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# The effectiveness of flame weeding and cultivation on weed control, yield and yield components of organic soybean as influenced by manure application

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## Abstract

Propane flaming in combination with cultivation could be a potential alternative tool for weed control in organic soybean production. Field experiments were conducted at the Haskell Agricultural Laboratory of the University of Nebraska-Lincoln (UNL), Concord, NE in 2010, 2011 and 2012 to determine the level of weed control and the response of soybean grain yield and its components to flaming and cultivation within two fertility regimes (FRs) (with and without manure) utilizing flaming equipment developed at the UNL. The treatments included: weed-free control, weedy season-long and different combinations of banded flaming (intra-row), broadcast flaming and mechanical cultivation (inter-row). The treatments were applied at VC (unfolded cotyledon) and V4–V5 (4-leaf–5-leaf) growth stages. Propane doses were 20 and 45 kg ha$^{-1}$ for the banded and broadcast flaming treatments, respectively. The data were collected for visual ratings of crop injury and weed control at 7 and 28 days after treatment (DAT) at V4–V5 growth stages, weed dry matter at 60 DAT, crop yield and yield components. The annual application of 101 t ha$^{-1}$ manure did not alter weed community or influence the effectiveness of weed management treatment; however, it decreased soybean yield by 0.25 t ha$^{-1}$ through an increased weed biomass of 0.16 t ha$^{-1}$. The weed-free control plots yielded 4.15 t ha$^{-1}$. The combination of mechanical cultivation and banded flaming applied twice (at VC and V4–V5) was the best treatment resulting in 80–82% weed control and 6–9% crop injury at 28 DAT and 3.41–3.67 t ha$^{-1}$ yield. Cultivation conducted twice provided only 19% weed control at 28 DAT and 1.75 t ha$^{-1}$ yield. Soybean plants recovered well after all flaming treatments, with the exception of broadcast flaming conducted twice (28% crop injury at 28 DAT). Combining flaming with cultivation has a potential to effectively control weeds in organic soybean production across a range of FRs.

**Key words:** crop injury, manure, non-chemical weed control, organic crop production, parallel and cross-flaming

## Introduction

Weed management is an important challenge in all farming systems, but it is especially difficult in organic crop production where the use of chemical herbicides is prohibited (Liebman and Davis, 2010). Favorable market opportunities for organic soybean (*Glycine max* [L.] Merr.) in the past decade have provided strong economic incentives for organic soybean producers to reduce the yield loss caused by weeds (Delate et al., 2003). Multiple surveys of organic producers also cite weed control as the foremost production-related problem in major agronomic crops (Walz, 2004; Cavingelli et al., 2008). There is a need for inexpensive weed control techniques that provides satisfactory weed control in organic crop production systems. Therefore, organic farmers usually rely on multiple weed suppression tactics, each of which might be individually weak but cumulatively effective (Liebman and

Gallandt, 1997). From the agro-ecological standpoint, higher diversification of the cropping system could be achieved through the implementation of systematic preventive and cultural practices, including crop rotations, cover crops, planting methods (e.g., no-till planting), tillage systems (e.g., minimum tillage), seed bed preparation, fertilization program and irrigation and drainage systems. These practices are needed for an effective long-term weed management in crop production systems (Gabe et al., 2014).

Tactics that soybean producers typically use to manage weeds organically can be divided into cultural and mechanical control. Most common cultural practices used in organic soybean, such as crop rotations or delayed planting, are usually not efficient enough to control weeds below the economic threshold (Gunsolus, 2011). Thus, organic producers largely depend on mechanical cultivation and hand weeding for their weed control. Cultivation, however, is often not efficient enough as it leaves a strip of uncontrolled weeds that remain within the 5–10 cm on either side of the row that directly influence crop yield (Mulder and Doll, 1993). Disadvantages of cultivation can also be seen through accelerated loss of soil organic matter, degradation of soil aggregates, increased chance of soil erosion and promotion of emergence of new weed flushes (Wszelaki et al., 2007). Although effective in controlling weeds, hand weeding is labor intensive, often too expensive (e.g., ranging from US$200 to 1200 $ha^{-1}$), time consuming and difficult to organize (Kruidhof et al., 2008). Hence, there is a need to reexamine the existing methods and evaluate alternative methods that could be utilized for weed control in organic cropping systems (Kruidhof et al., 2008).

Propane flaming is an alternative method for weed control in organic and conventional cropping systems, as it leaves no chemical residues in plants, soil, air or water, does not disrupt the soil surface thus reducing the risk of soil erosion, does not bring buried weed seeds to the soil surface and it is less costly than hand weeding (Nemming, 1994; Knezevic and Ulloa, 2007; Wszelaki et al., 2007). It has been reported that a propane dose of about 60 kg $ha^{-1}$ provided almost 80% control of grasses and 90% control of broadleaf weed species commonly found in Nebraska (Ulloa et al., 2010a, b). Grassy weed species were harder to control because the position of the growing point at the time of flaming was under the soil surface, thus protected from direct heat injury (Ulloa et al., 2010a, b). Consequently, flaming has the most potential to be used in grass-type crops such as maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* [L.] Moench) (Ulloa et al., 2010c, d, e, 2011a, b), but it can also be used in soybean if conducted at the appropriate growth stage (Ulloa et al., 2010f). Soybean is reported to be the most tolerant to flaming at the emergence stage when the cotyledons are closed around the growing point, but above ground (Ulloa et al., 2010f). After cotyledons unfold, soybeans become much more susceptible to flaming, and the growing point must be protected in order to avoid severe yield loss (Ulloa et al., 2010f). Although responses of various crops and weeds to flame weeding are well reported in the literature, most of these studies were conducted in the absence of interspecific (between species) competition (Ulloa et al., 2010a, b). Therefore, the response of weeds and crop to flaming needs to be evaluated while growing together in the real field situations.

Flaming is non-selective in nature and it can be used to control emerged weeds prior to crop emergence as a pre-emergence treatment (Stepanovic, 2013). Unlike tillage, flaming does not disturb the soil or bring new weed seeds to the soil surface where seeds have greater chance to germinate (Stepanovic, 2013). This method is commonly used for weed control in vegetable production where fresh flush of weeds are killed following the preparation of stale seedbed, or just before vegetable seedlings emerge (Cloutier et al., 2007).

Flaming can be used to selectively treat weeds without damaging the crop and the selectivity of post-emergence flaming is primarily achieved through differential tolerance between crop and weeds at the time of application as well as by using different flame-torch configurations (Stepanovic, 2013). In the present study, equipment configuration was utilized where torches were positioned parallel to the crop row, angled down 30°, and covered with hoods that reduced the energy consumption (up to 50%), increased duration of heat exposure to weeds, and protected the upper portion of the crop canopy from heat damage (Ascard, 1995; Bruening, 2009; Knezevic et al., 2012). In addition, we tested the effectiveness of combining within-row (intra-row) banded flaming with between-row (inter-row) cultivation to reduce energy use (propane consumption), decrease the number of passes through the field, and increase the overall efficiency of weed control treatment.

Fertility programs in organic crop production commonly include field application of cattle manure to increase the availability of essential and trace nutrients and add organic matter to the soil, which increases yield and improves soil structure (or tilth), increases water holding capacity and resistance to compaction and crusting, and slows runoff and erosion losses from fields (Kuepper, 2003). Manure application can, however, elevate the numbers of existing weed species in the seed bank as some seeds can remain viable after animal digestion and manure handling (Pleasant and Schlather, 1994). This can increase the number and the diversity of weed species present on the site, generating a variety of seedling emergence and growth patterns that can potentially reduce the efficiency of weed control measures, including flaming, and cause greater losses in crop yield (Cook et al., 2007). Therefore, the objective of this study was to compare the effectiveness of flaming and cultivation practices conducted alone or in combination for weed management in organic soybean grown under two fertility regimes (FRs).

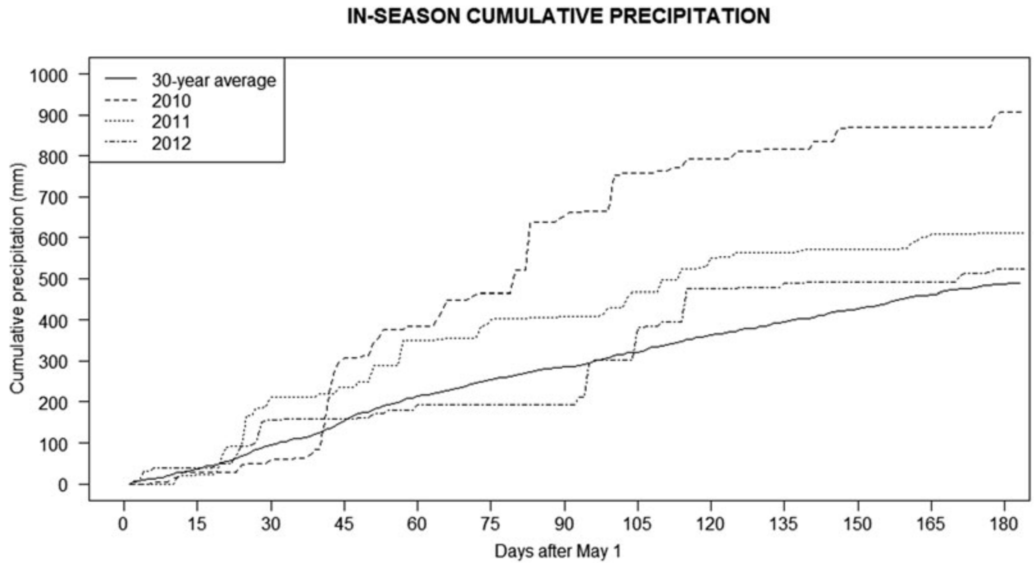


**Figure 1.** Cumulative in-season precipitation (mm) recorded in Concord, NE during months of May 1 through October 31 in 2010, 2011 and 2012 growing seasons and across 30-yr long average.

## Materials and methods

### Site description and field preparation

Field experiments were conducted at the Haskell Agricultural Laboratory of the Northeast Research and Extension Center, University of Nebraska, Concord, NE (42°37′N, 96°68′W) in 2010, 2011 and 2012 on a certified organic field where soybean was grown in rotation with maize. The experimental field had about 3–6% slope and the dominant soil series was an Alcester silty clay loam (fine-silty, mixed, mesic, Cumulic Haplustolls) with a pH of 6.6 and cation exchange capacity of 22, and sand, silt, clay and organic matter contents of 18, 58, 24 and 3.6%, respectively.

Field preparation included primary tillage in the fall (shortly after maize harvest) followed by disk harrow (Green Line Equipment, Norfolk, NE, USA) in the early spring. Weeds were allowed to germinate before secondary tillage was performed using a field cultivator (Green Line Equipment, Norfolk, NE, USA) about 1 week prior to planting. All tillage operations were performed uniformly throughout the whole field in direction perpendicular to the slope line.

To provide difference in soil FRs, beef cattle feedlot manure was collected from an adjacent university-owned beef feedlot and spread on to the pre-defined manure plots on May 5, April 4 and April 25 in 2010, 2011 and 2012, respectively. Enriched manure plots received 102, 106 and 96 t ha$^{-1}$ (wet weight) beef feedlot manure with 26, 29 and 25% moisture content in 2010, 2011 and 2012, respectively. Manure was applied to the same physical plots in all 3 years of study and was incorporated after application. Spreading was accomplished using tractors in the 65–90 HP (48.5–67.1 kW) range and a 2.4 m, 540 rpm-PTO-driven pull-type rear throw box manure spreader with horizontal beater tines (Model 250, Gehl Co, Inc., North Bend, WI, USA) manure spreader with a load capacity of 3.5 t.

Blue River organic soybean hybrids (2612034 in 2010 and 56M30 in 2011 and 2012) were planted in 76 cm rows with a four-row planter in 15 m × 3 m plots, with a seeding rate of 370,000 seed ha$^{-1}$. The planting, emergence and harvest dates in 2010 were June 10, June 13 and October 10; June 10, June 13 and October 11 in 2011 and June 10, June 13 and October 12 in 2012, respectively. Soybean growth was completely dependent on rainfall in 2010 and 2011, whereas in 2012 three 80 mm irrigations were applied 10 days apart from each other starting on August 3 (Fig. 1). Accumulation of growing degree days (GDD) was used as an assessment of differences of in-season temperatures during the years when experiment was conducted and 30-year long average (Fig. 2). Daily GDD was calculated using the following equation:

$$GDD = (T_{\max} + T_{\min})/2 - T_{\text{base}}$$

where GDD is growing degree days accumulated in 1 day, $T_{\max}$ is daily maximum temperature, $T_{\min}$ is daily minimum temperature and $T_{\text{base}}$ is 10°C (temperature below which plant growth ceases).

### Experimental design and treatments

The experiments were conducted using a split-plot design with three replications. The whole-plot was manure regime (manure or no-manure) and the sub-plots were 12 different weed management treatments (WMTs). Each experimental block consisted of 12 WMT within a given manure regime (either manure or no-manure), and blocking was done perpendicular to the slope line. The WMT consisted of weed-free control, weedy season-long control and

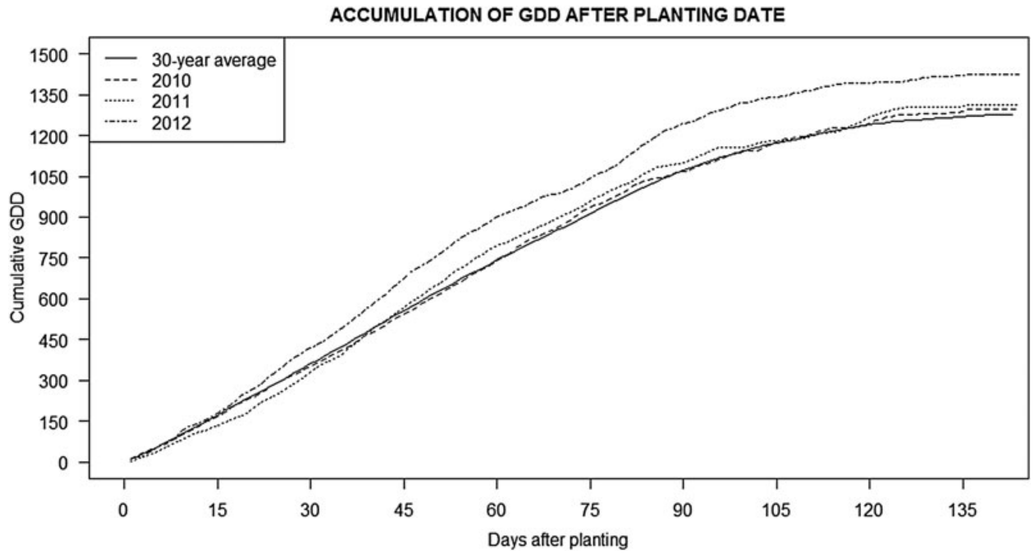


**Figure 2.** Cumulative GDD (°C) recorded in Concord, NE, USA accumulated after planting date in 2010, 2011 and 2012 growing seasons and across 30-year long average.

**Table 1.** List of WMTs with corresponding growth stages of soybean in field experiments at Concord, NE in 2010, 2011 and 2012.

| **WMTs** | | **Operation performed** | |
|---|---|---|---|
| | | **Growth stage**[1] | |
| **Treatment number** | **Abbreviation VC–V4** | **VC** | **V4–V5** |
| 1 | WF | Weed-free control | |
| 2 | WD | Weedy season-long control | |
| 3 | C–C | Cultivation | Cultivation |
| 4 | C–FC | Cultivation | Flame-cultivation |
| 5 | C–BF | Cultivation | Broadcast flaming |
| 6 | FC–C | Flame-cultivation | Cultivation |
| 7 | FC–FC | Flame-cultivation | Flame-cultivation |
| 8 | FC–BF | Flame-cultivation | Broadcast flaming |
| 9 | BF–C | Broadcast flaming | Cultivation |
| 10 | BF–FC | Broadcast flaming | Flame-cultivation |
| 11 | BF–BF | Broadcast flaming | Broadcast flaming |
| 12 | FCa–FCa | Banded flaming fb aggressive cultivation | Banded flaming fb aggressive cultivation |

[1] Weed control treatments were applied at two growth stages of soybean that included VC (unfolded cotyledon) and V4–V5 (4-leaf–5-leaf).

combinations of banded flaming (intra-row), broadcast flaming and mechanical cultivation (inter-row) applied at two growth stages (VC and V4–V5) of soybean (Table 1). Growth stages of soybean were based on leaf number that included VC (unfolded cotyledons) and V4–V5 (4-trifoliate–5-trifoliate) (Ritchie et al., 1997). Each individual weed control practice was applied either at VC or V4–V5 growth stage resulting in a total of 12 WMT (Table 1).

## *Equipment*

Two flame weeding units (four-row full-flamer and four-row flamer/cultivator) previously developed at the University of Nebraska (Bruening, 2009; Neilson, 2012; Stepanovic, 2013) were utilized for conducting WMT. Both units were tractor mounted driving at about 4.8 km h$^{-1}$.

Four-row full-flamer was used with two different torch setups, broadcast and banded. In the broadcast setup, eight torches were mounted 38 cm apart and positioned parallel to the crop row (19 cm away from each side) at 20 cm above the soil surface and angled back at 30°. Such setup provided a complete coverage of 76 cm of the inter-row space with a uniform distribution of flame and heat to all four rows in the plot (broadcast flaming treatment). In the banded setup, eight torches were

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**Table 2.** Crop growth stage, application date, time of day and weather conditions at Concord, NE during the soybean growing season in 2010, 2011 and 2012.

| | | | | Weather conditions | | |
|---|---|---|---|---|---|---|
| Year | Crop growth stage | Application date | Time of day | Air temperature (°C) | Relative humidity (%) | Wind direction-velocity (km $h^{-1}$) |
| 2010 | VC | June 25 | 10:00 h | 24 | 86 | SE-10 |
| | V5 | August 21 | 13:00 h | 27 | 84 | SE-14 |
| 2011 | VC | June 10 | 10:15 h | 16 | 88 | NW-13 |
| | V5 | August 6 | 14:00 h | 31 | 45 | E-3 |
| 2012 | VC | June 21 | 11:00 h | 26 | 40 | NW-8 |
| | V4–V5 | August 9 | 10:15 h | 23 | 50 | NW-6 |

flipped sideways in order to flame a band of 30 cm of intra-row space (banded flaming treatment). The flaming unit had four specially designed 1.2 m long hoods that confined the heat close to the soil surface and subsequently increase the exposure of weed to high-temperature flames. Each hood was positioned over the intra-row space and covered two torches. The hoods were 'closed' across the rows during flaming at VC growth stage, whereas hoods were 'open' during flaming at the V4–V5 stage with a 15 cm gap over the crop row, which allowed the crop row to pass through the gap as the flamer moved during the treatment. The open hood setup protected the upper portion of soybean plants, including the growing point, from the intense heat.

Four-row flamer/cultivator was designed to apply two field operations in a single pass: inter-row cultivation with intra-row banded flaming. Its support structure was modified by utilizing a Noble Row-Runner cultivator (Gibbsville Implement Inc., Waldo, WI, USA) that originally had five sweeps per gang. Two edge sweeps on each of the four gangs were replaced by 60 cm long hoods, leaving three middle sweeps for performing inter-row cultivation (Neilson, 2012). Each half of the hood covered one cylindrical torch angled back at 30° and mounted 15 cm away from the crop row and parallel to the slope of the hood (Neilson, 2012); thus, there was a total of eight torches that treated a 30 cm band with flaming over each of the four rows. This setup provided 50 cm of inter-row cultivation and 30 cm of intra-row banded flaming, with 4 cm overlap between the two operations to ensure the complete (76 cm) row coverage (flame/cultivation treatment). In performing these two operations simultaneously, cultivation always comes after flaming. Flaming torches were turned off when performing cultivation only treatment.

Differently, flame/cultivation (treatment 12) was applied in two separate operations (Table 1). Flaming was conducted first using the four-row full-flamer with banded setup (banded flaming) and then followed by aggressive cultivation with a buffalo-type cultivator (Fleischer Manufacturing Inc., Columbus, NE, USA) that had single, 50 cm wide sweep and set of hillers. The term 'aggressive cultivation' was used to describe a cultivation method that allowed throwing soil into intra-row space, which created a small ridge that buried flamed weeds.

## Equipment calibration and application of WMTs

Both the full-flamer and the flamer–cultivator were calibrated to deliver a propane dose of 45 kg $ha^{-1}$ to the effective flame-treated area. Therefore, the actual propane dose applied (per hectare basis) during broadcast flaming using the full-flamer was 45 kg $ha^{-1}$, while 30 cm banded flaming setup with the full-flamer or flamer–cultivator delivered a 20 kg $ha^{-1}$ dose due to 30/76 of total crop area covered. Propane dose (kg $ha^{-1}$) was calculated based on propane flow rate (nozzle orifice size and operating pressure), driving speed and effective treatment width (76 cm for broadcast flaming and 30 cm for banded flaming). WMTs were applied at a constant speed of 4.8 km $h^{-1}$ and propane pressure was adjusted to 450 kPa to deliver a 45 kg $ha^{-1}$ dose for broadcast flaming and 170 kPa to deliver a propane dose of 20 kg $ha^{-1}$ for banded flaming and flame-cultivation treatments (Knezevic et al., 2012). Weeds in the weed-free control plots were removed by hand weeding and hoeing as needed, while shanks and sweeps on both the flamer–cultivator and buffalo cultivator were set to 2.5 cm undercutting depth (Bowman, 2002). The treatment dates, time of day and weather conditions for each application are presented in Table 2.

## Data collection

Prior to manure application, representative samples of each load of manure spread were collected and analyzed at a Ward Laboratories, Inc. (Kearney, NE, USA) for total N (organic N, $NO_3$–N and $NH_4$–N), P ($P_2O_5$), K ($K_2O$), % organic matter, % organic carbon and C:N ratio. Pre-season soil samples were drawn shortly before (prior to planting) and post-season (after harvest) in each experimental plot at depth of 0–20 cm. Samples

**Table 3.** Significance levels in the three-way ANOVA of the effects of FR and WMTs on weed density, crop injury (7 and 28 DAT), weed control (7 and 28 DAT), weed dry matter (WDM) at 60 DAT, yield components and yield of soybean in the field experiments at Concord, NE in 2010, 2011 and 2012.

| | | Crop injury | | Weed control | | | Yield components | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Effect | Weed density (weeds $m^{-2}$) | 7 DAT | 28 DAT | 7 DAT | 28 DAT | WDM (t $ha^{-1}$) | Plants $m^{-2}$ | Pods $plant^{-1}$ | Seeds $pod^{-1}$ | 1000-seed weed (g) | Yield (t $ha^{-1}$) |
| WMT | ns | *** | *** | *** | *** | *** | ns | *** | ns | *** | *** |
| FR | ns | ns | ns | *** | *** | * | ns | ns | ns | ns | ** |
| WMT × FR | ns | * | ns | ns | ns | ns | ns | ns | ns | ns | ns |

ns, not significant.
*$P < 0.05$, **$P < 0.01$ and ***$P < 0.001$.

were collected using a truckbed-mounted hydraulically actuated soil probe (CSR 189, Giddings Machine Co., Windsor, CO, USA) and a 4.25 cm probe tip on a 5.08 cm tube. For each sample, at least two discrete soil sample cores were collected. Sample cores were broken up by hand while still field moist, then air-dried on $25 \times 25$ $cm^2$ of brown kraft paper, repackaged and sent to a commercial laboratory for analysis of N ($NO_3$–N), P ($P_2O_5$), K ($K_2O$) and % organic matter content.

Density, composition and height of weed species were collected from each plot prior to initiation of the treatment (VC stage). Counts were conducted by randomly positioning two 0.5 $m^2$ quadrats in each subplot. Weed biomass samples were hand harvested at 60 days after treatment (DAT) and dried at 50°C for 2 weeks and shoot dry weight was recorded. Visual ratings of weed control and crop injury were assessed at 7 and 28 DAT using a scale from 0 to 100%, where 0 representing no weed control or no crop injury and 100 representing complete weed control or crop death.

Before the final harvest, soybean yield components (number of plants $m^{-2}$, pods $plant^{-1}$, seeds $pod^{-1}$ and 1000-seed weight) were measured from 10 continuous plants randomly selected in each plot. For soybean grain harvest, 6.08 $m^2$ areas of the center two rows of each plot were hand clipped and run through a mechanical thresher. Reported yield was adjusted to 13% seed moisture content.

### *Statistical analysis*

All response variables (weed density, visual crop injury and weed control ratings, weed dry matter, yield components and yield) were subjected to analysis of variance (ANOVA) using the PROC GLIMMIX procedure of the Statistical Analysis Systems (SAS) to test for the significance ($P < 0.05$) of FR, WMT and their interactions (SAS, 2005). The effects of year, block nested within year and whole-plot (FR) × block nested within year were considered as random effects. The covariance for visual ratings of weed control and crop injury estimates at 7 and 28 DAT were analyzed as repeated measures because observations were taken at the same experimental unit at different times. Corrected Akaike's information criterion was used to ascertain that unstructured covariance structure (type = un) relative to other covariance structures was found to best account for covariance within experimental units. Pearson's correlation coefficient was obtained using PROC CORR in SAS (2005) to determine the relationship between yield and its components as well as to examine the validity of using visual weed control estimates and its correlation to weed biomass reduction. Means for the significant treatment effects were compared using Fisher's protected least significant difference (LSD) procedure at $P < 0.05$.

## Results

The interaction between FR and WMT was not significant for all of the evaluated parameters (except for crop injury at 7 DAT); therefore, the effect of FR and WMT on those parameters was presented separately (Table 3).

### *Fertility parameters*

The average annual application of manure nutrients was 462, 404, 566 and 604 kg $ha^{-1}$ of total N (organic N, $NO_3$–N and $NH_4$–N), Organic N, P ($P_2O_5$) and K ($K_2O$), respectively; 14 and 8% organic matter and organic carbon, respectively; and C:N ratio of 12. Pre-experiment soil samples did not differ much from fall 2011 samplings for manure and no-manure whole plots except for a 0.5 increase in pH, 8.5 ppm surface nitrates, 70 ppm soil K, 0.5 ppm Zn and 51 ppm increase in soil P in manure whole plots. The nutrient levels in the non-manured whole plots were above the minimum required for soybean production.

### *Characteristics of weed community*

Weed species composition, density and height prior to initiation of WMT were similar across FRs and WMT, indicating no significant change in weed community with different

**Table 4.** Mean weed density with standard errors (SE), average height and species composition collected 1 day prior to initiation of the WMT in field experiments at Concord, NE in 2010, 2011 and 2012 (combined).

| WMTs | Density (plants $m^{-2}$) mean ± SE | Average weed height (cm) | Species-specific contribution to weed community (%)[1] | | | |
|---|---|---|---|---|---|---|
| | | | SETVI | AMARE | ABUTH | CHEAL |
| *Fertility regime* | | | | | | |
| 1. Manure | 390 ± 128 | 1.7 | 78 | 7 | 14 | 1 |
| 2. No-manure | 390 ± 139 | 2.2 | 81 | 4 | 14 | 1 |
| *WMTs* | | | | | | |
| 1. Weed-free control | 475 ± 37 | 2.0 | 76 | 4 | 19 | 0 |
| 2. Weedy season-long | 377 ± 21 | 1.7 | 77 | 7 | 15 | 1 |
| 3. Cultivation (VC) fb cultivation (V4–V5) | 358 ± 27 | 1.8 | 78 | 6 | 16 | 1 |
| 4. Cultivation (VC) fb flame-cultivation (V4–V5) | 381 ± 22 | 1.8 | 83 | 8 | 10 | 0 |
| 5. Cultivation (VC) fb broadcast flaming (V4–V5) | 360 ± 28 | 2.0 | 76 | 9 | 15 | 1 |
| 6. Flame-cultivation (VC) fb cultivation (V4–V5) | 355 ± 39 | 1.8 | 84 | 3 | 11 | 2 |
| 7. Flame-cultivation (VC) fb flame-cultivation (V4–V5) | 362 ± 34 | 1.9 | 74 | 2 | 23 | 1 |
| 8. Flame-cultivation (VC) fb broadcast flaming (V4–V5) | 463 ± 40 | 1.9 | 75 | 5 | 19 | 1 |
| 9. Broadcast flaming (VC) fb cultivation (V4–V5) | 335 ± 33 | 2.8 | 86 | 3 | 11 | 0 |
| 10. Broadcast flaming (VC) fb flame-cultivation (V4–V5) | 429 ± 27 | 1.5 | 87 | 7 | 5 | 1 |
| 11. Broadcast flaming (VC) fb broadcast flaming (V4–V5) | 373 ± 34 | 2.0 | 76 | 6 | 17 | 1 |
| 12. Banded flaming fb aggressive cultivation (VC) fb banded flaming fb aggressive cultivation (V4–V5) | 412 ± 36 | 1.9 | 81 | 5 | 13 | 2 |

[1] Weed species were presented using the Weed Science Society of America (WSSA)-approved computer codes. SETVI, *S. viridis* (L.) Beauv., AMARE, *A. retroflexus* L., ABUTH, *A. theophrasti* Medik., CHEAL, *C. album* L.

FRs (Table 3). In general, the distribution of green foxtail (*Setaria viridis* [L.] Beauv.), redroot pigweed (*Amaranthus retroflexus* L.), velvetleaf (*Abutilon theophrasti* Medik.) and common lambsquarters (*Chenopodium album* L.) was fairly uniform throughout the study area (Table 4). Other weed species including witchgrass (*Panicum capillare* L.), yellow foxtail (*Setaria pumila* [Poir.] Roemer & J.A. Schultes), large crabgrass (*Digitaria sanguinalis* [L.] Scop.), common waterhemp (*Amaranthus rudis* Sauer) and Pennsylvania smartweed (*Polygonum pensylvanicum* L.) were also present; however, their presence did not influence the composition of weed community to a great extent, as occurrence of these species was <1% (data not shown). Overall, weed density ranged from 355 to 475 plants $m^{-2}$, with weed height ranging from 1.5 to 2.8 cm prior to initiation of the treatment (Table 4).

## Crop injury

Crop injury ratings at 7 and 28 DAT indicated that soybeans were able to recover after flaming treatment (Table 5). For each WMT, visual ratings at 28 DAT were generally lower than at 7 DAT. For example, treatment 8 (FC–BF) caused 43% crop injury at 7 DAT, whereas it was reduced to 14% at 28 DAT (Table 5). The magnitude of crop injury, however, varied with the type of weed management practice. While cultivation caused no injury to soybean, higher levels of injury were observed at 28 DAT (4–28%) when plants were flamed once or twice in the season (Table 5). Visual ratings at 28 DAT also indicated that all WMT had <14% crop injury, with the exception of broadcast flaming conducted twice where 28% crop injury was observed.

## Weed control and weed dry matter

Manure application decreased the efficacy of WMT as the addition of manure resulted in a decrease of visual weed control at 28 DAT by 8% and an increase of weed dry matter by 0.16 t $ha^{-1}$ compared with no-manure treatment (Table 5). When averaged over FRs, visual estimations of weed control at 28 DAT resulted in 49 and 57% for manure and no-manure treatment, respectively; while weed dry matter was 2.47 and 2.31 t $ha^{-1}$ for manure and no-manure treatment, respectively (Table 5). Among WMT, flame/cultivation was the most effective with treatments 7 (FC–FC) and 12 (FCa–FCa) being the only two treatments that had ≥80% weed control at 28 DAT and <0.85 t $ha^{-1}$ of weed dry matter (Table 5). In contrast, cultivation twice (treatment 3) was the least effective treatment

**Table 5.** Soybean injury (7 and 28 DAT), weed control (7 and 28 DAT) and weed dry matter (60 DAT) as affected by different FR and WMTs in field experiments at Concord, NE (2010, 2011 and 2012 mean values).

| Effect | Crop injury (%) | | Weed control (%) | | Weed dry matter |
|---|---|---|---|---|---|
| | 7 DAT | 28 DAT | 7 DAT | 28 DAT | (t ha$^{-1}$) |
| Fertility regime | | | | | |
| 1. Manure | 30 a[1] | 11 a | 62 b | 49 b | 2.47 a |
| 2. No-manure | 29 a | 11 a | 69 a | 57 a | 2.31 b |
| WMT*s* | | | | | |
| 1. Weed-free control | | | | | |
| 2. Weedy season-long | | | | | 5.37 a |
| 3. Cultivation (VC) fb cultivation (V4–V5) | | | 40 g | 19 f | 3.57 b |
| 4. Cultivation (VC) fb flame-cultivation (V4–V5) | 28 e | 9 c | 59 e | 41 d | 2.71 c |
| 5. Cultivation (VC) fb broadcast flaming (V4–V5) | 41 b | 12 b | 35 g | 23 ef | 3.05 bc |
| 6. Flame-cultivation (VC) fb cultivation (V4–V5) | 5 g | 3 e | 76 c | 62 c | 2.14 de |
| 7. Flame-cultivation (VC) fb flame-cultivation (V4–V5) | 27 e | 6 d | 84 b | 80 a | 0.82 f |
| 8. Flame-cultivation (VC) fb broadcast flaming (V4–V5) | 43 b | 14 b | 76 cd | 59 c | 2.04 e |
| 9. Broadcast flaming (VC) fb cultivation (V4–V5) | 9 f | 4 e | 51 f | 27 ef | 2.64 cd |
| 10. Broadcast flaming (VC) fb flame-cultivation (V4–V5) | 35 c | 14 b | 76 cd | 69 b | 1.65 e |
| 11. Broadcast flaming (VC) fb broadcast flaming (V4–V5) | 49 a | 28 a | 71 d | 68 b | 1.65 e |
| 12. Banded flaming fb aggressive cultivation (VC) fb banded flaming fb aggressive cultivation (V4–V5) | 31 d | 9 c | 90 a | 82 a | 0.64 f |

[1] Different letters refer to statistically significant differences following the Fisher's protected LSD procedure at $P < 0.05$.

**Table 6.** Yield components of soybean (plant m$^{-2}$, pod plant$^{-1}$, seeds pod$^{-1}$ and 1000 seed weight) as affected by different FR and WMTs in field experiments at Concord, NE (2010, 2011 and 2012 mean values).

| Effect | Yield components | | | | Yield |
|---|---|---|---|---|---|
| | Plants m$^{-2}$ | Pods plant$^{-1}$ | Seeds pod$^{-1}$ | 1000-seed weight (g) | (t ha$^{-1}$) |
| Fertility regime | | | | | |
| 1. Manure | 25 a[1] | 23 a | 2.55 a | 129 a | 2.52 b |
| 2. No-manure | 26 a | 24 a | 2.51 a | 128 a | 2.77 a |
| WMT | | | | | |
| 1. Weed-free control | 24 b | 35 a | 2.52 ab | 138 a | 4.15 a |
| 2. Weedy season-long | 25 ab | 11 e | 2.37 b | 115 h | 0.74 g |
| 3. Cultivation (VC) fb cultivation (V4–V5) | 26 ab | 22 c | 2.55 a | 122 g | 1.75 f |
| 4. Cultivation (VC) fb flame-cultivation (V4–V5) | 25 ab | 16 d | 2.47 ab | 124 fg | 2.30 de |
| 5. Cultivation (VC) fb broadcast flaming (V4–V5) | 24 b | 24 c | 2.56 a | 125 efg | 2.15 e |
| 6. Flame-cultivation (VC) fb cultivation (V4–V5) | 25 ab | 21 c | 2.53 a | 127 ef | 2.52 d |
| 7. Flame-cultivation (VC) fb flame-cultivation (V4–V5) | 24 b | 28 b | 2.48 ab | 134 ab | 3.41 bc |
| 8. Flame-cultivation (VC) fb broadcast flaming (V4–V5) | 25 ab | 25 c | 2.59 a | 129 cde | 2.59 d |
| 9. Broadcast flaming (VC) fb cultivation (V4–V5) | 25 ab | 25 c | 2.60 a | 128 def | 2.27 de |
| 10. Broadcast flaming (VC) fb flame-cultivation (V4–V5) | 26 ab | 23 c | 2.53 a | 133 bc | 3.10 c |
| 11. Broadcast flaming (VC) fb broadcast flaming (V4–V5) | 24 b | 23 c | 2.51 ab | 132 bcd | 3.11 c |
| 12. Banded flaming fb aggressive cultivation (VC) fb banded flaming fb aggressive cultivation (V4–V5) | 25 ab | 30 b | 2.62 a | 135 ab | 3.67 bc |

[1] Different letters refer to statistically significant differences following the Fisher's protected LSD procedure at $P < 0.05$.

resulting in 19% weed control at 28 DAT and weed dry matter of 3.57 t ha$^{-1}$, which was only a minor improvement over weedy season-long control that had 5.37 t ha$^{-1}$ of weed dry matter (Table 5). All other WMT provided weed control between 23 and 69% at 28 DAT and weed dry matter between 1.65 and 3.05 t ha$^{-1}$.

## *Yield components*

Variation in the evaluated yield components cannot be explained by manure application as no significant effect of FR on yield components was observed (Table 3). WMT had no effect on number of plants m$^{-2}$ and

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**Table 7.** Pearson correlation between yield, crop injury 28 DAT, weed control 28 DAT, weed dry matter 60 DAT, plants $m^{-2}$, pods $plant^{-1}$, seeds $pod^{-1}$ and 1000-seed weight in field experiments at Concord, NE (2010, 2011 and 2012).

| Terms | Yield ($t\ ha^{-1}$) | Crop injury 28 DAT (%) | Weed control 28 DAT (%) | Weed dry matter 60 DAT ($t\ ha^{-1}$) | Plants $m^{-2}$ | Pods $plant^{-1}$ | Seeds $pod^{-1}$ |
|---|---|---|---|---|---|---|---|
| Crop injury 28 DAT (%) | 0.05 | | | | | | |
| Weed control 28 DAT (%) | 0.61[1] | 0.07 | | | | | |
| Weed dry matter 60 DAT (g) | −0.39[1] | −0.09 | −0.79[1] | | | | |
| Plants $m^{-2}$ | 0.03 | −0.03 | −0.07 | 0.10 | | | |
| Pods $plant^{-1}$ | 0.71[1] | −0.17[1] | 0.54[1] | −0.41[1] | −0.08 | | |
| Seeds $pod^{-1}$ | 0.01 | 0.01 | 0.08 | −0.14[1] | −0.01 | 0.13[1] | |
| 1000 seed weight (g) | 0.46[1] | 0.04 | 0.34[1] | −0.18[1] | −0.06 | 0.43[1] | −0.1 |

[1] Significant at 10% levels of probability.

number of seeds $pod^{-1}$ (Table 3). On an average, soybean plant populations ranged from 24 to 26 plants $m^{-2}$ with 2.37–2.62 seeds $pod^{-1}$ (Table 6). In contrast, WMT had significant effect on number of pods $plant^{-1}$ and 1000-seed weight (Table 6). For example, the most effective WMT (treatment 12, FCa–FCa) had 30 pods $plant^{-1}$ and 1000-seed weight of 135 g, whereas moderately effective WMT (treatment 8, FC–BF) had 25 pods $plant^{-1}$ and 1000-seed weight of 129 g. In contrast, the least effective WMT (treatment 3, C–C) had 22 pods $plant^{-1}$ and 1000-seed weight of 122 g (Table 6).

### *Yield*

The addition of manure significantly reduced soybean yield by 0.25 $t\ ha^{-1}$ compared with no-manure plots (Table 6). When averaged across manure levels, soybean yield was 2.52 and 2.77 $t\ ha^{-1}$ for manure and no-manure treatment, respectively. Since manure application was not needed since the site had sufficient inherent fertility, application of manure may have caused more vegetative growth than needed which used nutrients for dry matter production that did not result in increased soybean yield.

Regardless of FR, soybean yield increased with an increase in the effectiveness of WMT (Table 6). Therefore, banded flaming followed by aggressive cultivation at VC and V4–V5 growth stages (treatment 12, FCa–FCa) was the most effective WMT resulting in the highest yield of 3.67 $t\ ha^{-1}$, which was only 0.48 $t\ ha^{-1}$ less than the weed-free control (Table 6). Flame-cultivation conducted twice (treatment 7, FC–FC) was the second best treatment with 3.41 $t\ ha^{-1}$ yield followed by broadcast flaming conducted twice (treatment 11, BF–BF) with 3.11 $t\ ha^{-1}$ yield (Table 6). Treatments that followed cultivation at VC (treatments 3–5) or were followed by cultivation at V4–V5 (treatments 6 and 9) were the least effective WMT with yield ranged from 1.75 to 2.27 $t\ ha^{-1}$ (Table 6).

### *Correlation analysis*

Correlation between crop injury at 28 DAT and yield was highly insignificant ($r = 0.05$) suggesting that crop injury was not a major driver of yield loss and cannot be exclusively used for determining the effectiveness of WMT (Table 7). On the other hand, yield was significantly correlated to weed control at 28 DAT ($r = 0.61$) and weed dry matter ($r = -0.39$) suggesting that an increase in weed control and consequently decrease in weed dry matter would most likely increase yield and the effectiveness of WMT. Strong negative linear relationship ($r = -0.79$) between weed control at 28 DAT and weed dry matter further indicates that an increase in weed control can be used to explain reduction in weed dry matter and vice versa (Table 7).

Yield components including number of pods $plant^{-1}$ and 1000-seed weight were positively correlated with weed control at 28 DAT (Table 7, $r = 0.54$ for pods $plant^{-1}$ and $r = 0.34$ for 1000-seed weight) suggesting that each soybean plant produced more pods with larger seeds when treated with more effective WMT (Table 7). Furthermore, pods $plant^{-1}$ and 1000 seed weight had significant positive correlation with yield ($r = 0.71$ and 0.47 for pods $plant^{-1}$ and 1000-seed weight, respectively); thus, increasing number of pods $plant^{-1}$ and 1000-seed weight resulted in a linear increase in yield (Table 7). Yield was not significantly correlated to number of plants $m^{-2}$ and number of seeds $pod^{-1}$ (Table 7).

## Discussion

In this experiment, manure addition did not influence the composition of weed community and the effectiveness of WMT. Similar response has also been reported where farmers' weed control practices were equally effective in manured and non-manured plots when species richness and diversity did not change (Cook et al., 2007).

Viability of seeds introduced with manure application could vary with type of feed, feed-pellet processing, feed ensiling, ruminal digestion, anaerobic digestion of manure and composting (Cook et al., 2007). None of these processes was monitored in the present study; thus, either the amount of viable weed seeds introduced with cow manure was negligible or species composition of introduced seeds was similar to the flora existing at the site. Tillage operations that were used for field preparation of the experimental site might have been the main factor in altering weed community; it has been reported that green foxtail (*S. viridis* [L.] Beauv.), which was the predominant weed at the field, becomes an increasing problem with intensified tillage (Cavingelli et al., 2008). Such hypotheses need to be tested.

Manure addition, however, contributed to a slight decrease in soybean yield (0.25 t $ha^{-1}$) by increasing weed biomass (e.g., feeding the weeds) and consequently weed competition. Variable response of soybean yield to manure has been reported in the literature (Schmidt et al., 2001; Helmers et al., 2008). For example, manure addition increased soybean yield at three out of seven sites that had lower available N and P (Schmidt et al., 2001). The positive or negative influence of manure on soybean yield is highly site specific and the reasons behind this manure-induced yield changes are often not clearly understood. We hypothesize that soybean yield would decrease with manure application at sites that have sufficient residual soil nutrients to meet the crop demand; thus, additional nutrients would only be available for weed uptake, increasing their competitive impact on crop yield.

Correlation analysis showed that differences observed in final yield were mainly driven by combined effect that WMT had on weed control, weed dry matter, pods $plant^{-1}$ and 1000-seed weight. Based on these parameters (weed control, weed dry matter, pods $plant^{-1}$, 1000-seed weight and yield) banded flaming followed by aggressive cultivation applied twice in the season (at VC and V4–V5 growth stages) was the best treatment, whereas the second best treatment was flame-cultivation conducted twice. Combining intra-row flaming with between-row cultivation into a single operation increased the effectiveness of these solely individual weed control methods. Previous reports also mentioned that two post-emergence flame-cultivations provided an acceptable weed control with no yield reduction in maize and cotton (*Gossypium hirsutum* [L.]) (Leroux et al., 1995; Seifert and Snipes, 1996).

When properly used flaming in combination with cultivation can be an effective tool in controlling most annual and some perennial weeds (Larson et al., 1960). It is also interesting to note that flame-cultivation was more effective when banded flaming was conducted with aggressive cultivation using a buffalo-type cultivator, as soil that was thrown into intra-row space severely reduced the ability of weeds (especially grassy species) to regrow after flaming treatment. This delay in regrowth could have provided just enough time for soybean plants to close up the canopy before the subsequent weed emergence. Additional studies are needed to test such a hypothesis. Although crop injury was substantial in some treatments (28% in broadcast flaming twice), correlation analysis indicated that crop injury was not an important parameter in determining soybean yield. This is mainly due to the utilization of specially designed hoods that minimized crop injury to the growing points from significant heat damage. It has been reported that utilizing hoods for parallel flaming in cotton reduced leaf damage in the bottom 10–30 cm of crop height; hence, providing more flexibility in controlling weeds early in the season (Stephenson, 1959). In the present study, broadcast flaming conducted twice was one of the most effective WMT with a decent weed control and higher yields. Based on the previous research, parallel-hooded flaming can be safely used in soybean if applied not more than twice in the growing season and at VC and/or after V4–V5 growth stage (Ascard, 1995). Timing of flaming application, however, should be adjusted based on weed size and types of weed species present to maximize its efficiency (Ascard, 1995; Knezevic et al., 2012).

## Conclusions

Manure application did not alter weed community or influence the effectiveness of WMT; however, it slightly decreased soybean yield by reducing the effectiveness of weed control (i.e., increasing weed biomass). Combining banded flaming and between-row cultivation into a single operation was the most efficient weed control practice providing >80% weed control. A major disadvantage of combining flaming with cultivation might be the lack of ability to apply the treatment when field conditions are too wet. In such situations, broadcast flaming could be employed to provide satisfactory weed control. These findings suggest that, if properly used, flaming could be another effective weed management tool available for soybean organic producers. Flaming, however, is not a single weed control practice, and it should be combined with cultivation and other non-chemical weed management strategies to increase the overall effectiveness of integrated weed control programs in both organic and conventional crops.

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