). Since it is known that grasses are very difficult to kill by flaming (Ulloa et al., 2010a), it can be inferred that the 2011 field had a much higher percentage of grasses to begin with than the 2010 field. Thus, the 2011 reduction in weed control may be simply a reflection of the higher grass percentage.

Yield

The yield results (table 8) support certain trends seen in the other results: FC2 and FF2 were the only treatments in 2010 with acceptable weed control, and crop injury in 2011 was not significantly different among treatments FC1, FC2, FF1, and FF2. Treatment FC2 was in the "a" statistical grouping in both years, yielding 11.98 t ha^{-1} in 2010 and 9.16 t ha^{-1} in 2011 (table 8). The WFC treatment was statistically similar to FC2 in both years, yielding 11.08 t ha^{-1} in 2010 and 9.81 t ha^{-1} in 2011 (table 8). Treatments FF2 and FC2 are statistically similar in both years, though FF2 had the highest yield in 2010 but was one of only two treatments statistically different than WFC in 2011 (table 8). The WSL treatment gave the lowest yield in both years. The WFC treatment had 11% lower yield in 2011 than in 2010, indicating differences in conditions between the two years other than equipment.

SOYBEAN

Weed Control and Weed Dry Matter

As in corn, a weed control level of 80% at 28 DAT was the criteria used for acceptable weed control in the soybean

Table 8. Corn yield in 2010 and 2011 as affected by treatments in field studies at Concord, Neb. (mean values of four replications).[a]

Treatment Abbreviation	Treatment Name[b]	2010 Yield (t ha^{-1})	2011 Yield (t ha^{-1})
WFC	Weed-free control	11.08 bc	9.81 a
WSL	Weedy season-long	8.48 e	7.40 b
FC1	Flaming + cultivation once (V3-V4)	10.71 bcd	7.99 ab
FC2	Flaming + cultivation twice (V3-V4 & V6-V7)	11.98 ab	9.16 ab
FF1	Full flaming once (V3-V4)	10.65 cd	8.27 ab
FF2	Full flaming twice (V3-V4 & V6-V7)	12.31 a	7.77 b
C1	Cultivation once (V3-V4)	9.44 de	8.46 ab
C2	Cultivation twice (V3-V4 & V6-V7)	9.88 d	7.96 ab

[a] Different letters refer to statistically significant differences in each year following Fisher's protected LSD procedure at p < 0.05.

[b] For corn, the growth stages listed represent the number of fully developed leaves (i.e., V3 = 3-leaf).

Table 7. Species breakdown of weed dry matter at 60 DAT in corn.

Year	% Broadleaves	% Grasses
2010	78	22
2011	36	64

study. In 2010, none of the treatments met this threshold (table 9). Even at 7 DAT in 2010, none of the treatments maintained 80% weed control. In 2011, FC2 was the only treatment that had an acceptable weed control level at 28 DAT (83%) (table 10). It was significantly better than the other treatments on this metric. Treatment F1C1, which was not conducted in the corn study, had the second-highest weed control level at 28 DAT (68%), and this was still significantly better than the other treatments (table 10). Treatment FF1 had the lowest weed control levels in both 2010 (11%) and 2011 (11%).

In 2010, treatment FC2 had significantly less weed dry matter at 60 DAT (10 g m^{-2}) than the other treatments (table 9). The WSL treatment had the highest weed dry matter at 60 DAT (321 g m^{-2}) (table 9). In 2011, treatments FC2 (42 g m^{-2}), F1C1 (52 g m^{-2}), and FF2 (111 g m^{-2}) had the least weed dry matter (table 10). Treatments WSL (251 g m^{-2}) and FF1 (291 g m^{-2}) had the highest weed dry matter at 60 DAT (table 10). The weed dry matter at 60 DAT in soybean was of similar composition in both years (table 11). Broadleaf species made up 37% of the weed dry matter at 60 DAT in 2010, and 48% in 2011.

Crop Injury

Note that the soybean injury sustained in treatment F1C1 was only from the full flaming at the cotyledon growth stage, as cultivation at the V4 stage did not present any soybean injury. In 2010, the soybean injury was not significantly different among the treatments (table 9), both at 7 and 28 DAT. The levels of soybean injury at 28 DAT are near-zero.

In 2011, treatments FC1 (4%), FF1 (6%), and F1C1 (10%) had the soybean injury control levels at 28 DAT (table 10). Although these treatments presented the lowest

Table 11. Species breakdown of weed dry matter at 60 DAT in soybean.

Year	% Broadleaves	% Grasses
2010	37	63
2011	48	52

crop injury, which should be minimized in a treatment, they have proven to be ineffective at weed control. Treatment FF2 had the highest soybean injury at 28 DAT in 2011 (36%) (table 10). The main reason for the higher injury that year may be due to the shorter height of the plants in 2011. The shorter height was likely due to the later planting date (table 1) and lower precipitation (table 2) in 2011. The differences in torch operating pressures mentioned in the corn results may have led to the soybean injury values being higher in 2011 than the near-zero values in 2010.

Yield

The treatments producing the highest soybean yields (table 12) were WFC, with 3.37 t ha^{-1} in 2010 and 2.68 t ha^{-1} in 2011, and FC2, with 3.34 t ha^{-1} in 2010, and 2.26 t ha^{-1} in 2011. Treatment F1C1 (2.25 t ha^{-1}) was statistically similar to WFC and FC2 in 2011, but not in 2010 (table 12), consistent with the weed dry matter results (tables 9 and 10). Treatment FF2 was not statistically similar to FC2 in either year (table 12). It seems that flaming alone was not enough in soybean; cultivation must also be part of the weed control strategy. Treatments that were in the lowest statistical grouping for both years were WSL and FF1 (table 12).

CONCLUSIONS

Two prototypes of a combined flamer/cultivator implement were designed, built, and tested in corn and

Table 9. 2010 soybean injury (7 and 28 DAT), weed control (7 and 28 DAT), and weed dry matter (60 DAT) as affected by treatments in field studies at Concord, Neb. (mean values of four replications).[a]

Treatment Abbreviation	Treatment Name[b]	Crop Injury (%)		Weed Control (%)[c]		Weed Dry Matter (g m^{-2})
		7 DAT	28 DAT	7 DAT	28 DAT	
WFC	Weed-free control					
WSL	Weedy season-long					321 a
FC1	Flaming + cultivation once (VC)	6 a	0 a	75 a	65 a	120 b
FC2	Flaming + cultivation twice (VC & V4-V5)	4 a	0 a	79 a	71 a	10 c
FF1	Full flaming once (VC)	6 a	1 a	78 a	11 b	167 b
FF2	Full flaming twice (VC & V4-V5)	13 a	1 a	21 b	6 b	171 b
F1C1	Full Flaming once at VC, followed by cultivation once at V4-V5	5 a	1 a	34 b	8 b	130 b

[a] Different letters refer to statistically significant differences following Fisher's protected LSD procedure at p < 0.05.
[b] For soybean, the VC growth stage represents unfolded cotyledons, and the others represent the number of trifoliate leaves (i.e., V4 = 4-trifoliate).
[c] Weed control is defined as the percentage decrease in weeds over weedy season-long.

Table 10. 2011 soybean injury (7 and 28 DAT), weed control (7 and 28 DAT), and weed dry matter (60 DAT) as affected by treatments in field studies at Concord, Neb. (mean values of four replications).[a]

Treatment Abbreviation	Treatment Name[b]	Crop Injury (%)		Weed Control (%)[c]		Weed Dry Matter (g m^{-2})
		7 DAT	28 DAT	7 DAT	28 DAT	
WFC	Weed-free control					
WSL	Weedy season-long					251 ab
FC1	Flaming + cultivation once (VC)	29 bc	4 c	93 a	29 c	204 b
FC2	Flaming + cultivation twice (VC & V4-V5)	44 b	21 b	71 b	83 a	42 c
FF1	Full flaming once (VC)	40 b	6 c	90 a	11 d	291 a
FF2	Full flaming twice (VC & V4-V5)	73 a	36 a	60 bc	29 c	111 c
F1C1	Full Flaming once at VC, followed by cultivation once at V4-V5	24 c	10 c	56 c	68 b	52 c

[a] Different letters refer to statistically significant differences following Fisher's protected LSD procedure at p < 0.05.
[b] For soybean, the VC growth stage represents unfolded cotyledons, and the others represent the number of trifoliate leaves (i.e., V4 = 4-trifoliate).
[c] Weed control is defined as the percentage decrease in weeds over weedy season-long.

Table 12. Soybean yield in 2010 and 2011 as affected by treatments in field studies at Concord, Neb. (mean values of four replications).[a]

Treatment Abbreviation	Treatment Name[b]	2010 Yield (t ha⁻¹)	2011 Yield (t ha⁻¹)
WFC	Weed-free control	3.37 a	2.68 a
WSL	Weedy season-long	1.34 c	1.68 b
FC1	Flaming + cultivation once (VC)	2.73 b	1.75 b
FC2	Flaming + cultivation twice (VC & V4-V5)	3.34 a	2.26 a
FF1	Full flaming once (VC)	1.52 c	1.35 b
FF2	Full flaming twice (VC & V4-V5)	2.79 b	1.61 b
F1C1	Full Flaming once at VC, followed by cultivation once at V4-V5	2.46 b	2.25 a

[a] Different letters refer to statistically significant differences in each year following Fisher's protected LSD procedure at $p < 0.05$.

[b] For soybean, the VC growth stage represents unfolded cotyledons, and the others represent the number of trifoliate leaves (i.e., V4 = 4-trifoliate).

soybean field studies during 2010 and 2011. Some of the treatments with this implement involved flaming and cultivating simultaneously, and others involved cultivation only. Another flaming implement, the full flamer, was utilized for two treatments in each year for comparison. Treatment FC2, flaming + cultivation twice, was the highest-performing treatment of those tested.

In corn, the yield of treatment FC2 was statistically similar to the weed-free control (WFC) in both years of the study. FC2 had the highest levels of weed control at 28 DAT in corn both years, and the lowest levels of weed dry matter at 60 DAT. In corn, the yield of treatment FF2, full flaming twice, was statistically similar to WFC and FC2 in 2010.

In soybean, treatment FC2 was the only treatment with yield statistically similar to the WFC in both years of the study. FC2 had the highest levels of weed control at 28 DAT in soybean both years, and the lowest levels of weed dry matter at 60 DAT. In soybean, treatment F1C1, flaming at VC followed by cultivation at V4, was statistically similar to WFC and FC2 in 2011.

It is also clear from the field study results that a single-application weed control treatment per season could not maintain sufficient weed control at 28 DAT. Also, cultivation alone has proven to be insufficient for weed control at 28 DAT, confirming one of the reasons stated in the introduction for combining flaming and cultivation. It appears that flaming alone can be used with success in corn for season-long weed control. The same cannot be said for flaming alone in soybean; at least one cultivation should be conducted per season.

The torches in 2011 used a higher operating pressure than in 2010 to give the same propane dose, changing the flame shape and temperature distribution. Hood design changes in the side profile and the crop guides (i.e., closed panel in 2010 vs. open strap in 2011) may have also contributed to different temperature distributions. Measurements of flame temperature in both of the flamer/cultivator prototypes should be conducted to identify causes for the differences in results between the two years. Differences in weed composition, planting date, and rainfall are other possible contributing causes to the differences in results between the two years.

While they are effective tools when used together, flaming and cultivation should be considered as just two of the many tools in the toolbox of integrated weed management.

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