Winter 12-2013

Positioning an Innovative Flame-weeding Technology Into Crop Production

Strahinja V. Stepanovic
University of Nebraska-Lincoln

POSITIONING AN INNOVATIVE FLAME-WEEDING TECHNOLOGY INTO CROP PRODUCTION

by

Strahinja V. Stepanovic

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Agronomy

Under the Supervision of Professor Stevan Knezevic

Lincoln, Nebraska

December, 2013

POSITIONING AN INOVATIVE FLAME-WEEDING TECHNOLOGY INTO CROP PRODUCTION

Strahinja V. Stepanovic, M.S.

University of Nebraska, 2013

Adviser: Stevan Knezevic

Propane flaming has a potential to be utilized for effective PRE and POST weed control in both organic and conventional farming systems. Field studies were conducted at the Haskell Agricultural Laboratory of the University of Nebraska in 2010, 2011, and 2012 to: (1) describe dose–response curves for propane when flaming selected weed species at different growth stages, (2) determine corn and soybean tolerance to single and repeated flaming by utilizing the equipment designed to selectively flame weeds in row crops with torches positioned parallel to the crop row, and (3) determine the effectiveness of flaming and cultivation for weed control management under two manure levels in organic corn and soybean. Results from these studies indicate that single application of broadcast flaming can be adjusted to effectively control tansy mustard, henbit, and common lambsquarters and temporary suppress of cutleaf evening primrose, field pennycress, and dandelion. Hood technology on four-row flamer protected the major portion of the leaves from any heat damage, thus minimizing crop injury when flaming was conducted at V5 stage of soybean and V4 and V6 stages of corn. Results suggest that that both corn and soybean were able to tolerate up to two flaming operations with propane dose of 45 g ha^{-1} without any yield reduction; but, for best results, soybeans should be flamed at VC and after V4-V5, while timing of flaming in corn is less critical. Combination of banded

flaming and between row cultivation applied twice in the season was the most effecting weed control treatment in both corn and soybean. Same treatment is some cases yielded statistically similar to weed-free control and compared to cultivation twice there was a significant improvement in weed control efficacy. Alternatively, broadcast flaming could be employed to provide satisfactory weed control when conditions are too wet to cultivate. Flaming should be combined with cultivation and other non-chemical weed control practices to increase overall effectiveness of weed management programs.

Acknowledgements

- First of all, I would like to thank my undergraduate advisor, Dr. Sava Vrbnicanin, for recognizing my potential and encouraging me to continue my education on a graduate level.
- My deepest gratitude to Dr. Stevan Knezevic for providing me with an opportunity to conduct research and helping me to mature as a person and as a scientist.
- Thank you also to the other members of my graduate committee, Dr. Avishek Datta, Dr. George Gogos, Dr. Charles Shapiro and Dr. Timothy Arkebauer for their constructive criticism, assistance and support.
- Thank you to Santiago Ulloa, Mike Mainz and Lynn Junk for teaching me the basics of field research and helping me operate farm equipment.
- Special thanks goes to my colleagues, David Glett, Brian Neilson and Chris Bruening, for being good friends, helping me with the field work and making graduate school an enjoyable experience. Thank you also to all the summer helpers who worked with me in the field.
- Additional thanks goes to Propane Education and Research Council and USDA for funding this research.
- Finally, I would like to thank my wife, Ana Stepanovic, and the rest of my family and friends for their love, understanding and constant support in my achieving my career goals.

Table of Contents

List of Tables

List of Figures

CHAPTER 1. Literature review

1.1. General Introduction

Weeds are one of the most important yield-reducing factors in agricultural systems (Sopes and Millington, 1991). Weeds reduce yield primarily by utilizing light, water and nutrients that would otherwise be available to the crop (Coble et al., 1978, 1981; Jordan et al., 1987), and producing chemicals that are harmful to the crop plants (allelopathy). In addition to this direct influence, weeds can also interfere with tillage, sowing and harvest operations and degrade quality of milk or other animal products throughout contamination of crop seeds (Anderson et al., 1983; Ashton and Monaco 1991; King, 1966).)

Weed control is as old as agriculture itself (Hay, 1974) and is one of the most expensive steps in crop production. Some studies indicate that weed control is more costly than plant diseases and insect pest control combined (Bridges, 1992). The reason for this might be that weeds pose a relatively constant problem, whereas outbreaks of insects and disease pathogens are sporadic (Gianessi and Sankula, 2003). Globally, damage caused by weeds is responsible for a loss of 13.2% of agriculture production or about $75.6 billion per year (Oerke et al., 1994). In the United States (U.S.), weeds deprive farmers of about 10% of their potential crop yields, at an annual monetary loss of $7 to $12 billion (Loux et al., 2013). Given these circumstances, farmers have a strong economic incentive to make weed management decisions carefully. Even though herbicide applications have been very successful in controlling weeds in the past several decades, many authors advocate integrating preventive, cultural, biological and mechanical weed control measures to ensure long-term sustainability of the system without damaging the environment (Knezevic and Cassman, 2003; Liebman and Gallandt, 1997).

1.2. Chemical weed control – pros and cons

In the past several decades, weed control among U.S. farmers has been largely based on herbicide application (Koskinen and McWhorter, 1986). The importance of herbicides in modern weed management is understood by estimates that it is used on approximately 220 million acres of U.S. crop land (Gianessi and Reigner, 2007). The development of new herbicides had been progressing steadily since about 1900. However, extensive use of herbicides and the beginning of the “Chemical Era” in agriculture started in the 1940s with the discovery of weed killing properties of phenoxyacetic acid (Hamner and Tukey, 1944). By the 1970s herbicides achieved a dominant role in managing weeds in crop fields. New herbicides with different modes of action were discovered approximately every 3 years, leading to a current use of approximately 16 known modes of action (Duke, 2011). Even though only one new herbicide mode of action has been introduced to the market since 1990 (Duke, 2011), development of herbicide-tolerant crops enhanced use of herbicides for weed control to present day.

Use of herbicides benefited farmers throughout the U.S. in many ways: (1) hand labor requirements for many agricultural activities (such as hand weeding) was severely reduced (Pacanoski, 2007); (2) it eliminated extensive tillage and cultivation operations, thus increasing energy use efficiency and reducing soil erosion (Triplett et al., 1977;

Triplett, 1985); (3) decreased crop yield losses by 5-67% depending on the crop (Gianessi and Sankula, 2003), subsequently providing better profit for producers; (4) indirectly benefited consumers by lowering prices of food (Zilberman et al., 1991). Contrary to the belief of many, glyphosate and glufosinate, widely-used herbicides that have little residual activity, are low in mammalian toxicity, and have an average half-life in soil of about 40-60 days, helping protect our environment (Pacanoski, 2006).

Despite the current emphasis on herbicides in U.S. agricultural system, several factors have recently led to a reappraisal of their use (Liebman & Janke, 1990). First, discoveries of herbicides in surface and ground water and herbicide residues in drinking water and food has increased public awareness of undesirable effects on environment and human health (Halberg, 1986). Second, the wide adoption of herbicide-resistant crops (primarily glyphosate-resistant) in conjunction with suppressing the introduction of new herbicide mechanisms of action (MOA) has led to the rapid development of herbicide-resistant weeds in the past 20 years. This increased impact of weed resistance to more than one MOA threatens to be economically devastating because of the scarcity of alternative herbicide choices (Vencull et al. 2011). Farmers may not have another herbicide MOA to go to when resistance to PSII, ALS, PPO, and EPSPS inhibitors becomes more widespread in one of our most common and troublesome weed species, the Amaranthus species (Vencill et al. 2011). A single weed control measure is not feasible due to the number of different weed species, their highly variable life cycles, and survival mechanisms (Shaw, 1982). In addition, controlling weeds with only one method gives weeds a chance to adapt to those practices (Knezevic and Cassman, 2003). Hence, systems-oriented approaches to weed management that make better use of alternative weed management tactics need to be developed (Kruidhof et al., 2008).

1.3. Weed control in organic agriculture

Organic agriculture is one of the fastest-growing sectors of U.S. agriculture, with sustained growth of approximately 20% per year for the last 15 years (Oberholtzer, et al. 2005). Sales of organic products were estimated at $1 billion in 1990 and reached $10 billion in 2003 or around 1.8% of total US food market (Thilmany, 2006). In 2006, sales of organic products exceeded $16 billion in the US and reached $40 billion globally, with no drop in this market expected in the near future (Yussefi and Willer, 2007). These favorable market opportunities for organic products in past decades (Delate et al., 2003) have given a strong economic incentive for organic producers to protect their crops from yield loss and to increase the efficiency of their crop production.

The problem of controlling weeds without herbicides has been cited numerous times as the single largest obstacle for organic producers (Walz, 1999). Lacking the equivalent of inexpensive and nearly complete chemical weed control, organic farmers rely on multiple weed suppression tactics, each of which is individually weak but cumulatively strong. Liebman and Gallandt (1997) characterized these multiple techniques as the use of “many little hammers”, in contrast with the single “big hammer” that herbicides and transgenic crop technology provide in conventional agriculture. This approach advocates the use of cultural measures that keep direct interventions to a minimum. The aim is to maintain balance between crop plants and weeds, with the grower adjusting the balance in favor of crop whenever possible (Bond and Grundy, 2001). Crop rotation is the essential part of this system, although selection of a well-adapted crop variety or hybrid with good early season vigor, appropriate planting patterns, optimal plant density, scheduling planting operations and improved timing and amount of manure application are usually linked and all contribute in different ways to manipulation of the weed population (Swanton and Murphy, 1996).

In agricultural row crops, such as corn and soybean, indirect cultural practices are usually not sufficient in controlling weeds below the economic threshold (Gunsolus, 2011). Therefore, organic producers relay extensively on mechanical cultivation and hand weeding for their weed control. However, repeated cultivation can accelerate loss of soil organic matter, destroy soil aggregate, increase the chance for soil erosion and promote emergence of new weed flushes (Wszelaki et al., 2007). The labor required for hand weeding is expensive (e.g., ranging from \$700 to \$1200 ha^{-1}), time consuming and difficult to organize (Kruidhof et al., 2008). Hence, alternative weed control methods need to be developed (Kruidhof et al., 2008).

1.4. Flaming - alternative method for weed control

1.4.1. Brief history of flame-weeding

Knezevic and Ulloa (2007) reported that propane flaming is one of the most promising alternatives for weed control in organic cropping systems, and it has potential to be used in conventional crops as well (Bond and Grundy, 2001). Flaming, however, is not a new tool for weed control. First use of flaming dates back to 1852, when John A. Craig of Arkansas patented a machine for selective flame-weeding in sugar cane (*Saccharum officinarum*). The extensive use of flame weeding didn't begin until mid-

1940s at the time when liquid fuels (kerosene and oil) were replaced with more efficient liquefied petroleum gasses (propane and butane) (Edwards, 1964). Soon after that, application procedures for selective flaming were developed in many crops, including cotton, corn, soybeans, sorghum, beans, alfalfa, and also different fruit and vegetable crops (Hansen and Gleason, 1965; Lalor and Buchele, 1969; Parks, 1964, 1965; Thompson et al., 1967). Parks (1964) estimated that there were 15000 thermal control units in use for different row crops in the U.S. alone in 1964. However, popularity of flaming started to decline in late 1950s due to rising liquid propane-gas (LP-gas) prices and the availability of less expensive and more efficient herbicides (Daar, 1987).

Recent concerns regarding the herbicide use such as negative effects of the environment, elevated prices and increased prevalence of herbicide-resistant weeds renewed interest in this practice (Seifert & Snipes, 1996). Since the introduction of organic certification in 1980, propane flaming has been steadily gaining popularity among organic farmers, who are always looking at ways to control weeds effectively and economically without herbicides.

1.4.2. How flaming works

It is a misconception that plant tissue ignites during flaming treatment. Flaming kills weeds by exposing plant tissue to an intense wave of heat (Leroux et al., 2001). Thus, it is a combination of thermal energy applied to the plant and exposure time that determines effectiveness of flaming (Ascard, 1995; Seifert & Snipes, 1996). It is reported in the literature that temperatures necessary to kill the plants range from 55 to 94^{o}C (Proterfield, 1971), which can be achieved with exposure time of 0.65 to 0.13 seconds (Daniell et al., 1969). Propane burners generate waves of heat with combustion temperatures of up to 1900^{o}C, which increases the internal temperature of the exposed plant tissues rapidly (Ascard, 1998). Direct heat injury results in denaturation of membrane proteins, which results in loss of cell function (Lague et al., 2001; Parish, 1990; Pelletier et al., 1995; Rifai et al., 1996) and eventually the plants die or their competitive ability is drastically reduced.

The effectiveness of flaming treatment can be assessed by pressing a treated weed leaf between the thumb and index finger – the so called “fingerprint test” (Knezevic et al., 2012). If a darkened impression is visible after firmly pressing on the leaf surface, it is likely evidence of a loss of internal pressure within the leaf due to water leakage from ruptured cell walls (Knezevic et al., 2012).

1.4.3. Advantages and disadvantages of flame-weeding

Flaming has a few advantages over herbicide application: (1) it leaves no chemical residues in plants, soil, air or water, (2) produces no drift hazards or herbicide carry-over to the next season and (3) can control herbicide-tolerant or resistant weeds (Nemming, 1994; Wszelaki et al., 2007). Flaming also provides benefits over mechanical cultivation and hand weeding. Because it does not disturbs the soil, flaming (1) does not bring buried weed seeds to the surface where germination is likely to occur, (2) reduces potential for soil erosion, (3) can be used when fields are too wet or stony for cultivation (Rifai, 1994), (4) it is less costly than hand weeding, and (5) it might provide benefits in insect or disease control (Lague et al., 1997; Seifert & Snipes, 1996).

The disadvantages of flame weeding when compared to conventional herbicides include: (1) higher cost of equipment compared to herbicide applicators, (2) lack of selectivity for crop safety, (3) low speed of application, (4) low field capacity due to narrow working widths and (5) lack of residual weed control (Ascard, 1995; Ascard et al., 2007). Most of the available flame weeding equipment may have almost the same capacity as mechanical cultivator for weed control, but are usually slower equipment than the ones for chemical weed control (Ascard et al., 2007).

1.4.4. Impact of propane flaming on the environment

During the flaming process the important greenhouse gas CO_2 is released to the Earth's atmosphere due to combustion of propane gas and diesel fuel consumed by the tractor utilized for carrying a flaming implement. Ulloa et al. (2011) conducted an experiment in which CO_2 emissions were estimated. Based on their estimations, a propane dose of 60 kg/ha produces 188.9 kgCO_2/ha (180.0 kgCO_2/ha from propane combustion plus 8.9 kgCO_2/ha from the diesel consumption). However, a banded flaming treatment produces 90.8 kgCO_2/ha, which can reduce CO_2 emissions by 67%. This could be compared, for example, with emissions from manufacturing and applying the recommended dose of glyphosate (98.2 kgCO_2/ha) (Ulloa et al., 2011). Although the high energy requirement and the release of carbon emissions could be seen as a disadvantage, propane fueled flame-weeding is applied on a much smaller scale compared to conventional herbicides (e.g. glyphosate) and its combustion is relatively clean compared to other fossil fuels (Ascard et al., 2007). In order to negate impact on the environment, flaming should be used less frequently (e.g. once per season) and along with herbicides or other weed control methods (Williford et al., 1973).

1.4.5. Economic aspects of propane flaming

Propane flaming is generally considered to be an inexpensive weed control measure. Contrary to the belief of many, fuel consumption is not the most expensive part of the total cost of a flaming treatment. Doses of propane that are commonly recommended in agronomy cost similarly to or lower than that of herbicides (Ascard, 1988). However, the total cost is greater mainly due to high purchase price of flaming machinery and low field capacity (Ascard, 1988). Other constraints that might influence total cost of flaming application include an inability for easy refill of a propane tank in the field. Obradovic et al (2011) compared the cost and benefits of various weed control treatments in corn and soybean. Treatments included: hand weeding, mechanical cultivation, broadcast flaming, flame/cultivation and several herbicide applications. The authors found that flame weeding alone conducted twice (cost $25/acre), or combined with mechanical cultivation (as banded flaming at cost of $16/acre) was much more profitable than hand weeding alone ($200/acre). Production of corn using this combination of mechanical cultivation (at V3-V4 growth stage) and banded flaming (V6-V7) could bring net revenue from $681 to $1284/acre depending on the price of grain. Calculations from this study indicate that flaming treatment was more expensive than mechanical cultivation; however, it was considered to be more profitable due to higher efficacy in controlling weeds.

1.5. Factors influencing flaming efficacy

Multiple factors influence the efficacy of flaming treatment. Biological factors are generally considered to be the most important and are reflected in plants' ability to tolerate heat and recover after flaming treatment. However, the extent to which heat from the flames penetrates plants also depends on optimizing the design parameters of flame-weeding equipment (procedural factors) and environmental factors (Parish, 1990). In the following sections how these factors influence the response of weeds and crops to propane flaming will be discussed.

1.5.1. Biological factors – plant response to propane flaming

The two most vital biological factors include: (1) plant size and (2) degree of exposure of the growing point at the time of flaming. Other biological factors such as presence of protective layers of hair and/or wax, lignification level, and condition of the overall plant water status have been shown to influence plant response to broadcast flaming (Ascard, 1995; Datta and Knezevic, 2013); however, there has been no extensive research conducted to evaluate the impact of these parameters on propane flaming efficacy.

1.5.1.1. Plant size

In general, larger plants are more tolerant to flaming than smaller ones. This is mainly due to greater surface of leaves and stem and greater plant biomass to heat ratio; thus, higher temperature and longer exposure is necessary to achieve control. Furthermore, as the plants get larger stems and leaves become more robust and some anatomical features such as presence of hair and/or wax or lignification level become more prevalent. In contrary, thin and delicate plant tissues and lower shoot biomass at the early vegetative stages are very heat sensitive. In addition, regrowth capacity of smaller plants is severely reduced because the growing point that is located in the shoot apex is permanently damaged (Ascard, 1995; Datta and Knezevic, 2013). In older plants, the shoot apex is often protected by the surrounding leaves and the larger amount of reserve food in the roots; thus, plant's capacity for regrowth is increased (Ulloa et al., 2010a,b). In dose–response studies done by Ascard (1994), a propane dose of 40 kg/ha was required to achieve 95% control of white mustard (Sinapsis alba L.) at 0 to 2 true leaves, while a higher dose was required (70 kg/ha) for the same level of weed control when plants were at 2 to 4 leaf stage. In similar study conducted by Ulloa et al (2010a,b), 90% dry matter (DM) reduction in velvetleaf was obtained with 42, 56 and 102 kg/ha of propane for 5-leaf (L), 7-L and 16-L stages, respectively, suggesting that larger velvetleaf was much more tolerant than the smaller one. Other studies also showed similar trends of increased tolerance to propane flaming with increase in plant size (Cisneros and Zandstra, 2008).

1.5.1.2. Exposure of the growing point at the time of flaming

It is frequently reported in the literature that weeds and crops with protected growing points are more likely to survive and recover after flaming treatment. The best example of this is a differential tolerance of grass and broadleaf species. Grassy weeds were more difficult to control with flaming than broadleaf weeds because their growing point is either below the soil surface (early growth stages) or well protected by the bundle of leaves (later growth stages). In contrast, the growing point in broadleaf weeds is always above the ground, thus exposed to the flame. This concept is extended to crops as well, given that grass-type crops such as corn or sorghum are much more tolerant to flaming than broadleaf crops such as soybean.

The most recent report by Knezevic et al. (2012) summarizes the tolerance of different grasses and broadleaf weed species (commonly found in Nebraska) to propane flaming at various growth stages. According to the authors, grass species including green foxtail, yellow foxtail, and barnyardgrass were controlled to 80% with average propane doses of about 42 kg/ha at early growth stages and about 57 kg/ha at later growth stages. Broadleaf species including common waterhemp, redroot pigweed, field bindweed, kochia, ivyleaf, morningglory, velvetleaf, Venice mallow, common ragweed, common lambsquarters, tansy mustard, and henbit were effectively controlled (90%) with propane dosages of about 50 kg/ha at early growth stages to about 75 kg/ha when flamed at later growth stages. Knezevic (2012) also suggested that repeated flaming over several years might be necessary to achieve a complete kill of some perennial and biennial weed species.

Knezevic’s findings are largely in agreement with classification done by Ascard (1995) almost two decades ago. Ascard (1995) classified weeds into four groups with respect to their tolerance to flaming, and degree of exposure of the growing point was the main criteria of classification. The first group consisted of sensitive species [e.g. common lambsquarters (Chenopodium album L.)] with unprotected growing points, that were completely killed with single flaming at relatively low doses (20-50 kg/ha), regardless of the growth stage. The second group consisted of moderately sensitive species [e.g. common knotgrass (Polygonum aviculare)] with a prostrate growth habit and protected growing points, that were controlled by single flaming but required propane doses higher than 50 kg/ha. The third group contained flame tolerant species such as shepherd's purse (Capsella bursa-pastoris), that have protected meristems and could only be completely controlled only at early growth stages. The fourth group consisted of very tolerant species with a creeping habit and well protected growing points (e.g. perennial broadleaf and grasses) that cannot be completely killed by single flaming treatment regardless of dose or developmental stage.

1.5.2. Environmental factors

1.5.2.1. Time of the day

Previous reports indicate that efficacy of the flaming application can be influenced by time of day (Ulloa et al., 2012; Wszelaki et al., 2007). Wszelaki et al. (2007) studied propane flaming in cabbage and tomato and found that flaming was more variable and sensitive to environmental conditions and control was of shorter duration than generally expected of herbicides. In this study, flaming in the morning resulted with better weed control and higher crop injury than flaming in the afternoon. This is in contrast to what was found by Ulloa et al (2012) who reported that plants were more susceptible to flaming during the afternoon when relative water content (RWC) in the leaves was lower. For instance, velvetleaf response at 7 days after treatment was such that propane dose of 87 kg/ha caused 80% injury when flaming was conducted at 0 hours after sunrise (HAS), whilst 93% injury was observed when plants were flamed at 12 HAS. The same trends in response were observed with other species evaluated including green foxtail, corn and soybean. Authors suggested that flaming should be conducted during afternoon because it improves the efficacy of weed control and reduces propane consumption rate (Ulloa et al., 2012).

1.5.2.2. Leaf surface moisture

Presence of moisture on the leaf surface can reduce the efficacy of flaming treatment because a portion of the thermal energy applied to kill the weeds is necessary the evaporation of the water (Knezevic et al., 2012). Parish (1990) found that flaming efficacy was reduced with increased amount of water applied (90-360 g/m^2) to the leaf surface. In a study conducted by Bertram (1991), nearly linear decrease in heat transfer to the plants was observed with increasing leaf surface moisture in the range from 0 to 50 g/m^2. If conditions are wet, higher doses of propane are required to achieve the equivalent of flame-weeding efficacy that occurs in dry conditions. The advantages of wet conditions might include increase in safety of flaming application by reducing the chance of igniting the plant residual material and decreasing the potential for severe crop injury (Knezevic et al., 2012).

1.5.2.3. Wind

Although flaming treatment has no potential for drift hazards, which are common to herbicide application, higher wind velocities, different wind directions (relative to the traveling direction) and wind gusts can change the predictable shape and pattern of the flames coming out of the burners. Some designs of flaming equipment might have advantages over the others, for example: (1) open flames without cover are more sensitive to wind conditions then covered flames (Ascard, 1995); or (2) torches positioned parallel to the crop row provide the advantage of being able to adjust traveling direction to the direction of wind, while the equipment with torches positioned perpendicular to the crop row don't have that ability. In order to increase safety and efficiency of flaming operation Ulloa (2011) suggested that flaming application should be conducted when the wind speed is less than 10 km/h.

1.5.3. Technical factors

Overall, technical factors can be divided into non-specific and crop-specific factors. Non-specific factors control heat applied to the targeted plants and duration of exposure of targeted plants to the source of heat (Lague et al., 1997); thus are responsible for the delivery of a particular propane dose in which one is interested. These factors do not determine selectivity to any crop (non-specific), are common to all flaming equipment available on the market, and include the following parameters: (1) gas operating pressure - which regulates of the amount of heat applied to plants, (2) nozzle type – which determines flame shape, and (3) travel speed – which is a measurement of the duration of exposure of targeted plants to the source of heat.

Crop-specific factors include optimizing equipment design parameters that improve selectivity of flaming in a given crop. There are several equipment components that are common to all flame-weeding equipment available on market: support structure (either frame or cultivator), supply tank, supply network with pressure gauge and pressure regulator, and flaming torch (Knezevic, 2012). However, particular design parameters that determine selectivity of flaming equipment include: (1) burner type, (2) burner configuration (number, height, angle and orientation) and (3) usage of open or covered flames (Ascard, 1995). When designing optimal flaming procedures these parameters should not be evaluated individually because they highly interact with each other. For example, burner types that produce thin, broad and short flames are more suitable for open torch selective flaming, while tabular burners that produce long and narrow flames are better suited for non-selective covered (or hooded) flaming (Holmoy and Storeheier, 1995). Similarly, burner height and angle will depend on the type of burner. If burner is too close to the ground flames will tend to deflect upwards or if burner is set too high hot part of the flames will not reach the weeds (Parish, 1989). Burner angles usually range from 22 to 90^o (Storeheier, 1994) depending on the torch used, but most authors recommend 30 to 45^o burner angles for selective flaming in row crops (Ascard, 1995). Using a cover over the burner is evaluated to be up to 60% more energy efficient than open burner (Ascard, 1995; Bruening, 2009); however, implementing cover might be limited by burner orientation (Stoeheier, 1994) or may cause problems of oxygen deficiency during propane combustion (Luttrell and Bennett, 1968).

1.6. Pre-emergence flaming

Similarly to herbicide applications, flaming treatments can be categorized as pre-emergence or post-emergence treatments. Pre-emergence flaming kills the first flush of weeds before the crop emerges. This is often the largest group of weeds to germinate during the season. The idea is to provide the alternative to shallow tillage that promotes new weed flushes by disturbing the soil. During the pre-emergence flaming application torches are positioned parallel to the travelling direction and usually covered with some kind of a hood to increase propane use efficiency (Ascard 1995). This technique is most commonly used in vegetable production where weeds are killed following the preparation of stale seedbed or just before vegetable seedlings emerge (peak emergence method) (Diver, 2002; Chapell and Ellwandger, 1969).

With stale seedbed technique planting is delayed and weeds are allowed to germinate. Flaming kills weeds without bringing new seeds to the surface and the vegetable crop is seeded in a weed-free bed. Sometimes the seedbed is pre-irrigated to stimulate weed emergence before flaming. Peak-emergence flaming technique is primarily used in slow germinating crops such as carrots, beets, parsnips, etc. (Diver, 2002; Daar, 1987; Bevan, 2000). When this technique is used vegetable crops are sown promptly and flaming application is timed just before crop emergence so that the maximum numbers of emerging weeds are exposed to the treatment (Daar, 1987). Although pre-emergence flaming controls only a fraction of the weeds that emerge during the growing season, it can still provide sufficient weed suppression allowing a crop the formation of full canopy closure, which inhibits future weed emergence. Previous reports indicate pre-emergence flaming treatment in onions, carrots, lettuce and cabbage can reduce weed population by 80%, depending on the timing of the treatment (Ascard, 1990; Balsari et al., 1994; Casini et al., 1993; Nemming, 1993; Netland et al., 1994; Rafai et al., 1996;).

1.7. Post-emergence flaming

Flaming can also be applied once the crop has emerged (post-emergence). Such treatment is selective and aims to direct the heat towards the weeds while avoiding damaging the crop (Knezevic, 2012). Selectivity of flaming treatment is achieved partially by adjusting the propane dose to a level that the crop can tolerate (Morelle, 1993), and partially by adjusting different technical parameters of the flaming equipment (e.g. burner type, burner setting, etc.). In order to achieve the maximum level of selectivity biological and technical factors should always be used in a complementary manner (Ascard, 1995).

1.7.1. Cross-flaming

In agronomic row crops post-emergence flaming is accomplished either by cross-flaming or by parallel-flaming (Sullivan, 2001). Most of the studies that investigated technical aspects of selective flame weeding in agronomic row crops recommend cross-flaming set up (Figure 1.1). In this set up open torches are usually angled down 30-45^{o} , 10-25 cm from the crop, and set perpendicular to the travelling direction in a staggered pattern so that flames that oppose each other do not collide (Ascard, 1995; Vester, 1985;). During the treatment heat is distributed from the base of the plant in the directions outwards, upwards and along the plant row (Anderson, 1997), selectively killing the weeds within the crop row. Anderson (1997) has developed a model that describes the heat dispersion and it can be used to select and evaluate suitable burners. Currently, there are three main flame weeding companies that provide technical support for flame weeding equipment, (1) Thermal Weed Control Systems, Inc. of Neillsville, WI and (2) Flame Engineering of LaCrosse, KS, (3) Agricultural flaming innovations and former tow companies recommend using cross-flaming set up for selective flaming in row crops (Sullivan, 2001). Although this method has been widely accepted, it has some major disadvantages: (1) it cannot be used early in the season when the crops are small (corn <10 cm , soybean <30 cm) because it causes severe crop injury, (2) it provides only weed control in intra-row space, (3) it cannot take the advantage of hooded flaming that is proved to be more energy efficient (up to 50%) than flaming with open torches (Luttrell and Bennett, 1968; Ascard, 1995; Bruening 2009), (4) changing torch configuration when flaming is combined with cultivation might be limiting (Leroux et al., 2001) and (5) lower heat exposure time on the weeds, which results in lower weed control (Ascard 1995).

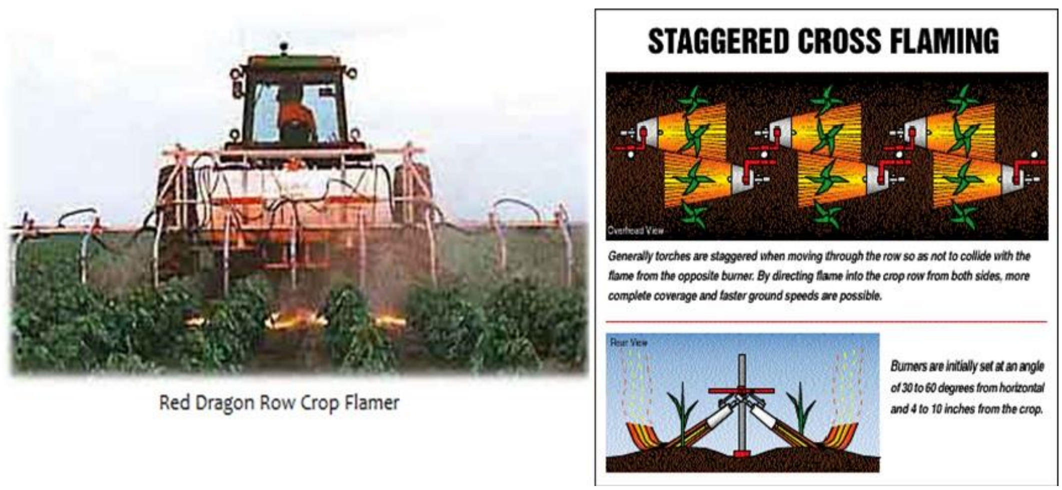

Figure 1.1. Flame-weeding unit preforming cross flaming treatments as recommended by Flame Engineering of LaCrosse, KS

1.7.2. Parallel-flaming

Parallel-flaming was developed along with the discovery of the midget burner in the late 1950s in Arkansas. Alternative options for early season weed control in cotton were needed, as the existing cross-flaming method caused serious burn damage and significant yield reduction (Trupper and Mathews, 1954). Work by Stephenson (1962) indicated that for early flaming of cotton when plants are 10-15 cm, turning the burners parallel to the row has given the best results. During the parallel flaming treatment, a high-velocity stream of intense heat is directed onto the weeds on either side of the crop row. As the stream strikes the row surface a fan-shaped pattern of heat distribution results deflecting a small portion of the heat into the crop row (Stephenson, 1962). This set up provided the following advantages over cross-flaming: (1) it can be applied earlier and reduce the height of leaf kill from 20-30 cm to about 10 cm (2) larger weeds can be controlled over a wider area of the row, (3) the precision of the burner settings and the smoothness of the row is less critical (Fitzgerald, 1963). More recent studies by Neilson (2012) suggested that positioning torches to shoot flames down the crop row creates a more predictable and easily controlled symmetrical temperature profile. Another advantage of parallel flaming is that shields can be employed to increase propane use efficiency and protect the crop from the intense heat (Ascard, 1995; Bruening, 2009). This method has gained fairly wide acceptance in the Cotton Belt in the 1960s; however, its practical use in other crops is seldom reported in the literature.

1.8. Combining flaming and mechanical cultivation

Mechanical cultivation was one of the most widespread weed control practices in row crops before the introduction of more efficient chemical herbicides. However, in the past two decades, mechanical weeders are gaining popularity, particularly among organic farmers. There are many different types of mechanical weeders that use cultivating tools such as hoes, harrows, tines and brush weeders, cutting tools like mowers and strimmers, and dual-purpose implements like thistle-bars (Bond and Grundy, 2001; Bowman, 1997).

However, burial to 1-cm depth, and cutting at the soil surface are considered to be the most effective ways to control weed seedlings mechanically (Jones et al., 1995.).

In organic row crop production systems, where use of herbicides is not allowed, farmers usually depend on multiple between row cultivations for their weed control (Mulder and Doll, 1993). However, cultivations remain to be ineffective because it leaves a strip of weeds that remains within the crop row. These weeds present the greatest challenge in mechanical cultivation, as they directly influence crop performance (Mulder and Doll, 1993). Flaming has the potential to remove these weeds without significantly damaging the crop, thus it can be combined with between-row cultivation to yield a more compete and more efficient weed control method.

The use of a flaming treatment in conjunction with conventional sweeps has proved to be an effective production practice. The potential of this method was first recognized by S. B. Jones of Illinois in the early 1900s, who patented an attachment (fuel tank and two burners) to be mounted on a one-row cultivator (Edwards, 1964). Seifert and Snipes (1996) reported that two flame cultivations (flaming in conjunction with sweeps that cut off weeds between the rows) provided acceptable weed control in cotton. Leroux et al. (1995) found that post-emergence flame cultivation (flaming + cultivation) conducted two times during the season at early (2-3-leafs) and later (6-7-leafs) growth stage did not have a negative impact on corn yield, when used after pre-emergence rotary hoe or broadcast flaming. Larson (1960) reported that flaming in combination with cultivation can be an effective tool in controlling most annual and some perennial weeds when properly used. By cultivating the row middles and flaming the crop row area simultaneously with one tractor unit, man power requirements are cut in half, machine operating costs are materially reduced, and excessive machine traffic through the field is eliminated (Larson 1960).

1.9. Research objectives

Flame weeding already showed to be an effective weed control method in agronomic row crops if properly used. Yet, there is a lack of information on how flaming can be utilized to control weeds in early spring (pre-emergence). In order to develop optimal flaming procedures for pre-emergence weed control more knowledge is needed on how various weed species, commonly found in early spring, respond to flaming treatment.

So far, practical use of the parallel-torch setup has been limited to selective flaming in cotton which dates back in 1960s, and non-selective pre-emergence weed control in vegetable production. More knowledge is needed to develop recommendations for post-emergence parallel flaming in other row crops such as corn and soybean. Since more than one application might be necessary to control the weeds throughout the season, crop tolerance to multiple flaming treatments using recommended propane dosages must be determined. Furthermore, crops' response to parallel flaming treatments must be evaluated in real field conditions where weeds and crops are growing together. Even though this method has existed for a long time, it has not been tested recently; thus, effectiveness of parallel flaming procedures in row crops should be compared with most common weed control practices such as cultivation and hand weeding.

Specifically, the purpose of this study was to:

1.) Describe dose–response curves for propane when flaming selected weed species at different growth stages (Chapter 2)

2.) Determine corn and soybean tolerance to single and repeated flaming by utilizing the equipment designed to selectively flame weeds in row crops with torches positioned parallel to the crop row (Chapters 3 and 4)

3.) Determine the effectiveness of flaming and cultivation for weed control management under two manure levels in organic corn and soybean (Chapters 5 and 6)

1.10. References

Anderson J (1997) Experimental trials and modeling of hydrogen and propane burners for use in selective flaming. Biological Agriculture and Horticulture 14:207-219

Anderson WP (1983) Weed Science: Principles - 2nd edition. West Publishing Co

Ascard J (1988) Termisk ogräsbekämpning. Flamning för ogräsbekämpning och blastdödning. (Summary: Thermal weed control. Flaming for weed control and crop defoliation). Report of Swedish University of Agricultural Sciences - Department of Agricultural Engineering 130:146. Alnarp, Sweden

Ascard J (1990) Thermal weed control with flaming in onions. Proceedings of the 3rd International Conference on Non-chemical Weed Control175:188. Linz, Austria.

Ascard J (1994) Dose–response models for flame weeding in relation to plant size and density. Weed Res 34:377–385

Ascard J (1995) PhD Dissertation: Thermal Weed Control by Flaming: Biological and Technical Swedish University of Agricultural Sciences - Department of Agricultural Engineering. Ultuna, Uppsala, Sweden

Ascard J (1998) Comparison of flaming and infrared radiation techniques for thermal weed control. Weed Res 38:69–76

Ascard J, Hatcher PE, Melander B, Upadhyaya MK (2007) Thermal weed control. In “Non-chemical Weed Management” (MK Upadhyaya and RE Blackshaw, Eds.) Chapter 10:155–175. CAB International, Wallingford, UK.

Ashton FM, Monaco TJ (1991) Weed Science - Principles and Practices, 3rd Ed. John Wiley and Sons

Balsari P, Berruto R, Ferrero A (1994) Flame weed control in lettuce crop. Acta Horticulturae 372:213-222

Bertram A (1991) Thermodynamische Grundlagen der Abflammtechnik. Diplomarbeit. Technische Universität München, Institut für Landtechnik:110. Weihenstephan, Germany

Bevan J (2000) Tackling weeds in the row. Organic Farming 67:17-20

Bond W, Grundy AC (2001) Non-chemical weed management in organic farming systems. Weed Res 41:383–405

Bowman G (1997) Steel in the Field: A Farmer's Guide to Weed Management Tools. Burlington VT: Sustainable Agriculture Publications, University of Vermont. Vermont, USA

Bridges DC (1992) Crop Losses Due to Weeds in the United States. Weed Sci Soc Am Champaign II:403

Bruening CA (2009) Development of Propane Flaming Equipment for Thermal Weed Control in Agronomic Crops. M.S. thesis, The University of Nebraska-Lincoln. Lincoln, NE.

Casini P, Calamai P, Vecchio V (1993) Flame weeding research in Central Italy. Communications of the 4th International Conference I.F.O.A.M 119:125. Dijon, France

Chapell EW, Ellwandger CT (1969) Control of weeds in direct seeded crops by pre-emergence flaming. Proceedings Sixth Annual Symposium on Thermal Agriculture: 25-26. Atalanta, Georgia, USA

Cisneros JJ, Zandstra BH (2008) Flame weeding effects on several weeds species. Weed Technol 22:290–295

Coble HD, Ritter RL (1978) Pennsylvania Smartweed Interference in Soybean. Weed Sci 26:556-560

Coble HD, Williams FM, Ritter RL (1981) Common Ragweed Interference in Soybean. Weed Sci 29:339–342

Daar S (1987) Update: Flame weeding on European farms. The IPM Practitioner XI 3:1-4

Daniell JW, Chapell WE, Couch HB (1969) Effect of sub-lethal and lethal temperature on plant cells. Plant Physiology 44:1684-1689

Datta A, Knezevic SZ (2013) Flaming as an alternative weed control method for conventional and organic agronomic crop production systems: a review. Adv Agron 118:399–428

Delate K, Duffy M, Chase C, Holste A, Friedrich H, Wantate N (2003) “An Economic Comparison of Organic and Conventional Grain Crops in a Long-Term Agroecological Research (LTAR) site in Iowa.” The American Journal of Alternative Agriculture 18(2):59-69

Diver S (2002) Flame weeding for vegetable crops. ATTRA, NCAT:16. www.attra.ncat.org/attra-pub/PDF/flameweedveg.pdf

Duke SO (2011) Why have no new herbicide modes of action appeared in recent years?. Pest Manag Sci. 68:505-512

Edwards FE (1964) History and Progress of Flame Cultivation. Proceedings of the First Annual Symposium of Research on Flame Weed Control: 3-6. Memphis, Tennessee, USA

Fitzgerald LW (1963) MS Thesis: Use of Flame as a Means to Control Weeds in Corn Production. Kansas State University. Manhattan, Knasas, USA

Gianessi L, Sankula S (2003) The Value of Herbicides in U.S. Crop Production. National Centre for Food and Agriculture Policy

Gianessi LP, Reigner NP (2007) The value of herbicides in U.S. crop production. Weed Tech 21:559-566

Gunsolus J (2011) Delayed planting, crop rotation keys to weed control in organic corn, soybeans. Ag News Wire - University of Minnesota Extention. St. Paul, Minnesota, USA

Halberg GR (1986) “From hoes to herbicides: Agriculture and groundwater quality”. J Soil Water Conserv 41(6):22-24

Hamner CL, Tukey HB (1944) Herbicidal action of 2,4-dichlorophenoxyacetic acid and trichlorophenoxyacetic acid on bind-weed. Science 100:154-155

Hansen MC, Gleason W (1965) Flame weeding of grapes, blueberries and strawberries. Proceedings of the 2nd Annual Symposium on the Use of Flame in Agriculture: 11-12

Hay JR (1974) Gain to the Grower from Weed Science. Weed Sci 22 (5):439-442

Holmoy R, Storeheier K (1995) Flaming: Fundamental knowledge and practical use in selective weed control. Proceedings EWRS 9th International Symposium on Challenges for Weed Science in a Changing Europe: 14. Budapest, Hungary

Jones AP, Blair MA, Orson J (1995) The effects of different types of physical damage to four weed species. In Proceedings 1995 Brighton Crop Protection Conference – Weeds: 653-658. Brighton, UK

Jordan TN, Coble HD, Waxet LM (1987) Soybeans: Improvement, Production and Use - 2nd Ed. American Soc. of Agron

King JL (1966) Weeds of the World-Biology and Control. Interscience Pub. Inc. New York, New York, USA

Knezevic SZ, Cassman KG (2003) Use of herbicide-tolerant crops as a component of an integrated weed management program. Online. Crop Management doi: 10.1094/CM-2003-0317-01-MG

Knezevic SZ, Dana L, Scott JE, Ulloa SM (2007) Building a research flamer. Proceedings of the North Central Weed Science Society Conference: 62:32. St. Louis, Missouri, USA

Knezevic ZS, Datta A, Bruening C, Gogos G (2012) Propane-Fueled Flame Weeding in Corn, Soybean, and Sunflower. Retrieved March 14, 2013, from University of Nebraska - Lincoln and PERC extension publication: http://www.agpropane.com/ContentPageWithLeftNav.aspx?id=1916

Koskinen WC, McWhorter CG (1986) Weed control in conservation tillage. J Soil Water Conserv 41:365-370

Kruidhof HM, Bastiaans L, Kropff MJ (2008) Ecological weed management by cover cropping: effects on weed growth in autumn and weed establishment in spring. Weed Res 48:492-502

Lague C, Gill J, Lehoux N, Peloquin G (1997) Engineering performances of propane flamers used for weed, pest insect and plant disease control. Applied Engineering in Agriculture 13(1):7-16

Lague C, Gill J, Peloquin G (2001) Thermal control in plant protection. Physical Control Methods in Plant Protection (C. Vincent, B. Panneton, and F. Fleurat-Lessard, Eds.): 35–46. Springer-Verlag, Berlin, Germany

Lalor FW, Buchele FW (1969) Thermal sensitivity of corn and soybeans to flame weeding. ASAE Paper 69-128. St. Joseph, Michigan, USA

Larson HG, Fairbanks LG, Fenton GF (1960) What does it cost to use Farm Machinery. University of Agricultural Experiment Station Bulletin 417

Leroux GD, Douheret J, Lanouette M, Martel M (1995) Selectivity of propane flamer as a mean of weed control. Hertscience 30(4):820

Leroux G D, Douheret J, Lanouette M (2001) Flame weeding in corn. Physical Control Methods in Plant Protection (C. Vincent, B. Panneton, and F. Fleurat-Lessard, Eds.): 47–60. Springer-Verlag, Berlin, Germany

Liebman M, Gallandt E (1997) Many little hammers: ecological approaches for management of crop-weed interactions. LE Jackson (ed.) Ecology in agriculture: 291-343

Liebman M, Janke RR (1990) Sustainable Weed Management Practices. In CA Francis, CB Flora, LD King - Sustainable Agriculture in Temperate Zones: 111-143

Loux MM, Diigab D, Dobbles AF, Reeb B, Johnson WG, Legleiter TR (2013) Weed Control Guide for Ohio and Indiana. Ohio State University Extention and Purdue Extention

Luttrell DH, Bennett SE (1968) Flaming equipment for thermal control of alfalfa weevil. Proceedings of Fifth Annual Symposium on Thermal Agriculture: 24. Atalanta, Georgia, USA

Morelle B (1993) Thermal weed control and its application in agriculture and horticulture. Communications of the 4th International Conference I.F.O.A.M. Non Chemical Weed Control: 111-116. Dijon, France

Mulder TA, Doll JD (1993) Integrating Reduced Herbicide Use with Mechanical Weeding in Corn (Zea mays). Weed Technology 7:382-389

Neilson B (2012) MS thesis: The Integration of Propane Flaming and Mechanical Cultivation for Effective Weed Control in Agriculture. Lincoln, Nebraska, USA

Nemming A (1993) Flame cultivation in row crops. Communications of the 4th International Conference I.F.O.A.M. Non Chemical Weed Control: 133-136. Dijon, France

Nemming A (1994) Costs of flame cultivation. Acta Hort 372:205–212

Netland J, Ballvoll G, Holmoy R (1994) Band spraying, selective flame weeding and hoeing in late white cabbage. Acta Horticulturae 372:235- 243

Oberholtzer L, Dimitri C, Greene C (2005) Price premiums hold on as organic produce market expands. Outlook Report VGS-308-01 USDA Economic Research Service: 22

Obradovic A, Datta A, Wilson R, Knezevic SZ (2011) Economic Analysis of Various Weed Control Treatments in Corn, Soybean, and Sunflower. Proceedings of 66th Annual Meeting of the North Central Weed Science Society: 10. Milwaukee, Wisconsin, USA

Oerke EC, Dehne HW, Schnbeck F, Weber A (1994) Crop Production and Crop Protection: Estimated Losses in Major Food and Cash Crops. Amsterdam, Netherlands

Pacanoski Z (2006) Herbicide-Resistant Crops - Advantages and Risks. Herbologia 7 (1):47-59

Pacanoski Z (2007) Herbicide use: benefits for society as a whole – A review. Pak J Weed Sci Res 13(1-2):135-147

Parish S (1989) Investigations into thermal techniques for weed control. Proceedings of the 11th International Congress on Agricultural Engineering: 2151-2156. Balkema, Rotterdam, Netherlands

Parish S (1990) The flame treatment of weed seedlings under controlled conditions. Crop protection in organic and low input agriculture, BCPC Monographs No.45:193-196. British Crop Protection Council, Farnham, Surrey, UK

Parks HJ (1964) Progress of flame cultivation in the Texas high plains and Rio Grande valley. Proceedings of the 1st Annual Flame Symposium: 8-17. Memphis, Tennessee, USA

Parks HJ (1965) Row crop flame weed control in the Texas high plains. Proceedings of the 2nd Annual Symposium on the Usw of Flame in Agric: 21-24

Pelletier Y, McLeod CD, Bernard G (1995) Description of sub-lethal injuries caused to the Colorado potato beetle by propane flamer treatment. J Econ Entomol 88:1203–1205

Porterfield GJ, Batchelder GD, Bashford L, McLaughlin G (1971) Two stage thermal defoliation. Proceedings Eight Annual Symposium on Thermal Agriculture: 32-34. Dallas, Texas, USA

Rifai MN, Zikla T, Mojzis M (1996) Flame and mechanical cultivation for weed control. ZemedelskÁ Technika 42:109-113

Rifai NM (1994) Flame and mechanical cultivation for weeds in Nova Scotia. The Techincal Workchop of the Atlantic Committee in Agricultural Engineering. Fredericton, New Brunswick

Seifert S, Snipes CE (1996) Influence of Flame Cultivation on Mortality of Cotton (Gossypium hirsutum) Pests and Beneficial Insects. Weed Technology 10:544-549

Shaw WC (1982) Integrated weed management systems technology for pest management. Weed Sci 30:2-12

Stephenson KO (1962) Mechanized Weed Control in Cotton. Arkanses Agricultural Experiment, Arcansas Farm Research 10:3

Stopes C, Millington S (1991) Weed control in organic farming systems. Proceedings of the Brighton Crop Protection Conference-Weeds: 185–192. Brighton, UK

Storeheier K (1994) Basic investigations into flaming for weed control. Acta Horticulturae 372:195-204

Sullivan P (2001) Flame Weeding for Agronomic Crops. http://counties.cce.cornell.edu/oneida/Agriculture/Ag/crops/flame%20weeding.pdf . Accessed 4-1-2013.

Swanton CJ, Murphy SD (1996) Weed science beyond the weeds: the role of integrated weed management in agroecosystem health. Weed Sci 44:437-445

Thilmany D (2006) The US Organic Industry: Important Trends and Emerging Issues for the USDA. Cooperative Extension, Colorado State University

Tompson J V, Scheibner AS, Tompson CW (1967) Flaming of alfalfa in Kentuchy for weevil and weed control - Results of 1967 winter. ASAE Paper 67:645. St. Joseph, Michigan, USA

Triplett GB (1985) Principles of Weed Control for Reduced-Tillage Corn Production. WSSA Monograph Series No.2

Triplett GB, Doren DM (1977) Agriculture Without Tillage. Scientific American 236(1):28-33

Trupper G, Mathews JB (1954) Early Flame Cultivation in Cotton. Arkansas Agricultural Experiment Far Research 11:4

Ulloa SM, Datta A, Knezevic SZ (2010a) Growth stage influenced differential response of foxtail and pigweed species to broadcast flaming. Weed Technol 24:319–325

Ulloa SM, Datta A, Knezevic SZ (2010b) Tolerance of selected weed species to broadcast flaming at different growth stages. Crop Prot 29:1381–1388

Ulloa SM, Datta A, Bruening C, Gogos G, Arkebauer TJ, Knezevic SZ (2012) Weed control and crop tolerance to propane flaming as influenced by the time of day. Crop Prot 31:1–7

Ulloa SM, Datta A, Bruening C, Neilson B, Miller J, Gogos G, Knezevic SZ (2011) Maize response to broadcast flaming at different growth stages: Effects on growth, yield and yield components. Eur J Agron 34:10–19

Vencill W, Grey T, Culpepper S (2011) Resistance of Weeds to Herbicides. Herbicides and Environment, Dr Andreas Kortekamp (Ed.), ISBN: 978-953-307-476-4. Available from: http://www.intechopen.com/books/herbicides-and-environment/resistance-of-weeds-to-herbicides

Vester J (1985) New experience with flame cultivation for weed control. Proceedings of the International Meeting on Flame Cultivation for Weed Control: 10-20. Opprebais, Belgium

Walz E (1999) Final Results of the Third Biennial National Organic Farmers' Survey. Organic Farming Research Foundation. Santa Cruz, CA, USA

Williford RJ, Wooten BO, Baker SR, Barrentine LW (1973) Water-shield flame cultivation for cotton and soybeans. Misissippi Agric and For Exp Stn Info Sheet: 1-2

Wszelaki AL, Doohan DJ, Alexandrou A (2007) Weed control and crop quality in cabbage [Brassica oleracea (capitata group)] and tomato (Lycopersicon lycopersicum) using a propane flamer. Crop Prot 26:134–144

Yussefi M, Willer H (2007) Organic Farming Worldwide 2007: Overview and Main Statistics. In: Willer, Helga and Yussefi, Minou (Eds.) The World of Organic

Agriculture - Statistics and Emerging Trends 2007, chapter 3: 9-16. IFOAM, Bonn, Germany

Zilberman D, Schmitz A, Casterline G, Lichtenberg E, Siebert JB (1991) The Economics of Pesticide Use and Regulation. Sci 253:518-522

CHAPTER 2. Growth stage impacts response of selected weed species to flaming

2.1. Abstract

Propane flaming could be an alternative tool for PRE control or suppression of early emerging weeds in organic and conventional crops. The objective of this study was to test the tolerance of selected early season weeds to broadcast flaming in no-till systems. Four winter annuals (tansy mustard, henbit, cutleaf evening primrose, and field pennycress), one summer annual (common lambsquarters), and one perennial (dandelion) species were included in the study. Except for dandelion, the response to propane flaming was evaluated at two growth stages. Flaming treatments were applied using an all-terrain vehicle mounted flamer moving 4.8 km h^{-1}, and propane pressure was adjusted to deliver doses of 0 (non-flamed control), 22, 34, 48, 67, and 90 kg ha^{-1}. The response of each species to propane doses was described by log-logistic models based on visual ratings of weed control and dry matter reduction. Response to broadcast flaming varied among species and growth stages. Common lambsquarters, tansy mustard, and henbit were more susceptible to flaming than cutleaf evening primrose, field pennycress, and dandelion. Based on visual ratings, propane doses between 54 and 62 kg ha^{-1} effectively controlled (90% control) common lambsquarters at the early growth stage (5-leaf), tansy mustard at both growth stages (9-leaf and flowering), and henbit (flowering). However, a higher propane dose (>80 kg ha^{-1}) was necessary to obtain 90% control of common lambsquarters in later growth stage (11-leaf) and early growth stage of henbit (9-leaf).

Cutleaf evening primrose, field pennycress, and dandelion exhibited higher level of tolerance to broadcast flaming. A 90% control of these species was not achieved even with the highest propane dose (90 kg ha^{-1}) utilized in the study. Results of this study indicates that a single application of broadcast flaming can be an effective tool for controlling tansy mustard, henbit, and common lambsquarters and temporary suppression of cutleaf evening primrose, field pennycress, and dandelion.

Nomenclature: Dandelion, *Taraxacum officinale* G.H. Weber ex Wiggers. TAROF; field pennycress, *Thlaspi arvense* L. THLAR; cutleaf evening primrose, *Oenothera laciniata* Hill. OEOLA; henbit, *Lamium amplexicaule* L. LAMAM; tansy mustard, *Descurainia pinnata* (Walt.) Britt. DESPI; common lambsquarters, *Chenopodium album* L. CHEAL.

Keywords: Flaming, dose–response, growth stage, nonchemical weed control.

2.2. Introduction

The widespread adoption of glyphosate-resistant crops and repeated use of glyphosate over the past decade has imposed unprecedented selection pressure on weed populations, which has resulted in an increase in winter annual species (Knezevic 2007; Knezevic et al. 2009) and glyphosate resistance (Heap 2013). Some other factors that have contributed to the overall increase in winter annuals include: adoption of conservation tillage (no-till and minimum tillage), reduced reliance on soil-applied herbicides, the lack of POST herbicides with residual activity, and mild winters over the last decade (Knezevic 2007; Knezevic et al. 2009; Krausz et al. 2003).

Most winter annuals complete their life cycles by the end of spring, or early summer, which can cause various crop production issues (Fishel et al. 2000). For example, the presence of winter annuals in early spring can interfere with crop planting or tillage operations, or delay crop emergence by slowing down soil warming. Winter annuals can also compete for nutrients during crop establishment, and certain weed species can serve as alternative hosts for various pests (e.g., henbit to soybean cyst nematode) (Dahlke et al. 2001; Venkatesh et al. 2000). If soil moisture is limited, controlling winter annuals in the fall can decrease their occurrence in the spring, thus directly helping conserve the soil moisture needed for crop establishment. If winter annuals have been allowed to produce seed for several years, the weed seed bank for those species will likely increase and require annual control (Sandell et al. 2008).

With reduced tillage practices in dry-land cropping systems, where soil moisture is the most limiting factor, organic farmers have limited options to control spring-emerging weeds. In contrast, the conventional producers typically rely on herbicides such as glyphosate to control spring-emerging weeds. However, there is a rapid worldwide increase in populations of herbicide-resistant weeds due to the extensive and repeated use of herbicides for weed control (Owen and Zelaya 2005). In addition, the general concerns about leaching of herbicides into surface and ground water contaminating drinking water and food have raised public awareness that has led many countries to develop policies mandating the reduction of herbicide use (Rifai et al. 2002; Wszelaki et al. 2007). Therefore, it is important to evaluate alternative and integrated weed management practices to reduce negative effects of herbicide on the environment and human health. Propane flaming could be one alternative weed control method (Datta and Knezevic 2013; Knezevic and Ulloa 2007). Flame weeding is an acceptable weed control option in both organic and conventional production systems (Bond and Grundy 2001). Propane flaming is much more affordable than many other weed control methods used by organic producers, especially those of hand weeding and organic herbicides (Boyd et al. 2006; Ulloa et al. 2011). Moreover, propane flaming can control herbicide-tolerant or resistant weeds and weeds are less likely to become resistant to heat from flaming (Knezevic et al. 2012; Wszelaki et al. 2007).

Flaming is a foliar contact treatment that kills plants by an intense wave of heat that ruptures the plant cells resulting in loss of water and plant death (Pelletier et al. 1995; Rifai et al. 1996). Previous research has demonstrated that weed susceptibility to flaming varied among species and plant size (Ascard 1994, 1995; Cisneros and Zandstra 2008; Sivesind et al. 2009; Ulloa et al. 2010a,b). Ascard (1994) reported that growth stage of weeds at the time of flaming determines plant sensitivity to heat, with small weeds being more sensitive to flaming than large ones. Ulloa et al. (2010a,b) reported that broadleaf weeds are more susceptible to flaming than grasses, regardless of the growth stage. To our knowledge, dose–response studies with propane flaming for control of winter annuals and early spring-emerging weeds have not been conducted yet. To optimize the use of flaming for early spring weed control, the biologically effective dose (ED) of propane must be determined. Therefore, the objective of this study was to describe dose–response curves for propane when flaming selected spring-emerging weed species at different growth stages.

2.3. Materials and methods

Study Site and Experimental Design

Field experiments were conducted in 2012 at two sites at the Haskell Agricultural Laboratory, University of Nebraska, Concord, NE. Six broadleaf weed species were investigated in this study including common lambsquarters, tansy mustard, henbit, dandelion, cutleaf evening primrose, and field pennycress. Within each site, different areas that had uniform populations of a particular weed species were identified and a separate experiment was established for that weed species. Common lambsquarters, tansy mustard, henbit, dandelion, and field pennycress studies were conducted in no-till fields where previous crop was corn (*Zea mays* L.), while cutleaf evening primrose experiment was established in conventionally tilled fields.

The experimental design for all weed species was a split-plot, where the main-plot treatments were growth stages of the weed and the sub-plot treatments were six propane doses (0, 22, 34, 48, 67, and 90 kg ha^{-1}). Doses higher than 90 kg ha^{-1} were not considered in this study due to economic and potentially safety reasons (higher propane doses require higher operating pressure that can jeopardize integrity of the flaming machine's plumbing system). The only exception was dandelion, which was flamed only at one growth stage; thus, the experimental set up was a randomized complete block design with the same propane doses. The sub-plot treatments were applied to individual plots of 1.2 m × 6 m with three replicates. The growth stages for weed species were defined by number of true leaves (-L) or rosette diameter (RD), and reported with corresponding plant height (cm). The growth stages included were 5-L (4 cm height) and 11-L (11 cm height) for common lambsquarters; 9-L (9 cm height) and flowering (34 cm height) for tansy mustard; 9-L (17 cm height) and flowering (31 cm height) for henbit; flowering (10 cm RD, 13 cm height) for dandelion; 7 cm RD (2 cm height) and 18 cm RD (3 cm height) for cutleaf evening primrose; and 8-L (6 cm RD, 3 cm height) and 14-L (15 cm height) for field pennycress.

Flaming Specifications

Faming treatments were applied utilizing a custom built propane flamer mounted on a four-wheeler (all-terrain vehicle) which was driven through the plot (Figure 2.3). The flamer used propane as a source for combustion and there were four burners "LT 2 × 8 Liquid Torch" (Flame Engineering 2007) mounted 30 cm apart providing a 120 cm wide flaming swath. Burners were positioned 20 cm above the soil surface and angled back at 30^{o}. Flaming treatments were applied using a constant speed of 4.8 km h^{-1}. Calibration procedure was based on combining propane pressure and operating speed (Knezevic et al. 2012). Combining pressure and speed, the doses of propane applied were 0, 22, 34, 48, 67, and 90 kg ha^{-1}.

Measurements

Percent weed control was visually assessed at 21 d after treatment (DAT) using a scale from 0 to 100%, with 0 representing no weed control and 100 representing complete plant death. After visual ratings were conducted at 21 DAT, plants from 0.25 m^2 of each plot were cut at ground level and shoot dry matter (DM) was determined after drying at 70 C for 48 h. Plant DM was expressed as a percentage of non-flamed plants using a scale from 0 to 100.

Statistical analysis

ANOVA was performed by using the PROC MIXED procedure in SAS (SAS Institute 1999) to test for significance ($P < 0.05$) of sites, treatments, replications, and their interactions based on the visual ratings of weed control and DM data. Data were subjected to a non-linear regression analysis over propane dose using the four-parameter log-logistic model (Knezevic et al. 2007) where the upper asymptote was fixed to 100:

$$Y = C + (D - C)/\{1 + exp[B(logX - logE)]\} \qquad [1]$$

where Y is the response (e.g., percent dry matter reduction), C is the lower limit, D is the upper limit, B is the slope of the line at the inflection point, X is the propane dose, and E is the dose resulting a 50% response between the upper and lower limit (also known as inflection point, I_{50} or ED_{50}). All statistical analyses and graphs were performed with the open-source statistical software R (R version 2.10.1, R Development Core Team 2006) utilizing the dose–response curves statistical add-on package (Knezevic et al. 2007).

The data were combined over two sites as there was no treatment-by-site interaction. However, there was a significant effect of growth stage on the flaming treatment; therefore, the data were presented separately for each growth stage. The values of ED_{60} (60% control), ED_{80} (80% control), and ED_{90} (90% control) were determined from the regression model utilizing the delta method (Vaan der Vaart 1998; Ritz and Streibig 2005) and used as a measure of the level of weed control by flaming. It is important to mention that dandelion, cutleaf evening primrose, and field pennycress had a high level of tolerance to propane flaming, resulting in maximum of about 60% control. Therefore, the reported ED_{80} and ED_{90} values for those weed species calculated from the curve resulted in considerably higher number and with larger standard errors as there were no data points observed in the upper portion (>60% control) of the curve. Thus those ED values are speculative and do not guarantee indicated level of control. An ED_{60} value was provided for these species to present a more realistic response of the doses used. A test of lack-of-fit at the 5% level was not significant for any of the dose–response curves (Figures 2.1 and 2.2) tested indicating that the log-logistic model was appropriate (Knezevic et al. 2007).

2.4. Results

In general, propane dose and growth stage of flaming affected the response of spring-emerging weed species to broadcast flaming, and the response also varied among species (Table 2.1).

Plant Injury

Based on visual plant injury ratings, common lambsquarters, tansy mustard, and henbit were more sensitive compared to dandelion, cutleaf evening primrose, and field pennycress, which required higher doses of propane to achieve the same level of weed control, regardless of the growth stage (Figure 2.1). At 21 DAT, 54 to 108 kg ha^{-1} propane was needed to obtain 90% control of common lambsquarters, tansy mustard, and henbit for their growth stages ranging from 5-L to flowering. In comparison, the same dose range provided only about 50% control of dandelion, cutleaf evening primrose, and field pennycress (Tables 2.2 and 2.3).

Results from this study show that plant size influenced plant response to flaming (Figure 2.1, Table 2.2). Common lambsquarters flamed at 5-L stage needed a lower dose of propane (57 kg ha^{-1}) compared to much higher dose of 108 kg ha^{-1} to obtain the same level of control (90%) when flamed at 11-L stage. The opposite response was observed in henbit, where a less dose of propane (58 kg ha^{-1}) was needed to achieve 90% control of larger plants at flowering stage compared to higher dose (87 kg ha^{-1}) for the same level of control of much smaller plants at 9-L stage (Figure 2.1, Table 2.2).

Tansy mustard was the most susceptible species to broadcast flaming as propane dose of ≤62 kg ha^{-1} was sufficient enough to effectively control the plant at each of two evaluated growth stages (Figure 2.1, Table 2.2). At 21 DAT, propane doses that caused 90% injury at 9-L and flowering tansy mustard were 54 and 62 kg ha^{-1}, respectively. The same dose, however, provided <50% control of cutleaf evening primrose and field pennycress, suggesting that these species were much more tolerant to broadcast flaming (Figure 2.1, Table 2.3). We speculate that the thicker leaves of cutleaf evening primrose embedded with larger amounts of water may have provided higher level of tolerance to flaming. Additional studies are needed to test that hypothesis. Dandelion was flamed only at flowering stage, when it had a rosette of 10 cm in diameter and 13 cm tall flowering petiole. The dose–response curve estimated an ED_{80} value of 99 kg ha^{-1} for dandelion (Table 2.2). It is important to note that dandelion did eventually recover after flaming treatment even though complete kill of its flowering structures was observed with much lower propane dose (34 kg ha^{-1}). The plant recovery is a result from growth of new leaves from the perennial taproot.

Dry Matter Reduction (DMR)

In general, the ED values based on visual ratings of weed control are expected to be similar to those based on DMR (Knezevic et al. 2007). In this study, such similarities were observed at early growth stages when the plants were physically small, regardless of the weed species. For example, the ED_{90} values for visual weed control and DMR of common lambsquarters at early growth stage (5-L) were 57 and 60 kg ha^{-1}, respectively (Tables 2.2 and 2.4).

The ED values based on visual ratings of weed control and DMR were not similar when flaming was conducted at later growth stages on physically larger plants. For instance, a propane dose of 62 kg ha^{-1} was needed to obtain 90% control of tansy mustard at flowering stage based on visual ratings, whereas the same response based on DMR required a propane dose of 103 kg ha^{-1} (Tables 2.2 and 2.4). This inconsistency was observed because plant material utilized for calculating DMR was harvested from plants without any active growth in the plots flamed with higher propane doses. Thus, even though plants were visually dead, some amount of dead plant material was harvested and reflected in ED values. Consequently, DMR calculations indicated weaker-than-realistic level of weed control (Tables 2.2–2.5). For these reasons, propane doses based on DMR were slightly higher than the ones based on visual ratings at those later growth stages (Tables 2.2–2.5). Similar trends were observed in common lambsquarters, henbit, and cutleaf evening primrose.

2.5. Discussion

Our results are similar to those of others (Ascard 1994, 1995; Cisneros and Zandstra 2008; Sivesind et al. 2009; Ulloa et al. 2010a,b) who reported that small plants are more sensitive to heat than large ones. The thin and delicate plant tissue at the early vegetative stage is very heat sensitive (Ascard 1994), while the shoot apex of older plant is often protected by the surrounding leaves, and the larger amount of reserve food in the roots also gives an increased capacity for regrowth (Ascard 1995a). However, some species flamed at a later growth stages, specifically flowering stage, could be more susceptible to propane flaming despite the larger biomass, suggesting that plant tolerance to propane flaming does not always increase with plant size. Our results in henbit show that the ED_{90} values based on visual ratings flamed at flowering stage had lower ED_{90} values than at 9-L stage. This type of response might be a species specific, as henbit might lose ability to recover after flaming at flowering stage because of lack of active growth after flowering stage, which is typical for many broadleaf species. More research needs to be done to confirm such a hypothesis.

In our study, common lambsquarters at 5-L, tansy mustard at 9-L and flowering, and henbit at flowering were effectively controlled (90% control) with propane dose of <62 kg ha^{-1}, while the same dose provided <50% control in dandelion, field pennycress, and cutleaf evening primrose, regardless of the growth stage. This differential tolerance among the species might be directly related to morphology of the plant, and its ability to recover after flaming treatment, either from a tap root (dandelion) or undamaged growing point, as suggested as well by Sivesind et al. (2009). Similar results had been previously reported by Ascard (1995a) who found that weed species with a prostrate stature and protected growing points such as prostrate knotweed (*Polygonum aviculare* L.) and common groundsel (*Senecio vulgaris* L.) are more tolerant to flaming than species with upright growth stature, like common lambsquarters. In another study, as high as 200 kg ha^{-1} of propane was needed to effectively control groundsel at later growth stages (Sivesind et al. 2009). Likewise, a higher propane dose of 125 kg ha^{-1} was necessary to achieve 95% control in shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.] in rosette stage (Sivesind et al. 2009). These findings are similar to the response of dandelion reported in this study, where 90% control was observed with 131 kg ha^{-1} propane when flamed at flowering stage. Perennial weed species had also been reported difficult to control with flaming (Ascard 1998). Besides the growth stature that determines the degree of exposure of the growing point to the heat, other factors such as presence of protective layers of hair and/or wax, lignification level, cuticle thickness, and condition of the overall plant water status could also influence plant response to broadcast flaming (Ascard, 1995a; Datta and Knezevic, 2013; Sivesind et al. 2009; Ulloa et al. 2012).

It might be interesting to note that heavy crop residue in no-till fields can be set on fire with flame weeding operations. Such response was observed in our study only with the highest propane dose of 90 kg ha^{-1}, due to intense heat (>1,000 C) produced by such high propane dose (Knezevic et al. 2012). Practitioners can reduce the chance for fire by wetting the crop reside with irrigation few hours before flaming, or conducting flaming operation after rain. Note that weeds should not have water present on their surface during flaming as that can reduce efficacy of flaming operation (Knezevic et al. 2012).

Flame weeding is considerably more economic than hand weeding (Ulloa et al. 2011; Wszelaki et al. 2007). For example, the costs of a single hand weeding operation in Nebraska could range from US $700 to $1200 ha^{-1}, compared to only US $30 ha^{-1} [the current price of propane ($0.50 kg^{-1}) in Nebraska was multiplied by the recommended usage dose of 60 kg ha^{-1}] (Ulloa et al. 2011). Efficiency of flaming, however, can be increased by designing hoods that cover the torches (Ascard 1995b, Bruening et al. 2009a,b). Hoods keep the heat closer to the weeds and increase the time of weed exposure to the heat, thereby increasing the efficiency of propane flaming up to 50% (Bruening et al. 2009a,b).

We believe that propane flaming has a potential to be used as PRE broadcast tool for early spring weed control. Although complete kill was not achieved in dandelion, field pennycress, and cutleaf evening primrose, the heat from flaming severely reduced their growth and competitive ability. Most importantly, weed control methods such as flame weeding is not a single weed control practice. It can be repeated as needed during the growing season for a maximum of two times per season (Knezevic et al. 2012; Knezevic et al. 2013), and should be integrated with other weed management strategies for better result. More research is needed to determine the biologically effective dose of propane for control of other important weed species, especially perennial species in not-till systems. Information from such research would allow further adoption of flame weeding into an integrated weed management programs for both organic and conventional production systems.

2.6. Acknowledgements

We thank the Propane Education and Research Council, USDA and the Nebraska Propane Association for partial financial support of this project.

2.7. References

Ascard J (1994) Dose–response models for flame weeding in relation to plant size and density. Weed Res 34:377–385

Ascard J (1995a) Effects of flame weeding on weed species at different developmental stages. Weed Res. 35:397–411

Ascard J (1995b) Thermal Weed Control by Flaming: Biological and Technical Aspects. Ph.D. thesis, Swedish University of Agricultural Sciences, Department of Agricultural Engineering, Alnarp, Sweden, Report 200

Ascard J (1998) Comparison of flaming and infrared radiation techniques for thermal weed control. Weed Res 38:69–76

Bond W, Grundy AC (2001) Non-chemical weed management in organic farming systems. Weed Res 41:383–405

Boyd NS, Brennan EB, Fennimore SA (2006) Stale seedbed techniques for organic vegetable production. Weed Technol 20:1052–1057

Bruening CA (2009a) Development of Propane Flaming Equipment for Thermal Weed Control in Agronomic Crops. M.S. thesis, The University of Nebraska-Lincoln. Lincoln, NE.

Bruening CA, Gogos G, Ulloa SM, Knezevic SZ (2009b) Performance Advantages of Flaming Hood. Proc North Cent Weed Sci Soc 64:30

Cisneros JJ, Zandstra BH (2008) Flame weeding effects on several weeds species. Weed Technol 22:290–295

Dahlke BJ, Hayden TA, Leif JW, Medlin CR (2001) Fall application of imazaquin plus glyphosate (premix) for winter annual weeds control in soybeans. Proc North Cent. Weed Sci Soc 56:93

Datta A, Knezevic SZ (2013) Flaming as an alternative weed control method for conventional and organic agronomic crop production systems: a review. Adv Agron. 118:399–428

Fishel F, Johnson B, Peterson D, Loux M, Sprague C (2000) Early spring weeds of no-till crop production. North Central Regional Extension Publication No. NCR 614. University of Missouri-Columbia http://weeds.cropsci.illinois.edu/extension/Other/NCR614.pdf. Accessed: February 13, 2013.

Flame Engineering (2007) Red Dragon Liquid Torches. Flame Engineering Inc, LaCrosse, KS, 67548. http://www.flameengineering.com/Liquid_Burners.html. Accessed: February 06, 2013

Heap I (2013) International Survey of Herbicide Resistant Weeds. Most Recent Cases of herbicide Resistant Weeds. http://www.weedscience.com/Details/RecentCases.aspx. Accessed: March 28, 2013

Knezevic SZ, Ulloa SM (2007) Flaming: potential new tool for weed control in organically grown agronomic crops. J Agric Sci 52:95–104

Knezevic SZ (2007) Herbicide tolerant crops: 10 years later. Maydica 52:245–250

Knezevic SZ, Streibig J, Ritz C (2007) Utilizing R software package for dose–response studies: the concept and data analysis. Weed Technol 21:840–848

Knezevic SZ, Datta A, Scott J, Charvat LD (2009) Adjuvants influenced saflufenacil efficacy on fall-emerging weeds. Weed Technol 23:340–345

Knezevic SZ, Datta A, Bruening C, Gogos G (2012) Propane fuelled flame weeding in field corn, soybean, and sunflower crops. Flame Weeding Manual by Propane Education and Research Council, Washington, DC. http://www.agpropane.com/uploadedFiles/Agriculture/Program_Safety_On_The_Farm/Flame%20Weeding%20Training%20Manual_08-27-12_final%20(2).pdf. Accessed: February 13, 2013.

Knezevic SZ, Stepanovic S, Datta A, Nedeljkovic D, Tursun N (2013) Soybean yield and yield components as influenced by the single and repeated flaming. Crop Prot 50:1–5

Krausz RF, Young BG, Matthews JL (2003) Winter annual weed control with fall-applied corn (*Zea mays*) herbicides. Weed Technol 17:516–520

Owen MDK, Zelaya IA (2005) Herbicide-resistant crops and weed resistance to herbicides. Pest Manag Sci 3:301–311

Pelletier Y, McLeod CD, Bernard G (1995) Description of sub-lethal injuries caused to the Colorado potato beetle by propane flamer treatment. J Econ Entomol 88:1203–1205

R Development Core Team (2006) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/. Accessed: February 07, 2013

Rifai MN, Lacko-Bartosova M, Puskarova V (1996) Weed control for organic vegetable farming. Rostl Vyr 42:463–466

Rifai MN, Astatkie T, Lacko-Bartosova M, Gadus J (2002) Effect of two different thermal units and three types of mulch on weeds in apple orchards. J Environ Eng Sci 1:331–338

Ritz CJ, Streibig C (2005) Bioassay analysis using R. J. Statistical Software 12:1–22

Sandell L, Bernards ML, Knezevic SZ (2008) Fall herbicide applications for winter annual weed control. University of Nebraska-Lincoln Extension. http://weedscience.unl.edu/pdfarticles/08FallHerbApps.pdf. Accessed: February 08, 2013

[SAS] Statistical Analysis Systems (1999) SAS. Version 8.1. Cary, NC: Statistical Analysis Systems Institute

Sivesind EC, Leblanc ML, Cloutier DC, Seguin P, Stewart KA (2009) Weed response to flame weeding at different developmental stages. Weed Technol 23:438–443

Ulloa SM, Datta A, Knezevic SZ (2010a) Growth stage influenced differential response of foxtail and pigweed species to broadcast flaming. Weed Technol 24:319–325

Ulloa SM, Datta A, Knezevic SZ (2010b) Tolerance of selected weed species to broadcast flaming at different growth stages. Crop Prot 29:1381–1388

Ulloa SM, Datta A, Bruening C, Neilson B, Miller J, Gogos G, Knezevic SZ (2011) Maize response to broadcast flaming at different growth stages: Effects on growth, yield and yield components. Eur J Agron 34:10–19

Ulloa SM, Datta A, Bruening C, Gogos G, Arkebauer TJ, Knezevic SZ (2012). Weed control and crop tolerance to propane flaming as influenced by the time of day. Crop Prot 31:1–7

Van der Vaart AW (1998) Asymptotic Statistics. Cambridge, UK: Cambridge University Press

Venkatesh R, Harrison SK, Riedel RM (2000) Weed hosts of soybean cyst nematode (*Heterodera glycines*) in Ohio. Weed Technol 14:156–160

Wszelaki AL, Doohan DJ, Alexandrou A (2007) Weed control and crop quality in cabbage [*Brassica oleracea* (capitata group)] and tomato (*Lycopersicon licopersicum*) using a propane flamer. Crop Prot 26:134–144

2.8. Figures

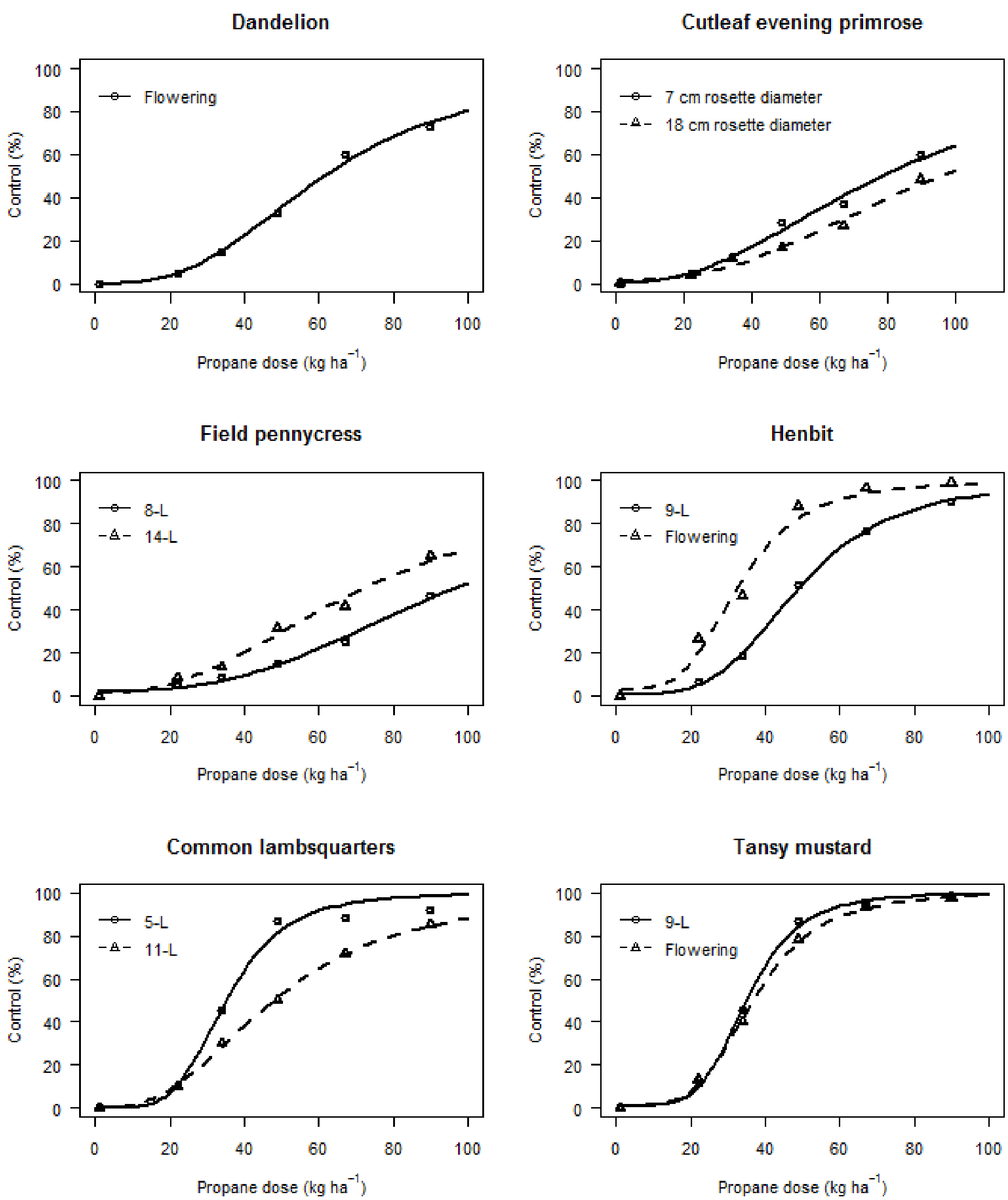

Figure 2.1. Effects of propane dose on visual weed control (%) of dandelion, cutleaf evening primrose, field pennycress, henbit, common lambsquarters, and tansy mustard as influenced by growth stage at 21 d after treatment in field experiments at two sites in 2012, Concord, NE. The regression lines are plotted using Equation 1, and the parameter values are presented in Tables 2.2 and 2.3.

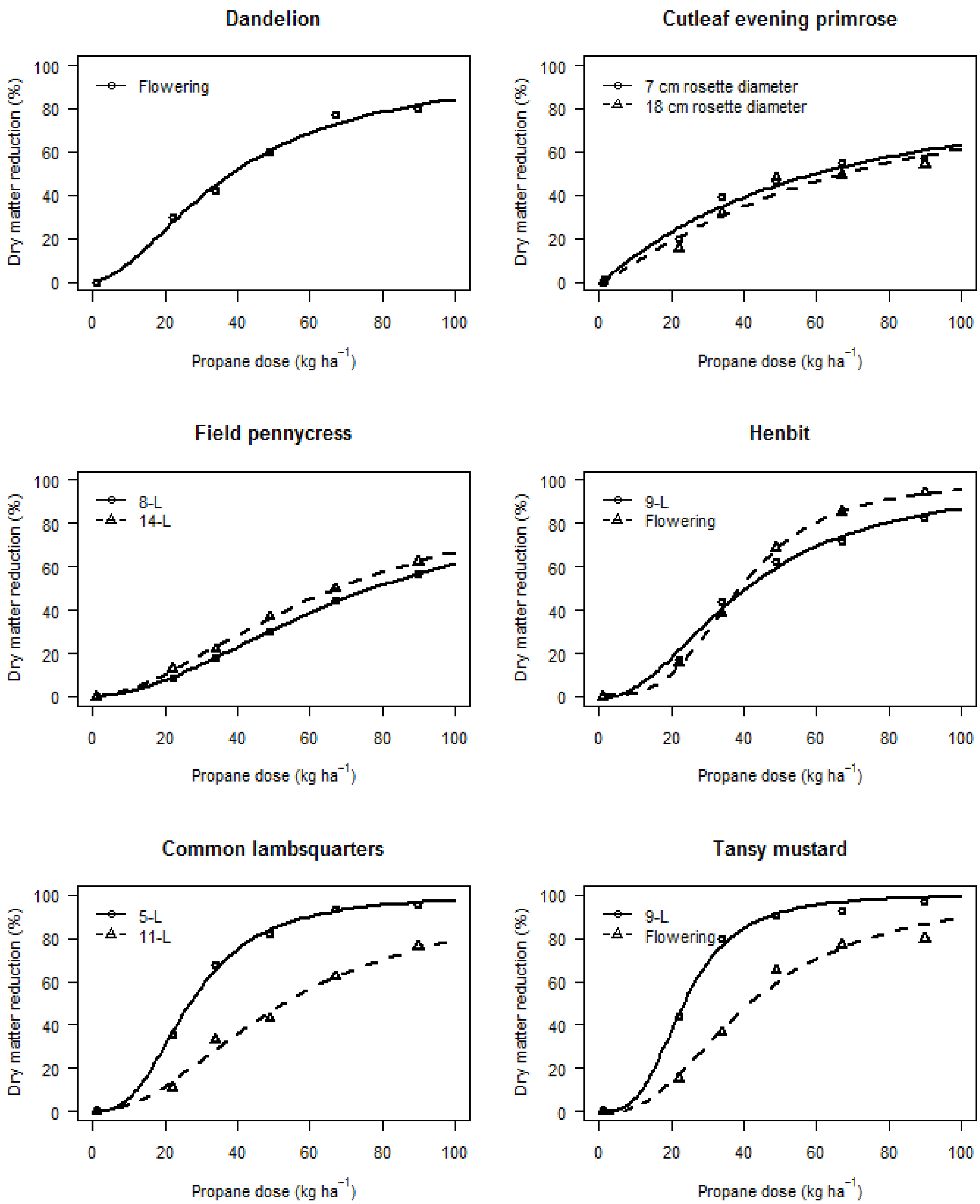

Figure 2.2. Effects of propane dose on dry matter reduction (%) of dandelion, cutleaf evening primrose, field pennycress, henbit, common lambsquarters, and tansy mustard as influenced by growth stage at 21 d after treatment in field experiments at two sites in 2012, Concord, NE. The regression lines are plotted using Equation 1, and the parameter values are presented in Tables 2.4 and 2.5.

Figure 2.3. Custom built propane flamer mounted on a four-wheeler (all-terrain vehicle) with four burners “LT 2 × 8 Liquid Torch” (Flame Engineering 2007) mounted 30 cm, positioned 20 cm above the soil surface and angled back at 30^{o}

2.9. Tables

Table 2.1. Significance levels (5 % level) in the two-way ANOVA of the effects of propane dose (PD), growth stages (GS), and their interaction on percent weed control and percent dry matter reduction for weed species evaluated in the field experiments at Concord, NE, 2012.

Weed species	Terms	P values	
		% weed control	% dry matter reduction
Common lambsquarters	Propane Dose (PD)	<0.0001	<0.0001
	Growth Stage (GS)	<0.0001	<0.0001
	PD × GS	0.0006	0.0146
Tansy mustard	PD	<0.0001	<0.0001
	GS	0.353	<0.0001
	PD × GS	0.8626	0.0011
Henbit	PD	<0.0001	<0.0001
	GS	<0.0001	0.0111
	PD × GS	<0.0001	0.0044
Dandelion	PD	0.0002	0.0006
Cutleaf evening primrose	PD	<0.0001	<0.0001
	GS	0.5087	0.3545
	PD × GS	0.8898	0.948
Field pennycress	PD	<0.0001	<0.0001
	GS	<0.0001	0.0029
	PD × GS	0.0011	0.7164

Table 2.2. Regression parameters (Equation 1) for each weed species (common lambsquarters, tansy mustard, henbit, dandelion) and dose of propane (kg ha^{-1}) needed to obtain 80% and 90% weed control [ED_{80} and ED_{90} (± SE)] based on visual ratings at 21 d after treatment as a function of growth stage (Figure 2.1).[a,b]

Weed species	Growth stage	Plant height (cm)	Regression parameters (±SE)		ED_{80} (± SE)	ED_{90} (± SE)
			B	I_{50}		
		-cm-			--------kg ha^{-1}------	
Common lambsquarters	5-L	4	–4.5 (0.8)	35 (2)	48 (3)	57 (5)
	11-L	11	–2.7 (0.2)	48 (2)	80 (3)	108 (6)
Tansy mustard	9-L	9	–5.0 (0.8)	35 (1)	46 (2)	54 (3)
	Flowering	34	–4.3 (0.6)	37 (1)	51 (2)	62 (4)
Henbit	9-L	17	–3.8 (0.2)	49 (1)	70 (5)	87 (3)
	Flowering	31	–3.8 (0.4)	33 (1)	47 (2)	58 (3)
Dandelion	Flowering (10 cm rosette diameter)	13	–2.9 (0.4)	61 (3)	99 (7)	131 (14)

[a] Abbreviations: B, the slope of the line at the inflection point; I_{50}, the dose of propane resulting in a 50% response between the upper and lower limit.
[b] No treatment-by-site interaction occurred, so the data were pooled over two site

Table 2.3. Regression parameters (Equation 1) for each weed species (cutleaf evening primrose, field pennycress) and dose of propane (kg ha^{-1}) needed to obtain 60%, 80%, and 90% weed control [ED_{60}, ED_{80}, and ED_{90} (± SE)] based on visual ratings at 21 d after treatment as a function of growth stage (Figure 2.1).[a,b]

Weed species	Growth stage	Plant height	Regression parameters (±SE)		ED_{60} (± SE)	ED_{80} (± SE)	ED_{90} (± SE)
			B	I_{50}			
		-cm-			---------------kg ha^{-1}	--------------	
Cutleaf evening primrose	7 cm rosette diameter	2	–2.4 (0.3)	79 (4)	93 (5)	141 (13)	200 (28)
	18 cm rosette diameter	3	–2.4 (0.3)	96 (3)	113 (5)	169 (15)	235 (30)
Field pennycress	8-L	3	–2.8 (0.4)	97 (4)	112 (6)	159 (16)	211 (30)
	14-L	15	–2.4 (0.3)	73 (3)	86 (3)	130 (9)	183 (19)

[a] Abbreviations: *B*, the slope of the line at the inflection point; I_{50}, the dose of propane resulting in a 50% response between the upper and lower limit.

[b] No treatment-by-site interaction occurred, so the data were pooled over two sites.

Table 2.4. Regression parameters (Equation 1) for each weed species (common lambsquarters, tansy mustard, henbit, dandelion) and dose of propane (kg ha^{-1}) needed to obtain 80% and 90% dry matter reduction [ED_{80} and ED_{90} (± SE)] at 21 d after treatment as a function of growth stage (Figure 2.2).[a,b]

Weed species	Growth stage	Plant height	Regression parameters (±SE)		ED_{80} (± SE)	ED_{90} (± SE)
			B	I_{50}		
		-cm-			---------kg ha^{-1}-------	
Common lambsquarters	5-L	4	–2.8 (0.4)	27 (2)	44 (3)	60 (6)
	11-L	11	–2.1 (0.3)	53 (4)	102 (11)	151 (23)
Tansy mustard	9-L	9	–3.2 (0.5)	23 (1)	36 (2)	47 (5)
	Flowering	34	–2.4 (0.3)	41 (2)	73 (6)	103 (11)
Henbit	9-L	17	–2.1 (0.2)	40 (2)	78 (4)	116 (9)
	Flowering	31	–3.3 (0.2)	39 (1)	59 (5)	76 (3)
Dandelion	Flowering (10 cm rosette diameter)	13	–1.8 (0.3)	38 (4)	84 (10)	134 (24)

[a] Abbreviations: *B*, the slope of the line at the inflection point; I_{50}, the dose of propane resulting in a 50% response between the upper and lower limit.
[b] No treatment-by-site interaction occurred, so the data were pooled over two sites.

Table 2.5. Regression parameters (Equation 1) for each weed species (cutleaf evening primrose, field pennycress) and dose of propane (kg ha^{-1}) needed to obtain 60%, 80%, and 90% dry matter reduction [ED_{60}, ED_{80}, and ED_{90} (± SE)] at 21 d after treatment as a function of growth stage (Figure 2.2).[a,b]

Weed species	Growth stage	Plant height	Regression parameters (±SE)		ED_{60} (± SE)	ED_{80} (± SE)	ED_{90} (± SE)
			B	I_{50}			
		-cm-			-----------------kg ha^{-1}---------------		
Cutleaf evening primrose	7 cm rosette diameter	2	–1.1 (0.2)	29 (9)	86 (14)	213 (68)	449 (210)
	18 cm rosette diameter	3	–1.2 (0.3)	67 (10)	94 (16)	216 (66)	413 (191)
Field pennycress	8-L	3	–1.8 (0.2)	77 (3)	96 (4)	164 (12)	255 (28)
	14-L	15	–1.8 (0.1)	67 (2)	84 (3)	147 (10)	232 (22)

[a] Abbreviations: *B*, the slope of the line at the inflection point; I_{50}, the dose of propane resulting in a 50% response between the upper and lower limit.
[b] No treatment-by-site interaction occurred, so the data were pooled over two sites.

CHAPTER 3. Impact of single and repeated flaming on yield components and yield of maize

3.1. Abstract

Weeds are a major yield-limiting factor in both conventional and organic crop production systems. In maize (*Zea mays*) production, propane flaming could be used as an additional tool for weed control. Thus maize tolerance to single and repeated flaming was studied with eight treatments, which included: non-flamed control, and broadcast flaming conducted once at V2 (2-leaf), V4 (4-leaf), and V6 (6-leaf) stage, two times (each at V2 and V4, V2 and V6, and V4 and V6 stages), and three times (at V2, V4, and V6 stages). Weeds were removed in all treatments by hoeing for the entire growing season. A propane dose of 45 kg ha^{-1} was applied with torches parallel to the crop row and at an operating speed of 4.8 km h^{-1} for all treatments. Crop response was assessed visually at 7 and 28 days after treatment, with effects on yield components and yield. Maize exhibited excellent tolerance to single and double flaming regardless of the growth stage. However, the triple flaming resulted in more than 30% injury. Maize flamed once and twice produced between 11.1 and 11.6 t ha^{-1} yield, which was statistically similar to the yield obtained from the non-flamed control (11.7 t ha^{-1}). Maize flamed three times yielded 9.9 t ha^{-1}, which was 8.5% lower compared to the non-flamed control yield, and likely would not be acceptable by producers. Results of this study indicate that maize is able to tolerate up to two flaming treatments per season without a loss of yield.

Keywords: Organic crop production; Organic agriculture; Non-chemical weed control; Crop tolerance.

3.2. Introduction

Flame weeding has gained considerable attention recently due to an increase in organic crop production and rising public concerns about the effects of synthetic chemicals on water quality and human health in general (Rifai et al. 2002; Sivesind et al. 2012). The higher prices of organic produce also make organic crop production an attractive business for growers (Abouziena et al. 2009; Penfold et al. 1995). Weeds are major problems in both conventional and organic crop production (Walz 1999).

Weed control in organic crop production is achieved primarily by hand weeding and cultivation (Hiltbrunner et al. 2007). However, labor costs associated with hand-weeding are high, and repeated cultivation increases the chance of soil erosion, thus, alternative methods of weed control are necessary (Wszelaki et al. 2007). Flame weeding is the most utilized thermal weed control method and has proved to be an essential tool of a multi-component weed control program (Datta and Knezevic in press; Ulloa et al. 2010a,b,c,d,e,f; 2011a,b; 2012), which could reduce or eliminate the amount of costly hand-weeding, and/or mechanical cultivation (Sivesind et al. 2012; Wszelaki et al. 2007).

Earlier studies have demonstrated that flaming could be utilized as an alternative weed control method (Ascard 1995; Ulloa et al. 2010a,b). The efficacy of flame weeding depends on the weed species, their growth stage at the time of flaming, and propane dose (Datta and Knezevic in press; Ulloa et al. 2010a,b).

Ulloa et al. (2011a) flamed maize (*Zea mays* L.) at different growth stages only once with torches positioned directly over the crop row to determine crop tolerance under weed-free conditions. Their findings demonstrated that maize is tolerant to single flame weeding treatment when flaming was conducted at selective growth stage. However, the ability of one flame weeding treatment to provide an effective weed control for an entire season (Sivesind et al. 2012) or perhaps until the canopy closure has not been well investigated. Thus we hypothesized that more than one flame weeding treatment might be needed to achieve longer season weed control in maize. Therefore, the objective of this study was to determine maize tolerance to single and repeated flaming by utilizing the equipment designed to selectively flame weeds in maize with torches positioned parallel to the crop row.

3.3. Materials and methods

Experimental site and experimental setup

Field experiments were conducted at the Haskell Agricultural Laboratory of the University of Nebraska, Concord, NE, USA in 2010 and 2011. Maize and soybean [*Glycine max* (L.) Merr.] crop rotations usually dominate this region. The soil is classified as an Alcester silty clay loam with 36 g kg^{-1} soil organic matter and pH of 6.6 in the surface soil. Soybean was grown in the year before the current experiment and crop residues were removed before maize planting.

One of the commonly grown maize cultivars in Nebraska, 56M30, was sown into a non-tilled rain-fed ground on May 12 in 2010 and June 1 in 2011 with a row spacing of

76 cm and a density of 63,500 seeds ha^{-1}. The experimental plot size was 10 m by 3 m. The experiments were maintained weed-free during the entire growing season by hand hoeing as weeds appeared. The treatments were arranged in a randomized complete block design with three replications. The timing of the treatment was conducted according to the leaf stage of the crop, which included V2 (2-leaf stage, and is defined when the collar of the second leaf is visible), V4 (4-leaf), and V6 (6-leaf). The treatments consisted of one non-flamed control, and broadcast flaming conducted once (at V2, V4, and V6), two times (each at V2 and V4, V2 and V6, and V4 and V6), and three times (at V2, V4, and V6) resulting in a total of eight treatments. Flaming was conducted on June 2, June 16, and June 24 which corresponded to the growth stages of V2, V4, and V6, respectively, in 2010. In 2011, maize was flamed on June 13, June 20, and June30, which corresponded to the same growth stages flamed in 2010.

Flaming specifications

Flaming treatments were conducted using a tractor pulled four-row flamer developed at the University of Nebraska (Bruening 2009; Bruening et al. 2009). The four-row flamer had eight torches mounted 38 cm apart and positioned parallel to the crop row at about 15 cm away from each side of the crop row and 20 cm above the soil surface angled back at 30^o (Figure 5.1). 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. Specially designed 1.2 m long hoods kept the heat close to the ground (Figure 5.1). The hoods were designed in such a way that each hood was positioned over the intra-row space and covered two torches (Figure 5.1). The hoods were ‘closed’ across the rows during flaming at growth stages of V2 and V4 whereas hoods were ‘open’ during flaming at V6 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 (Figure 5.1). The open hood set up protected the upper portion of maize plants, including the growing point, from the intense heat (Figure 5.1). It is important to point out that the torch set up in this study was different than what Ulloa et al. (2011a) used in their experiment, where hoodless torches were intentionally positioned directly over the crop to determine crop tolerance to a direct heat (e.g., the worst case scenario of heat related injury). A propane dose of 45 kg ha^{-1} was applied for all treatments by adjusting propane pressure at a set application speed of 4.8 km h^{-1} (Knezevic and Ulloa 2007).

Measurements

Maize injury was visually evaluated at 7 and 28 days after treatment (DAT) using a 0 to 100% scale, where 0 represented no crop injury (relative to the non-flamed control) and 100 represented plant death. It is important to note that visual crop injury ratings were assessed after conducting the last flaming treatment. For example, for any plot which received broadcast flaming treatment twice (each at V2 and V6 growth stages), visual ratings were assessed at 7 and 28 days after conducting the last flaming treatment (at V6 stage).

For yield components, cobs were hand harvested from 0.76 m^2 areas (1 m row) of each plot and plants m^{-2}, ears plant^{-1}, seeds ear^{-1}, and 1000-seed weight were measured. Total number of plants from the center two rows each of 4 m length was counted to determine number of plants m^{-2}. Yield was measured at crop maturity by harvesting a 4 m length (6.08 m^2 areas) of the center two rows of each plot, shelled and adjusted to 155 g kg^{-1} moisture content.

Statistical analysis

All data (visual crop injury ratings, 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 years, treatments, replications, and their interactions (SAS Institute 2005). There was no treatment-by-year interaction (Table 3.1); thus, the data were pooled over years. However, there was a significant main effect differences among the treatments and between the years for most of the response variables. Means for the significant treatment effects were compared using Fisher's protected least significant difference (LSD) procedure at P<0.05.

3.4. Results

Overall response of maize to single and repeated flaming was influenced by the growth stage of flaming and number of flaming treatments.

Crop injury

In general, maize exhibited excellent tolerance to flaming at all three tested growth stages (Figure 3.1). However, there were still various levels of canopy injury as the torches produce flames that generate as high as 1900°C heat (Ascard, 1998; Knezevic et al. 2012). More specifically, there was higher maize injury rating at early evaluation dates

(7 DAT) compared to later rating dates (28 DAT), demonstrating the ability of maize to recover over time (Figure 3.1). For example, flaming conducted once at V2, or V4, or V6 growth stages resulted in 38%, 30%, and 20% crop injury, respectively, at 7 DAT compared to significantly lower injury levels of 8%, 6%, and 6% for the corresponding growth stages by 28 DAT. Similar trends occurred when plants were flamed two times (e.g., V2 and V6 as well as V4 and V6) exhibiting injury rating about 6% by 28 DAT. However, maize plants did not recover well over time when flamed three times (e.g., at V2, V4, and V6 growth stages), which resulted in over 50% injury at 7 DAT and more than 30% injury by 28 DAT.

Initial injury symptoms in the form of whitening and browning of the leaves (including slight crop stunting) completely disappeared when maize reached tasseling stage, regardless of the treatment. However, the speed of maize recovery was dependent on the growth stage of flaming. Maize plants flamed at V2 stage needed more time to recover compared to the plants flamed at V4 and V6 stages, because the shorter plants (e.g., V2 stage) had higher percent of their canopy exposed to the flames and heat. Higher crop injury levels were observed in plants flamed multiple times. For example, flaming three times (at V2, V4, and V6 stages) resulted in about 55% injury at early evaluation date (7 DAT) and about 30% injury at late evaluation date (28 DAT).

Yield components

Among the yield components, single and repeated flaming treatments had no effect on plant population and on number of ears plant^{-1} (Table 3.1). All plots had a similar population stand (3.6 plants m^{-2}) and similar number of ear plant^{-1} (0.98) (Table 3.2).

Maize flamed once (at V2, or V4, or V6 stage) or two times (each at V2 and V4, or V2 and V6, or V4 and V6 stages) produced statistically similar seeds ear^{-1} and 1000-seed weight compared to the non-flamed control. However, number of seeds ear^{-1} and 1000-seed weight response variables were affected by multiple flaming treatments (Table 3.1). Maize flamed three times (at V2, V4, and V6 stages) produced significantly lower number of seeds ear^{-1} and 1000-seed weight compared to the non-flamed control (Table 3.2). The number of seeds ear^{-1} was 543 in the plots flamed three times compared to significantly higher seeds number ear^{-1} of 637 in the non-flamed control plots. Maize plants flamed once and twice averaged between 644 and 697 seeds ear^{-1} (Table 3.2). It is interesting to note that the average weight of 1000-seed was significantly higher in plots flamed three times (323 g) compared to the non-flamed control plots (299 g); however, that did not help improve the overall yield.

Yield

Yields ranged from 11.1 to 11.6 t ha^{-1} in the plots flamed once or two times, which were statistically similar to the yield obtained from the non-flamed control (11.7 t ha^{-1}). Flaming conducted three times (at V2, V4, and V6 growth stages) was the only treatment that resulted in significantly lower yield (9.9 t ha^{-1}) compared to the non-flamed control. Maize flamed three times produced about 8.5% lower yield than the non-flamed control. From a practical standpoint, an 8.5% yield reduction of maize may not be acceptable by producers.

3.5. Discussion

None of the flaming treatments caused delays in maize maturity, which is similar to the finding of Sivesind et al. (2012) in onion (*Allium cepa* L.). However, Bartolo et al. (1994) suggested that severe onion injury and foliage loss due to flame weeding can lead to delay in crop maturity.

With the exception of plants m^{-2} and ears $plant^{-1}$, the number seeds ear^{-1} and 1000-seed weight were the most affected yield components when maize plants were flamed three times. The same treatment caused a significant reduction in the number of seeds ear^{-1}, which probably provided more space for the remaining seeds to increase in size and ultimately increase the average weight of 1000-seed. However, this positive effect was unable to compensate the overall weight of lower number of seeds ear^{-1}; therefore, the yield was significantly reduced. All treatments that included one and two flaming applications yielded similarly to the non-flamed control. Flaming treatment conducted three times resulted in significantly lower yield compared to the non-flamed control. These results indicate that maize can tolerate a maximum of two flaming operations per season.

In this study, maize plants fully recovered when flamed twice under weed-free situations. These findings suggest that broadcast flaming two times in the season could be an acceptable alternative for weed control. The timing of flaming can be also adjusted based on the weed size and the types of weed species present.

In this experiment, the four-row flamer with its hood technology has showed a great potential when flaming was conducted particularly from V4 to V6 stage of maize by protecting the growing point and sparing the major portions of leaves from any heat damage. Maize also can be safely flamed after V6 stage, up to V10 growth stage (Knezevic et al. 2012). When using flame weeding after V6 stage, the flames should be kept as low as possible to the ground to avoid potential loss of leaf area from the heat. The flamed leaves will be injured; however, the injury will not affect crop yield.

This study shows the potential for utilizing flaming as an additional tool for weed control in organic maize production with selection of proper growth stage of crop and flaming technique. Previous research has demonstrated that propane doses of 50 to 60 kg ha^{-1} were highly effective in controlling (> 90%) various broadleaf weeds at early growth stages, that include *Abutilon theophrasti* Medik., *Amaranthus retroflexus* L., *Amaranthus rudis* Sauer, *Convolvulus arvensis* L., *Kochia scoparia* (L.) Schrad., *Ipomoea hederacea* Jacq., and *Hibiscus trionum* L. (Ulloa et al. 2010a,b). The same dose of propane also provided 80% control of several grass weed species, including *Echinochloa crus-galli* (L.) Beauv., *Setaria viridis* (L.) Beauv., and *Setaria pumila* (Poir.) Roemer & J.A. Schultes (Ulloa et al. 2010a,b). Two broadcast flaming treatments applied separately with a propane dose of 45 kg ha^{-1} during the maize growing season, therefore, could provide an acceptable alternative for weed control without a reduction in yield.

3.6. Aknowledgements

We thank the Propane Education and Research Council, USDA and the Nebraska Propane Association for partial financial support of this project. We are also grateful for the help provided by Jon Scott, and many summer helpers.

3.7. References

Abouziena H FH, Omar AAM, Sharma SD, and Singh M (2009) Efficacy comparison of some new natural-product herbicides for weed control at two growth stages. Weed Technol 23:431–437

Ascard J (1995) Effects of flame weeding on weed species at different developmental stages. Weed Res 35:397–411

Ascard J (1998) Comparison of flaming and infrared radiation techniques for thermal weed control. Weed Res 38:69–76

Bartolo ME, Schwartz HF, Schweissing FC (1994) Yield and growth response of onion to simulated storm damage. HortScience 29:1465–1467

Bruening CA (2009) Development of Propane Flaming Equipment for Thermal Weed Control in Agronomic Crops. M.S. thesis, The University of Nebraska-Lincoln, Lincoln, NE, USA

Bruening CA, Gogos G, Ulloa SM, Knezevic SZ (2009) Performance Advantages of Flaming Hood. In: Proceedings of the North Central Weed Science Society Conference (R.G. Hartzler and A.N. Hartzler, Eds.), 64:30, Kansas City, MO, USA

Datta A, Knezevic SZ (in press) Flaming as an alternative weed control method for conventional and organic agronomic crop production systems: A review. Adv Agron

Knezevic SZ, Ulloa SM (2007) Flaming: potential new tool for weed control in organically grown agronomic crops. J Agric Sci 52:95–104

Knezevic SZ, Datta A, Bruening C, Gogos G (2012) Propane-fueled flame weeding in corn, soybean, and sunflower. http://www.agpropane.com/uploadedFiles/Agriculture/Program_Safety_On_The_Farm/Flame%20Weeding%20Training%20Manual_08-27-12_final%20(2).pdf. Accessed 30 November 2012

Penfold CM, Miyan MS, Reeves TG, Grierson IT (1995) Biological farming for sustainable agricultural production. Aust J Exp Agric 35:849–856

Sivesind EC, Leblanc ML, Cloutier DC, Seguin P, Stewart KA (2012) Impact of selective flame weeding on onion yield, pungency, flavonoid concentration, and weeds. Crop Prot 39:45–51

Statistical Analysis Systems (SAS) (2005) The GLIMMIX Procedure. Online Documentation. SAS Institute, Inc., Cary, NC, USA. Version 9.1

Ulloa SM, Datta A, Knezevic SZ (2010a) Growth stage influenced differential response of foxtail and pigweed species to broadcast flaming. Weed Technol 24:319–325

Ulloa SM, Datta A, Knezevic SZ (2010b) Tolerance of selected weed species to broadcast flaming at different growth stages. Crop Prot 29:1381–1388

Ulloa SM, Datta A, Knezevic SZ (2010c) Growth stage impacts tolerance of winter wheat (*Triticum aestivum* L.) to broadcast flaming. Crop Prot 29:1130–1135

Ulloa SM, Datta A, Malidza G, Leskovsek R, Knezevic SZ (2010d) Timing and propane dose of broadcast flaming to control weed population influenced yield of sweet maize (*Zea mays* L. var. *rugosa*). Field Crops Res 118:282–288

Ulloa SM, Datta A, Cavalieri SD, Lesnik M, Knezevic SZ (2010e) Popcorn (*Zea mays* L. var. *everta*) yield and yield components as influenced by the timing of broadcast flaming. Crop Prot 29:1496–1501

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

Ulloa SM, Datta A, Bruening C, Neilson B, Mille, J, Gogos G, Knezevic SZ (2011a) Maize response to broadcast flaming at different growth stages: Effects on growth, yield and yield components. Eur J Agron 34:10–19

Ulloa SM, Datta A, Knezevic SZ (2011b) Growth stage influenced sorghum response to broadcast flaming: Effects on yield and its components. Agron J 103:7–12

Ulloa SM, Datta A, Bruening C, Gogos G, Arkebauer TJ, Knezevic SZ (2012) Weed control and crop tolerance to propane flaming as influenced by the time of day. Crop Prot 31:1–7

Walz E (1999) Final Results of the Third Biennial National Organic Farmers' Survey. Organic Farming Research Foundation, Santa Cruz, CA, USA

Wszelaki AL, Doohan DJ, Alexandrou A (2007) Weed control and crop quality in cabbage [*Brassica oleracea* (capitata group)] and tomato (*Lycopersicon lycopersicum*) using a propane flamer. Crop Prot 26:134–144

3.8. Figures

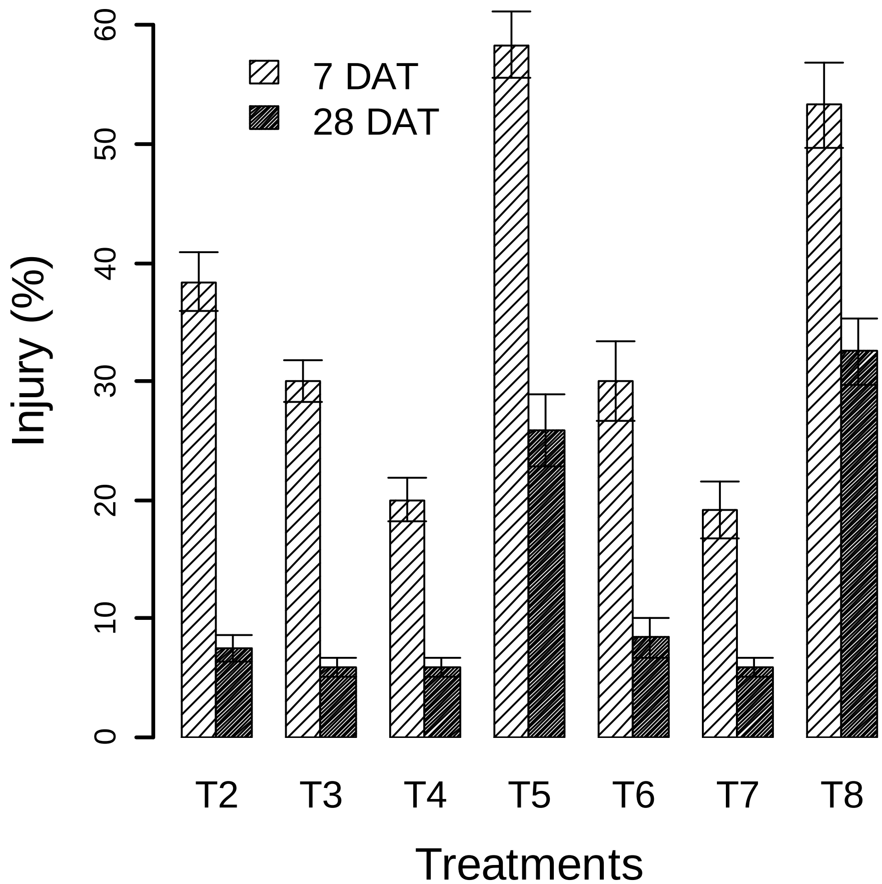

Figure 3.1. Maize injury as influenced by single and repeated flaming at 7 and 28 days after treatment (DAT). The treatments included were: flaming once at V2-2 leaf (T2), flaming once at V4-4 leaf (T3), flaming once at V6-6 leaf (T4), flaming twice at V2 and V4 (T5), flaming twice at V2 and V6 (T6), flaming twice at V4 and V6 (T7), and flaming three times at V2, V4, and V6 (T8). The vertical bars represent the standard error of the means

3.9. Tables

Table 3.1. Significance levels in the two-way ANOVA of the effects of year and number of flaming treatments on crop injury (7 and 28 days after treatment-DAT), yield components, and yield of maize in the field experiment at Concord, NE, USA, 2010 and 2011

Term	Crop injury		Yield components				Yield (kg ha^{-1})
	7 DAT	28 DAT	Plants m^{-2}	Ears plant^{-1}	Seeds ear^{-1}	1000-seed weight (g)	
Year (Y)	***	*	ns	ns	***	*	***
Treatment (T)	***	***	ns	ns	*	*	***
Y × T	ns	ns	ns	ns	ns	ns	ns

***P<0.001; **P<0.01; *P<0.05; ns = not significant

Table 3.2. Yield components and yield of maize as affected by the number of flaming treatments in the field experiment at Concord, NE, USA (2010–2011, mean values). The growth stages tested were V2 (2-leaf), V4 (4-leaf), and V6 (6-leaf)

Effect	Yield components				Yield (t ha^{-1})
	Plants m^{-2}	Ears $plant^{-1}$	Seeds ear^{-1}	1000-seed weight (g)	
Year					
2010	3.6 a	0.98 a	685 a	299 a	11.6 a
2011	3.6 a	0.98 a	600 b	386 b	10.1 b
Treatment					
Non-flamed control	3.7 a	1.00 a	637 a	299 b	11.7 a
Flaming once (at V2)	3.6 a	0.99 ab	684 a	281 b	11.2 a
Flaming once (at V4)	3.8 a	0.98 ab	634 a	290 b	11.6 a
Flaming once (at V6)	3.6 a	0.99 ab	651 a	285 b	11.3 a
Flaming twice (at V2 and V4)	3.5 a	0.98 ab	644 a	294 b	11.2 a
Flaming twice (at V2 and V6)	3.5 a	0.98 ab	697 a	284 b	11.4 a
Flaming twice (at V4 and V6)	3.6 a	0.98 ab	650 a	283 b	11.1 a
Flaming three times (at V2, V4, and V6)	3.6 a	0.97 b	543 b	323 a	9.9 b

Different letters within each response variable refer to statistically significant differences following the Fisher's Protected LSD procedure at $P<0.05$

CHAPTER 4. Soybean yield and yield components as influenced by the single and repeated flaming

4.1. Abstract

Field experiments were conducted to study the impact of single and multiple flaming on crop injury, yield components, and yield of soybean. The goal of this experiment was to determine the number of the maximum flaming treatments which soybean could tolerate without any yield loss. The treatments consisted of a non-flamed control, and broadcast flaming conducted one time (at VC-unfolded cotyledon, V2-second trifoliate, and V5-fifth trifoliate), two times (each at VC and V2, VC and V5, and V2 and V5 stages), and three times (at VC, V2, and V5 stages) resulting in a total of eight treatments. All plots were kept weed-free for the entire growing season by hand hoeing. A propane dose of 50 kg ha^{-1} was applied with torches parallel to the crop row and at an operating speed of 4.8 km h^{-1} for all treatments. The response of soybean was measured as visual injury ratings (at 7 and 28 days after treatment-DAT) as well as effects on yield components and yield. Broadcast flaming conducted once (at VC or V5 stage), as well as twice (at VC and V5 stages) exhibited the lowest injury of about 8% at 28 DAT. Any treatment that contained flaming at V2 stage resulted in more than 70% injury at 28 DAT. The highest crop yields were obtained from the non-flamed control (3.45 t ha^{-1}) and the plots flamed once at VC (3.35 t ha^{-1}), V5 (3.32 t ha^{-1}), and two times at VC and V5 (3.24 t ha^{-1}), which were all statistically similar. Soybean flamed at V2 stage had lower yields (1.03 t ha^{-1} at V2, 0.46 t ha^{-1} at VC and V2, and 0.38 t ha^{-1} at V2 and V5). The lowest

yields were in soybean flamed three times (VC, V2, and V5 stages), which yielded only 0.36 t ha^{-1}. These results indicate that soybean could tolerate a maximum of two flaming treatments at VC and V5 growth stages per season without any yield reduction.

Keywords: Organic crop production; Organic agriculture; Non-chemical weed control; Crop tolerance.

4.2. Introduction

The interest for organic crop production is on the increase due to strong consumer demand for organic food and an attractive income potential for organic farmers (Johnson, 2004). The main reasons for the adoption of organic farming practices are the detrimental effects of synthetic chemicals on human health, soil, and the environment as well as the price premiums for farmers (Penfold et al., 1995; Abouziena et al., 2009). Weeds are one of the major problems encountered in both conventional and organic crop production systems and weeds must be controlled in order to produce acceptable yields and crop quality. Especially in organic farming systems, producers rank weed management as the number one production-limiting factor (Walz, 1999).

Organic agriculture prohibits the use of synthetic herbicides in organic systems; therefore, controlling weeds can be challenging and difficult to achieve under the rules of organic agriculture (Kruidhof et al., 2008). There are a few organically approved herbicides that can be used in organic production, but they are costly and non-selective, thus can cause crop injury (Datta and Knezevic, 2013). Mechanical cultivation and hand weeding are, therefore, the most preferred choices for weed control by organic producers.

However, repeated cultivation can lead to a breakdown of soil structure, loss of soil organic matter, and can increase the chance for soil erosion (Wszelaki et al., 2007). In addition, repeated cultivation can also promote new flushes of weed emergence. From the economic standpoint, the labor required for hand weeding is expensive, time-consuming, and often difficult to organize when needed due to unavailability at the time of high demand for hand weeding (Kruidhof et al., 2008; Ulloa et al., 2011a; Sivesind et al., 2012). Hence, systems-oriented approaches that emphasize alternative and integrated systems of weed management need to be developed to help reduce losses that weeds cause in the short- and long-tem (Kruidhof et al., 2008) and provide alternatives to economical weed control.

Propane flaming is one of the most promising alternatives for weed control in organic cropping systems, and with the potential for use on the conventional crops as well (Ulloa et al., 2010a,b,c; 2011a,b; 2012). Flaming is an acceptable weed control method in organic production, which could lessen the reliance on organic herbicides, hand weeding, and/or mechanical cultivation as well as could eliminate concerns over direct residual effects on soil, water, and food quality (Bond and Grundy, 2001; Rifai et al., 2002; Wszelaki et al., 2007; Sivesind et al., 2012). From economic standpoint, flaming is less costly than hand weeding (Wszelaki et al., 2007; Ulloa et al., 2011a). For example, the costs of a single hand weeding operation in Nebraska could range from US \$700 to \$1200 ha^{-1}, which is much higher than a single flame weeding treatment that typically cost about US \$40 ha^{-1} (Ulloa et al., 2011a).

Ulloa et al. (2010c) flamed soybean [*Glycine max* (L.) Merr.] intentionally only once per season with torches positioned directly over the crop row at different growth stages to determine crop tolerance under weed-free conditions. Their findings demonstrated that soybean is tolerant to single flame weeding treatment when flaming was conducted at selective growth stage. However, the ability of flame weeding alone to control weed populations for the entire growing season or perhaps until the canopy closure, has not been well established. Moreover, weeds also have a varied level of response to flaming, with grasses being more difficult to control than broadleaf species (Ascard, 1994; Ulloa et al., 2010a,b; Datta and Knezevic, 2013). More than one flame weeding operation, therefore, might be required to obtain longer season weed control in soybean. The objective of this study was to determine soybean tolerance to single and repeated flaming by utilizing the equipment designed with torches positioned parallel to the crop row.

4.3. Materials and methods

Study site and experimental set up

Field experiments were conducted at the Haskell Agricultural Laboratory, Northeast Research and Extension Center of the University of Nebraska located near Concord in northeast Nebraska (42.37°N, 96.68°W) in 2010 and 2011. A biennial rotation of soybean and maize (*Zea mays* L.) usually dominates in this region. The soil type was an Alcester series silty clay loam (fine-silty, mixed, mesic, Cumulic Haplustolls) with 3.6% organic matter and pH of 6.6. One of the commonly grown soybean cultivars in Nebraska, 20C1, was planted in 76-cm row spacing with a four-row planter in 10 m by 3 m plots. The seeding rate was 368,000 seeds ha^{-1} for both years, and the planting dates were May 14 in 2010 and June 11 in 2011. All plots including the non-flamed control were kept weed-free for the entire growing season by hand hoeing as weeds appeared. The plots used in this experiment were planted with maize in the previous season and the residues were removed before soybean planting. Crop growth was dependent on precipitation; no irrigation was applied.

Experimental design and treatments

The experiment was set up as randomized complete block design with eight treatments replicated three times. The timing of the treatment was based on the growth stage of the crop. The growth stages of soybean for flaming were based on leaf number that included VC (unfolded cotyledons), V2 (second trifoliate stage), and V5 (fifth trifoliate stage), as described by Ritchie et al. (1997). There were three levels of the number of flaming treatments: plots were flamed once (at VC, V2, or V5), two times (each at VC and V2, VC and V5, and V2 and V5 stages), or three times (at VC, V2, and V5 stages) at the pre-specified crop growth stages. In addition, one control plot was included for comparison that received no flaming treatment, and hereafter will be referred to as non-flamed control.

Flaming was conducted on May 28, June 16, and June 29 which corresponded to the growth stages of VC, V2, and V5, respectively, in 2010. The study in 2011 was flamed on June 18, July 4, and July 19 which corresponded to the same growth stages as in 2010. Flaming treatments were applied utilizing a tractor pulled four-row flamer developed at the University of Nebraska (Figure 5.1) (Bruening, 2009; Knezevic et al., 2012). The four-row flamer had eight torches mounted 38 cm apart and positioned parallel to the crop row at about 15 cm away from the crop row and 20 cm above the soil surface angled back at 30^{o}. Such setup covered 76 cm of the inter-row space providing a uniform flame and heat over all four rows in the plot. A simple flat-laying hood device kept the heat close to the ground and the hoods were closed during flaming at VC and V2 stages. Hoods were open during flaming at 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. In this set up the upper portion of soybean plants, including the growing point, were protected from the heat by the hoods (e.g., hoods kept most of the heat close to the ground level). It is important to note that the torch set up in our study was different than what Ulloa et al. (2010c) used in their experiment, where hoodless torches were positioned directly over the crop row, as the objective in that study was to determine soybean tolerance to direct heat. Flaming treatments were applied at a constant speed of 4.8 km h^{-1}, and propane pressure was adjusted in order to deliver a propane dose of 50 kg ha^{-1}.

Data collection

Crop injury was assessed visually at 7 and 28 days after treatment (DAT) using a scale of 0–100%, where 0 = no visual plant injury and 100 = complete plant death. In addition to visual ratings of crop injury, yield components and yields were also collected. Before final harvest, soybean yield components (number of plants m^{-2}, branches $plants^{-1}$, pods $plant^{-1}$, seeds pod^{-1}, and 1000-seed weight) were measured from 10 adjacent plants randomly selected in each plot. For soybean grain harvest, 6 m^{2} areas of the center two rows of each plot were hand clipped and run through a mechanical thresher. All the plots were harvested at physiological maturity when plants were dry and seed had almost same moisture content, which was about 8.4% to 8.7%. The moisture content was then adjusted to 13% for the comparison among treatments.

Data analysis

An ANOVA was performed by PROC GLIMMIX procedure in SAS (SAS Institute, 2005). The effects of replicate and year were considered random, and the effects of applied treatments were considered fixed. ANOVA of visual estimates of plant injury (7 and 28 DAT) was subjected to normality test. Data on percent crop injury were subjected to an arcsine square root transformation. Means of percent injury were compared on the transformed scale and were converted back to the original scale (actual values) for presentation of results as the transformation did not change the results of the analysis. Mean separation was accomplished using Fisher's Protected LSD test at $P \leq 0.05$.

4.4. Results

Soybean response to single and repeated flaming varied with growth stage of flaming and number of flaming treatments.

Crop injury

In general, VC and V5 were the most tolerant growth stages for broadcast flaming with the least crop injury. Flaming conducted once at VC or V5 stages, or twice (at VC and V5 stages) resulted in 23%, 19%, and 24% crop injury at 7 DAT, respectively, whereas the injury levels were reduced to 8%, 10%, and 12% for the corresponding growth stages by 28 DAT (Table 4.1). These results suggest that soybean plants flamed at VC or V5 stages were able to recover over time.

In contrast, any treatment combination that had flaming at V2 stage resulted in over 70% injury at both evaluation dates, thus showing no soybean recovery over time. Flaming conducted once (at V2), twice (at VC and V2), and three times (at VC, V2, and V5) resulted in 72%, 83%, and 92% injury, respectively, at 28 DAT (Table 4.1). These results indicated that soybean was extremely sensitive to heat when flamed at V2 stage, regardless of the number of flaming operations. This sensitivity is primarily the result of the heat induced damage to the growing point of soybean (Ulloa et al., 2010c), as the soybean plants were not tall enough to avoid the heat, despite presence of the hoods.

Yield components

All yield components were affected by flaming treatments with the exception of number of seeds pod^{-1} (Table 4.2). For example, treatments that included broadcast flaming at VC and/or V5 stages resulted in more plants m^{-2}, fewer branches plant^{-1}, fewer pods plant^{-1}, and greater 1000-seed weight compared to any of the treatments containing flaming at V2 stage (Table 4.2). With the exception of plants m^{-2}, there were no significant differences among yield components when flaming was conducted at VC and/or V5 stages compared to the non-flamed control. For instance, flaming once at V5 stage resulted in similar plant number m^{-2} compared to the non-flamed control, but 0.29 more branches plant^{-1} and 2.2 more pods plant^{-1}, which were also statistically similar to the non-flamed control (Table 4.2). However, flaming soybean once at VC stage and twice at VC and V5 stages significantly reduced plant number m^{-2} compared to the non-flamed control. There was about 18.4 plants m^{-2} in the non-flamed plots compared to significantly lower number of plants m^{-2} of 16.5 and 15.8 for flaming once at VC and flaming twice at VC and V5 stages, respectively (Table 4.2). The weight of 1000-seed was the only yield component statistically different from the non-flamed control when flaming was conducted at V5 stage. Soybean plants produced almost 10.0 g less in 1000-seed weight at V5 flaming stage compared to the non-flamed control (Table 4.2).

Any flaming treatment that included V2 stage resulted in significant loss of soybean stand, which provided greater space for the survived plants to develop more branches and consequently more pods plant^{-1} compared to the non-flamed control (Table 4.2). For example, flaming treatment conducted three times (at VC, V2, and V5) produced 1.59 more branches plant^{-1} and 54.1 more pods plant^{-1} than the non-flamed control. In contrast, the 1000-seed weight for the same treatment decreased by 27.5 g compared to the non-flamed control (Table 4.2). From practical standpoint, this increase in branch number plant^{-1} and pods plant^{-1} could not compensate for the loss in plant number area^{-1}, thus the yields were the lowest in all treatments that contained flaming at V2 stage.

Yield

The highest crop yields were obtained from the non-flamed control (3.45 t ha^{-1}), which was not statistically different from the plots flamed once at VC (3.35 t ha^{-1}), V5 stages (3.32 t ha^{-1}), and two times at VC and V5 stages (3.24 t ha^{-1}) (Table 4.2). Significantly lower yields were in all plots flamed at V2 stage (1.03 t ha^{-1} at V2, 0.46 t ha^{-1} at VC and V2, and 0.38 t ha^{-1} at V2 and V5). The lowest yields were in soybean flamed three times (VC, V2, and V5 stages), which yielded only 0.36 t ha^{-1}. These results suggest that soybean could tolerate a maximum of two flaming applications per season (e.g., at VC and V5 growth stages).

4.5. Discussion

Plant susceptibility to propane flaming varies with species and growth stages (Ulloa et al., 2010c; 2011a,b; Datta and Knezevic, 2013). In our study, soybean plants flamed at V2 stage were the least tolerant to flaming, while VC and V5 stages were the most tolerant. Ulloa et al. (2010c) also reported that VC was the most tolerant growth stage of soybean for broadcast flaming. This differential response is attributed to the position of the growing point relative to the heat source during flaming. At VC stage, the growing point of soybean is between the cotyledons (Ritchie et al., 1997), which are full of moisture and swollen, thus providing a physical barrier to protect the growing point from the flame and direct heat (Ulloa et al., 2010c). In contrast, the growing point was exposed to heat during flaming at V2 stage resulting in many dead or severely stunted plants, with little or no potential to regrow. At V5 stage, the growing point was at the top of the soybean plant, thus it was physically at least 30 cm above the specially designed hoods, and away from the heat. Hoods kept the heat primarily to the bottom 20 cm of soybean plants; therefore, the heat did not damage the growing point. Despite the fact that the bottom leaves were damaged by the heat, the plants were able to continue growing and produce yields statistically similar to the non-flamed plots.

Compared to the non-flamed control, flaming soybean once at VC stage, and twice at VC and V5 stages, reduced plant number m^{-2}, which resulted in 1.9 and 2.6 fewer plants m^{-2}, respectively. Despite that slight reduction in plant number on an area basis, soybean was able to compensate by producing more branches $plant^{-1}$ (Table 4.2), as suggested as well by Ulloa et al. (2010c). It was observed (data not collected) that time of soybean flowering and pods ripening were delayed approximately by 2-4 days depending on the plot, when flaming was conducted once at VC and twice at VC and V5 stages. However, despite that slight delay, soybean produced statistically similar number of pods $plant^{-1}$ and yields compared to the non-flamed control (Table 4.2). Others also reported that the pod number $plant^{-1}$ could be one of the most important yield components that determined the ultimate soybean yield (Herbert and Litchfield, 1982; Board et al., 1999; Mathew et al., 2000). This may explain the reason for obtaining similar yields between the plots which were flamed once at VC, V5 stages, and two times at VC and V5 stages compared to the non-flamed control, despite the slight delay in maturity and reduction in crop stand in our study.

This study was conducted under weed-free conditions utilizing a propane dose of 50 kg ha^{-1}. The same propane dose was highly effective in controlling many broadleaf weeds at early growth stages (up to 10 cm tall), providing over 90% control of *Ipomoea hederacea* Jacq., *Abutilon theophrasti* Medik., *Amaranthus rudis* Sauer, *Amaranthus retroflexus* L., *Convolvulus arvensis* L., *Kochia scoparia* (L.) Schrad., and *Hibiscus trionum* L. (Ulloa et al., 2010a,b). The same dose of propane also provided 80% control of several grass species that include *Setaria viridis* (L.) Beauv., *Setaria pumila* (Poir.) Roemer & J.A. Schultes, and *Echinochloa crus-galli* (L.) Beauv. (Ulloa et al., 2010a,b).

These weed species are among the most troublesome weeds responsible for significant yield reduction in agronomic crops including soybean throughout the Midwestern United States (Shoup et al., 2003).

Conducting weed removal with flaming (or other methods) at VC and V5 stages can provide a weed free environment needed for soybean growth according to the concept of the critical period of weed control. For example, it was reported that the critical period for weed control in soybean was from the V1-V2 stage until the beginning pod stage (e.g., almost canopy closure in 76 cm row spacing) (Van Acker et al., 1993; Mulugeta and Boerboom, 2000). Therefore, conducting weed removal treatment at VC stage (first flaming time in this study) would reduce the potential for weed competition during the early stages of the critical period of weed control. Then controlling additional flush of weeds at V5 stage (second flaming time in this study) would help minimize weed competition during the later stages of the critical period of weed control. An additional weed control operation might be needed to control any weed flushes that occur between VC and V5 stages, in order to remove weed competition from the entire critical period of weed control. Additional studies are perhaps needed to confirm the above hypothesis.

In summary, flaming treatments conducted twice at VC and V5 stages exhibited the lowest crop injury with little effect on yield components and resulted in statistically similar yield to the non-flamed control. Therefore, we believe that flaming two times at VC and V5 stages would be an acceptable practice in the tool box of integrated weed management that can be utilized by the soybean producers. Flaming can be also conducted after V5 stage (e.g., until canopy closure), however, the heat from the flame has potential to damage flowers on the bottom of soybean plant. Additional studies are needed to determine the extent of such damage.

From the practical standpoint, it is important to note that an additional weed control treatment might be needed for weed flushes that emerge between VC and V5 stages of soybean. Therefore, propane flaming should not be the only method of weed control, it should be part of an integrated weed management program, as previously suggested by others (Datta and Knezevic, 2013). Flaming can be also a viable alternative from the economic standpoint as it is much more economical than hand weeding (e.g., US $40 ha^{-1} for a single flaming versus US $700 to $1200 ha^{-1} for a hand weeding operation).

4.6. Acknowledgements

The authors would like to acknowledge Jon Scott and many summer helpers for assisting with field operations. We would also like to thank the Propane Education and Research Council, USDA and the Nebraska Propane Association for partial financial support of this project.

4.7. References

Abouziena HFH, Omar AAM, Sharma SD, Singh M (2009) Efficacy comparison of some new natural-product herbicides for weed control at two growth stages. Weed Technol 23:431–437

Ascard J (1994) Dose–response models for flame weeding in relation to plant size and density. Weed Res 34:377–385

Bond W, Grundy AC (2001) Non-chemical weed management in organic farming systems. Weed Res 41:383–405

Board JE, Kang MS, Harville BG (1999) Path analyses of the yield formation process for late-planted soybean. Agron J 91:128–135

Bruening CA (2009) Development of Propane Flaming Equipment for Thermal Weed Control in Agronomic Crops. M.S. thesis, The University of Nebraska-Lincoln, Lincoln, NE, USA

Datta A, Knezevic SZ (2013) Flaming as an alternative weed control method for conventional and organic agronomic crop production systems: A review Adv Agron 118, 399–428

Herbert SJ, Litchfield GV (1982) Partitioning soybean yield components. Crop Sci 22:1074–1079

Johnson WC (2004) Weed Control with Organic Production. Proceedings of the Southeast Regional Fruit and Vegetable Conference: 13-14. Savannah, GA, USA

Knezevic SZ, Datta A, Bruening C, Gogos G (2012) Propane Fuelled Flame Weeding in Field Corn, Soybean, and Sunflower Crops. Propane Education and Research Council, Washington, DC, USA http://www.agpropane.com/uploadedFiles/Agriculture/Program_Safety_On_The_Farm/Flame%20Weeding%20Training%20Manual_08-27-12_final%20(2).pdf. Accessed: 24.02.2013

Kruidhof HM, Bastiaans L, Kropff MJ (2008) Ecological weed management by cover cropping: effects on weed growth in autumn and weed establishment in spring. Weed Res 48:492–502

Mathew JP, Herbert SJ, Zhang S, Rautenkranz AA, Litchfield GV (2000) Differential response of soybean yield components to the timing of light enrichment. Agron J 92:1156–1161

Mulugeta D, Boerboom CM (2000) Critical time of weed removal in glyphosate-resistant *Glycine max*. Weed Sci 48:35–42

Penfold CM, Miyan MS, Reeves TG, Grierson IT (1995) Biological farming for sustainable agricultural production. Aust J Exp Agric 35:849–856

Rifai MN, Astatkie T, Lacko-Bartosova M, Gadus J (2002). Effect of two different thermal units and three types of mulch on weeds in apple orchards. J Environ Eng Sci 1:331–338.

Ritchie SW, Hanway JJ, Thompson HE, Benson GO (1997) How a soybean plant develops. Special Report 53. Iowa State University, Cooperative Extension Service, Ames, IA, USA

Shoup DE, Al-Khatib K, Peterson DE (2003) Common waterhemp (*Amaranthus rudis*) resistance to protoporphyrinogen oxidase-inhibiting herbicides. Weed Sci 51:145–150

Sivesind EC, Leblanc ML, Cloutier DC, Seguin P, Stewart KA (2012) Impact of selective flame weeding on onion yield, pungency, flavonoid concentration, and weeds. Crop Prot 39:45–51

Statistical Analysis Systems (SAS) (2005) The GLIMMIX Procedure. Online Documentation. SAS Institute, Inc., Cary, NC, USA. Version 9.1

Ulloa SM, Datta A, Knezevic SZ (2010a) Growth stage influenced differential response of foxtail and pigweed species to broadcast flaming. Weed Technol 24:319–325

Ulloa SM, Datta A, Knezevic SZ (2010b) Tolerance of selected weed species to broadcast flaming at different growth stages. Crop Prot 29:1381–1388

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

Ulloa SM, Datta A, Bruening C, Neilson B, Miller J, Gogos G, Knezevic SZ (2011a) Maize response to broadcast flaming at different growth stages: Effects on growth, yield and yield components. Eur J Agron 34:10–19

Ulloa SM, Datta A, Knezevic SZ (2011b) Growth stage influenced sorghum response to broadcast flaming: Effects on yield and its components. Agron J 103:7–12

Ulloa SM, Datta A, Bruening C, Gogos G, Arkebauer TJ, Knezevic SZ (2012) Weed control and crop tolerance to propane flaming as influenced by the time of day. Crop Prot 31:1–7

Van Acker RC, Swanton CJ, Weise SF (1993) The critical period of weed control in soybean [*Glycine max* (L.) Merr.]. Weed Sci 41:194–200

Walz E (1999) Final Results of the Third Biennial National Organic Farmers' Survey. Organic Farming Research Foundation, Santa Cruz, CA, USA

Wszelaki AL, Doohan DJ, Alexandrou A (2007) Weed control and crop quality in cabbage [*Brassica oleracea* (capitata group)] and tomato (*Lycopersicon lycopersicum*) using a propane flamer. Crop Prot 26:134–144

4.8. Tables

Table 4.1. Soybean injury as influenced by single and repeated flaming at 7 and 28 days after treatment (DAT) in the field experiment at Concord, NE, USA, 2010 and 2011.

Treatment	Percent visual injury (DAT)[a]	
	7	28
Flaming once (at VC)	23 c	8 d
Flaming once (at V2)	83 b	72 c
Flaming once (at V5)	19 c	10 d
Flaming twice (at VC and V2)	86 ab	83 b
Flaming twice (at VC and V5)	24 c	12 d
Flaming twice (at V2 and V5)	85 ab	82 b
Flaming three times (at VC, V2, and V5)	93 a	92 a

[a] Different letters within each response variable refer to statistically significant differences following the Fisher's Protected LSD test at $P < 0.05$.

Table 4.2. Soybean yield components and yield as affected by the number of flaming treatments in the field experiment at Concord, NE, USA, 2010 and 2011.

Treatment	Yield components[a]					Yield[a] (t ha^{-1})
	Plants m^{-2}	Branches plant^{-1}	Pods plant^{-1}	Seeds pod^{-1}	1000-seed weight (g)	
Non-flamed control	18.4 a	0.41 c	33.3 d	2.4 a	139.8 a	3.45 a
Flaming once (at VC)	16.5 b	0.63 c	34.1 d	2.3 a	131.2 b	3.35 a
Flaming once (at V2)	9.4 c	2.10 a	44.6 c	2.3 a	115.2 c	1.03 b
Flaming once (at V5)	17.0 ab	0.70 c	35.5 d	2.4 a	129.8 b	3.32 a
Flaming twice (at VC and V2)	6.5 d	1.93 a	54.7 b	2.3 a	116.7 c	0.46 c
Flaming twice (at VC and V5)	15.8 b	1.13 b	33.4 d	2.5 a	129.2 b	3.24 a
Flaming twice (at V2 and V5)	6.3 d	1.80 a	58.3 b	2.4 a	114.8 c	0.38 c
Flaming three times (at VC, V2, and V5)	1.8 e	2.00 a	87.4 a	2.2 a	112.3 c	0.36 c

[a] Different letters within each response variable refer to statistically significant differences following the Fisher's Protected LSD test at $P < 0.05$.

CHAPTER 5. Integrating flaming and cultivation for weed control in organic maize: Crop yield and yield components

5.1. Abstract

Weed management is a major constraint in organic crop production. Propane flaming combined with mechanical cultivation in a single operation could be an additional tool for weed control in organic maize. Field studies were conducted at certified organic field at the Haskell Agricultural Laboratory of the University of Nebraska in 2010, 2011, and 2012. 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 maize grown under two manure levels. There were 12 weed management treatments (WMT) that included: weed-free control, weedy season-long, and combinations of banded flaming (intra-row), broadcast flaming, and mechanical cultivation (inter-row), applied at the three-leaf (V3) and/or the six-leaf (V6) growth stages. Treatments were applied utilizing flaming equipment developed at the University of Nebraska. Propane doses were 20 and 45 kg ha^{-1} for the banded and broadcast flaming, respectively. Crop response and weed control was evaluated visually at 7 and 28 days after treatment (DAT). All evaluated parameters (weed control, weed biomass, crop injury, yield, and yield components) indicated that there was no interaction between manure application and treatment; however, there was an increase in maize yield with addition of manure. Overall, maize showed good tolerance to all flaming treatments. The best weed control was achieved with banded flaming followed by cultivation conducted twice (at V3 and

V6 stages), which provided greater than 90 % weed control at 28 DAT. Banded flaming followed by aggressive cultivation at V3 and V6 growth stages was the best treatment in all three years providing the highest yield (7.6–9.9 t ha^{-1}). Flame-cultivation conducted twice was the second best treatment resulting in 6.8–9.6 t ha^{-1} yields, while broadcast flaming conducted twice yielded 5.3–8.1 t ha^{-1}. These results suggest that flaming and cultivation have a potential for use in maize production systems.

Keywords: Organic crop production; Nonchemical weed control; Manure; Parallel and cross flaming; Crop injury.

5.2. Introduction

Weeds are one of the major problems in both conventional and organic crop production systems, and are responsible for significant crop yield reduction (Milberg and Hallgren 2004). Weeds are especially hard to control in organic farming systems where use of chemical herbicides is prohibited (Kruidhof et al. 2008); therefore, producers cite weed control as their foremost production-related problem (Sumption et al. 2004). Over the past decade, the demand for organic maize (*Zea mays* L.) has been on increase due to growth in organic dairy, poultry, and livestock production (Roth 2013). Furthermore, organic maize premiums have been also increasing with an average of about 142% over conventional maize (Clark and Alexander 2010). Given the above favorable market opportunities, organic farmers seem to have strong economic incentives to protect their crop from yield loss from weeds (Liebman and Davis 2010).

Flaming is one the most promising tools for weed control in organic cropping systems and it has potential to be used in conventional crops as well (Bond and Grundy, 2001; Datta and Knezevic 2013). Flame weeding dates back to mid-1940s when liquid fuels such as kerosene and oil were replaced with more efficient liquefied petroleum gasses such as propane and butane (Edwards 1964). Popularity of flaming, however, started to decline in the late 1950s due to rising prices of liquid propane-gas (LP-gas), and the availability of less expensive and more efficient herbicides (Daar 1987). However, recent concerns regarding herbicide use, such as negative effects on the environment, increased prices, and occurrence of herbicide-resistant weeds renewed interest in alternative methods for weed control, including cultivation and flame weeding (Boutin et al. 2004; Seifert and Snipes 1996).

Propane fueled flame weeding is gaining popularity among organic producers, especially with the introduction of organic certification in 1980s, which allowed the use of flaming as a tool for weed control. Flaming controls weeds by heating plant tissue rather than burning it (Leroux et al. 2001). Propane torches can generate flames with temperatures of up to 1900 °C, which raises the temperature of the exposed plant tissues rapidly (Ascard 1998). Direct heat exposure causes denaturation of membrane proteins, which results in loss of cell function and eventually the plants die (Carrubba and Millitello 2013; Lague et al. 2001), or their competitive ability is drastically reduced (Datta and Knezevic 2013). Flame weeding leaves no chemical residues in plants, soil or water, produces no drift hazards, or herbicide carry-over to the next season, and can control herbicide-tolerant or resistant weeds (Wszelaki et al. 2007). In addition, a mechanical cultivation can be also used as an alternative method of weed control.

Mechanical cultivation is one of the oldest weed control practices used in row crops (Bond and Grundy 2001). In organic cropping systems, where use of herbicides is not allowed, farmers typically utilize 3–5 cultivations per season for their weed control in maize (Mulder and Doll 1993). Cultivation, however, leaves a strip of uncontrolled weeds that remain within the 5–10 cm strip on either side of the crop row, where they directly influence crop yield (Mulder and Doll 1993). Flaming has a potential to remove the weeds that are within crop row without significantly damaging the crop (Knezevic et al. 2012). 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 maize grown under two manure levels.

5.3. Materials and methods

Study site and experimental set up

Field experiments were conducted in 2010, 2011, and 2012 at the Haskell Agricultural Laboratory of the University of Nebraska, Concord, NE, USA (42.37°N, 96.68°W) on certified organic field where maize was grown in rotation with soybean [*Glycine max* (L.) Merr.]. Each year field was disked and cultivated about one week prior to planting. One of the organic maize hybrids, brand 56M30 (Blue River Hybrids Organic Seed, Kelley, IA, USA), was planted in 76 cm row spacing with a four-row planter in 15 m by 3 m plots using a seeding rate of 54,800 seeds ha^{-1}. Agronomic practices such as planting and harvest were conducted according to the local cropping practices (Table 5.1). Two out of three years had a typical weather conditions and rainfall patterns characteristic of eastern Nebraska. However, there was a severe drought during the 2012 season (Table 5.2), which required three irrigation events each of 80 mm of water applied 10 days apart starting from 3 August.

Experimental design and treatments

The experiments were conducted using a split-plot design with three replications. The main-plot was manure regime (manure or no-manure) and the sub-plots were 12 different weed management treatments (WMT). A manure rate of about 110 t ha^{-1} was applied to manure blocks on 5 May, 4 April, and 25 April in 2010, 2011, and 2012, respectively. Manure was stockpiled for a year before it was utilized.

The WMT included: weed-free control, weedy season long control, and combinations of banded flaming (intra-row), broadcast flaming, and mechanical cultivation (inter-row) applied at two growth stages (V3–V4 and V6–V7) of maize (Table 5.3). Growth stages of maize were determined by counting the number of fully developed leaves that have visible collar (e.g. V3–the collar of the third leaf is visible, and is designated as the 3-leaf stage). Each individual weed control practice was applied either at V3–V4 or V6–V7 growth stage resulting in a total of 12 WMT (Table 5.3). Weeds in the weed-free control plots were removed by hand weeding and hoeing as needed. Weed management treatments were applied at a constant speed (4.8 km h^{-1}) and propane pressure was adjusted in order to deliver 45 kg ha^{-1} for broadcast flaming and 20 kg ha^{-1} for banded flaming and flame-cultivation treatments (Knezevic et al. 2012). The treatment dates, time of day, and weather conditions for each application are presented in Table 5.4.

Equipment

Two flame weeding units (4-row full flamer and 4-row flamer-cultivator), previously developed at the University of Nebraska (Bruening 2009; Bruening et al. 2009; Neilson 2012), were utilized for conducting all treatments. Both units were tractor mounted driving at about 4.8 km h^{-1}.

A four-row full flamer was used with two different torch setups, broadcast and banded (Figure 5.1, Figure 5.2). 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 over the land area, and to all four rows in the plot (broadcast flaming treatment). In the banded setup, torches were positioned at a 30° angle toward crop row so that flame only covered a band of 30 cm of intra-row space (banded flaming treatment). The weed 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 the heat. Each hood was positioned over the intra-row space and covered two torches. The hoods were ‘closed’ across the rows during flaming at V3–V4 growth stage, whereas hoods were ‘open’ during flaming at V6–V7 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 set up protected the upper portion of maize plants, including the growing point, from the intense heat.

A four-row flamer-cultivator was designed to apply flaming and cultivation in a single pass with inter-row cultivation and intra-row (banded) flaming (Figure 5.3). The flamer-cultivator was built by modifying a Noble Row-Runner cultivator 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 to perform 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). 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). During flaming-cultivation torches were mounted in front of cultivators, and when preforming cultivation only, flaming torches were turned off.

In addition, the flame-cultivation treatment 12 (Table 5.4) was applied in two separate operations. Flaming was conducted first using the 4-row full flamer with banded setup (banded flaming), and then followed by aggressive cultivation with a Buffalo type cultivator that has single 50 cm wide sweep and a set of hillers (Figure 5.4). We utilized the term “aggressive cultivation” as a way to describe a cultivation method that allowed throwing soil into the intra-row space, which creates a small ridge that buried the flamed weeds.

Data collection

Density, composition, and height of weed species were collected in each plot prior to initiation of the treatment (V3 maize stage). Weed counts were conducted prior to treatment initiation and weed biomass samples hand harvested at 60 days after treatment (DAT) from 1 m^2 area approximately 2 m from the bottom edge of the plot. Samples were dried at 50 °C for two 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.

Yield and yield components data were collected by hand harvesting a 4 m length (6.08 m^2 area) of the center two rows of each plot. Harvested samples were shelled, weighed, and adjusted to 15.5 % moisture content to obtain yield data. Yield components data were also collected, which included: plants m^{-2}, ears $plant^{-1}$, seeds ear^{-1}, and 1000-seed weight. The total number of plants and ears in the harvest area (6.08 m^2) was used to determine plants m^{-2} and ears $plant^{-1}$. To obtain the 1000-seed weight, smaller subsamples of shelled maize were taken, counted, and weighted. The number of seeds ear^{-1} was calculated by using the following equation:

$$Y = \frac{(G \times 1000)/SW}{N} \qquad (1)$$

where *Y* is the number of seeds ear^{-1}, *G* is the weight of harvested sample (g), *SW* is the weight of 1000 seeds from the same sample (g), and *N* is the number of ears from the same sample.

Statistical analyses

All data (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 years, treatments, replications, and their interactions (SAS

Institute, 2005). Means for the significant treatment effects were compared using Fisher's protected least significant difference (LSD) procedure at $P<0.05$.

5.4. Results

Characteristics of weed community

Weed species composition, density, and height were similar in all three years; thus, data were combined over years (Table 5.5). In general, 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 5.5). 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 composition of the weed community to a greater extent, as occurrence of these species was < 1 % (data not shown). Overall weed density in this study was around 192 plants m^{-2}, with weed height ranging from 1.7–2.3 cm prior to initiation of the treatment (Table 5.5).

Crop injury

Maize showed good tolerance to flaming, as it demonstrated the ability to recover after various types of flaming treatments. Temporary injury symptoms in the form of initial whitening and then browning of the lower leaves were still apparent visually at 7

DAT, with 12–33 % injury levels (Table 5.7). However, by 28 DAT, crop injury ratings declined to ≤ 8 %, and by the time maize plants reached tasseling the symptoms completely disappeared, regardless of the treatment (Table 5.7). Delay in maize maturity was not observed. Ulloa et al. (2011) also observed higher maize injury from flaming at early evaluation dates compared to later rating dates. Similar to our results, Ulloa et al. (2011) also reported the recovery of flamed maize plants over time.

It was notable, however, that maize plants flamed only once during the season (either at V3–V4 or V6–V7 growth stage) appeared to recover faster than maize plants that were flamed twice (at V3–V4 and V6–V7 stages). For example, cultivation at V3–V4 followed by flame-cultivation at V6–V7 (C–FC) caused 17 and 3 % crop injury for 7 and 28 DAT, respectively; whereas for the same corresponding evaluation dates broadcast flaming twice (BF-BF) caused significantly higher crop injuries of 33 and 8 % (Table 5.7).

Weed control and weed dry matter

There was no significant interaction between years, manure levels, and weed management practices (WMT) (Table 5.6), thus, weed control and weed dry matter data were combined across three years, two manure levels, and three replications for each WMT (Table 5.7). Correlation analyses showed that 90% of the variation in weed biomass can be explained by visual ratings of weed control. A strong negative linear relationship (r = –0.902) between the two variables indicated that an increase in weed control caused a linear decrease in weed biomass (Table 5.7).

In general, the best weed control was achieved by a combination of flame-cultivation conduced twice, whereas cultivation alone provided the poorest weed control. For example, combined banded intra-row flaming and inter-row cultivation applied twice [treatments 7 (FC–FC) and 12 (FCa–FCa)] provided the highest weed control levels (88 and 94 % at 28 DAT) and resulted in the lowest weed dry matter (114 and 59 g m^{-2}), respectively (Table 5.7). In contrast, cultivation alone conducted twice (treatment 3; C–C) was the worst WMT, with weed control level of 33 % at 28 DAT and resulting in a 441 g m^{-2} of weed dry matter.

Weed management treatments that consisted of one flame-cultivation and one broadcast flaming (treatments 8 and 10) also provided fairly acceptable weed control level at 28 DAT (~80 %). For instance, broadcast flaming at V3–V4 stage followed by flame-cultivation at V6–V7 (treatment 10; BF–FC) resulted in 80 % weed control and weed dry matter of 182 g m^{-2}, whereas 75 % weed control and 174 g m^{-2} of weed dry matter was obtained when flame-cultivation at V3–V4 stage was followed by broadcast flaming application at V6–V7 stage (treatment 8; FC–BF) (Table 5.7). All other WMT had ≤ 59 % weed control and ≥ 265 g m^{-2} of weed dry matter, suggesting that cultivation alone was not an effective weed control practice (Table 5.7).

Weed dry matter in plots with manure was significantly greater than in those plots without manure ($P < 0.001$) in one of the three years (Table 5.6). Weed dry matter in manure and no-manure blocks for 2010 and 2012 were statistically the same with an average of 274 and 283 g m^{-2}, respectively. In 2011, weed dry matter in plots with manure (349 g m^{-2}) was statistically higher than in no-manure plots (278 g m^{-2}). This interaction, however, was not captured visually, as the weed control ratings were similar between manure blocks (Table 5.7).

Yield components

The number of seeds ear^{-1} was the only yield components that had significant year by manure interaction (Table 5.6), which was the case in two out of three years. Manure application in 2010 and 2011 caused a significant increase in number of seeds ear^{-1}, whereas there was no effect of manure in 2012. For example, without manure application maize in the treatment 6 (FC–C) produced 442 and 526 seeds ear^{-1} in 2010 and 2011, respectively; compared to 585 seeds ear^{-1} in 2010 and 656 seeds ear^{-1} in 2011 with the addition of manure (Table 5.8). Similar trends were observed with other treatments.

WMT had no significant effect on plants m^{-2}, ears plant^{-1} and 1000-seed weight (Table 5.9). However, maize population was statistically similar (4.43–5.00 plants m^{-2}) among treatments, except in the weedy control plot where maize stand was significantly reduced (4.26 plants m^{-2}). Likewise, all plots had similar number of ears plant^{-1} (0.94–1.01 ears plant^{-1}) and similar 1000-seed weight that ranged from 236 to 261 g. Results also showed that 1000 seeds weight was significantly greater in 2010 (307 g) than in 2012 (279 g) and 2011 (158 g m), which caused a significant effect of year on 1000-seed weight (Table 5.6). This might be due to differences in total precipitation amounts, which were 849, 621, and 291 (+240 mm applied through three irrigation events) mm in 2010, 2011, and 2012, respectively (Table 5.2).

Out of all yield components, only seeds ear^{-1} was significantly affected by WMT (Table 5.6). Overall, the highest and the lowest number of seeds ear^{-1} were observed in the weed-free (611) and weedy season long (313) controls, respectively, across years and manure levels (Table 5.8). Both treatments 7 (FC–FC) and 12 (FCa–FCa), that included combined banded flaming and cultivation applied twice at V3–V4 and V6–V7 growth stages were consistently the best weed control treatments in all three years and averaging with the highest number of seeds ear^{-1}, whereas the lowest number of seeds ear^{-1} was in plots where cultivation alone was conducted twice (treatment 3, Table 5.8). Similar trends were observed in other years as well.

Yield

Manure application significantly increased yield in two out of three years. In 2010 and 2011, maize yields were significantly higher across all WMT in manure treated plots (Table 5.10). In 2012, manure plots showed no significant difference in yield compared to yield obtained from no-manure plots, which is likely the result of drought conditions in that year (Table 5.10). For example, when manure was added in 2010 and 2011 weed free maize yielded 10.3 and 9.0 t ha^{-1}, respectively; whereas significantly lower maize yields (8.8 and 7.8 t ha^{-1}) was observed in plots without manure (Table 5.10).

There was a significant year by WMT interaction (Table 5.6). Regardless of this interaction, general trend indicated that flame-cultivation was the most effective weed control practice and in combination with broadcast flaming and/or cultivation may provide acceptable yield.

Significant correlation between weed biomass and yield ($r = -0.71$) suggested that WMT with the lowest weed dry matter (also highest weed control level) resulted in the highest crop yield. Therefore, banded flaming followed by aggressive cultivation at V3–V4 and V6–V7 (FCa–FCa) growth stages was the best treatment in all three years providing the highest yield (7.6–9.9 t ha^{-1}). Flame-cultivation conducted twice (FC–FC) was the second best treatment resulting in 6.8–9.6 t ha^{-1} yields, while broadcast flaming conducted twice yielded 5.3–8.1 t ha^{-1} (Table 5.10).

5.5. Discussion

Manure application increased crop yield in two out of three years (2010 and 2011). However, when drought conditions occurred in 2012, manure had no significant influence on crop yield. Yield increase in maize with manure application is not surprising as it is well documented in the literature (Eghball et al. 2004; Jokela 1992; Lithourgidis et al. 2007). However, the use of manure during drought years has little or no positive effects of yields due to the lack of soil moisture that reduces plant nutrient uptake (Federer 1982; Guswa 2005).

Among WMT, banded flaming followed by aggressive cultivation applied twice in the season had the best weed control and crop yields, suggesting that combining flaming and cultivation into a single operation was more effective weed control practice than applying them individually. Our results are similar to those of Leroux et al. (1995) who reported that post-emergence flame-cultivation in maize conducted two times during the season at early (2–3 leaf) and later (6–7 leaf) growth stages did not have any negative impact on maize yield, when used after pre-emergence rotary hoe or broadcast flaming. Others also reported that flaming in combination with cultivation can be an effective tool in controlling most annual and some perennial weeds, if properly used (Seifert and Snipes 1996).

Utilizing specially designed hoods during flaming process minimized crop injury, by protecting most of maize canopy from significant heat damage. Similarly, Stephenson (1959) reported that utilizing hoods for parallel flaming in cotton [*Gossypium hirsutum* (L.)] reduced leaf damage in the bottom 10–30 cm of crop height; hence, providing more flexibility in controlling weeds early in the season. Unlike cotton, growing point of maize is either under soil surface (V1–V5) or well protected by surrounding leaves (>V5), which makes it very tolerant to flaming (Ulloa et al. 2011). Thus, selective hooded flaming in maize can be safely used any time between V1–V10 growth stages (Knezevic et al. 2012). Timing of flaming application, however, should be adjusted based on weed size and types of weed species present to maximize its efficiency (Ascard 1995; Ulloa et al. 2010a,b).

Combining flaming and cultivation was the most effective weed control practice. When applied twice in the season, flame-cultivation also yielded similarly to season long weed-free control. Alternatively, substituting one flame-cultivation operation with broadcast flaming could also provide satisfactory weed control. Therefore, these findings suggest that flaming can be successfully integrated into weed management program for organic maize production as it does not adversely affect crop yield. Flaming is efficient in controlling weeds, and can provide flexibility for weed control, especially during wet field conditions. Flaming, however, should not be a single weed control practice, and combining it with cultivation and other non-chemical weed management strategies when possible will aid the effectiveness of weed control programs in both organic and conventional crops (Ascard 1995; Datta and Knezevic 2013; Leroux et al. 2001; Wszelaki et al. 2007).

5.6. Acknowledgments

This study was partially funded by the Propane Education, USDA and Research Council and the Nebraska Propane Association. The authors are also grateful for the help provided by Jon Scott, and many summer helpers.

5.7. References

Ascard J 1995 Effects of flame weeding on weed species at different developmental stages. Weed Res 35:397–411

Ascard J (1998) Comparison of flaming and infrared radiation techniques for thermal weed control. Weed Res 38:69–76

Bond W, Grundy AC (2001) Non-chemical weed management in organic farming systems. Weed Res 41:383–405

Boutin C, Elmegaard N, Kjaer C (2004) Toxicity testing of fifteen non-crop plant species with six herbicides in a greenhouse experiment: implications for risk assessment. Ecotoxicology 13:823–825

Bruening CA (2009) Development of Propane Flaming Equipment for Thermal Weed Control in Agronomic Crops. M.S. thesis, The University of Nebraska-Lincoln, Lincoln, NE, USA

Bruening CA, Gogos G, Ulloa SM, Knezevic SZ (2009) Performance Advantages of Flaming Hood. In: Proceedings of the North Central Weed Science Society Conference (R.G. Hartzler and A.N. Hartzler, Eds.), 64:30, Kansas City, MO, USA

Carrubba A, Millitello (2013) Nonchemical weeding of medicinal and aromatic plants. Agron Sustain Dev 33:551–561

Clark C, Alexander C (2010) The profitability of transitioning to organic grain crops in Indiana. Purdue Agricultural Economics Report. At: http://www.agecon.purdue.edu/extension/pubs/paer/2010/february/alexander.asp. Accessed 29 September 2013

Daar S (1987) Update: Flame-weeding on European farms. IPM Practitioner 11:1–4

Datta A, Knezevic SZ (2013) Flaming as an alternative weed control method for conventional and organic agronomic crop production systems: A review. Adv Agron 118:399–428

Edwards FE (1964) History and progress of flame cultivation. In: Proceedings of the First Annual Flame Symposium (pp. 3–6). Memphis, TN: Natural Gas Processors Association

Eghball B, Ginting D, Gilley JE (2004) Residual effects of manure and compost applications on corn production and soil properties. Agron J 96:442–447

Federer CA (1982) Transpirational supply and demand: Plant, soil, and atmospheric effects evaluated by simulation. Water Resour Res 18:355–362

Guswa AJ (2005) Soil-moisture limits on plant uptake: An upscaled relationship for water-limited ecosystems. Adv Water Resour 28:543–552

Jokela W (1992) Nitrogen fertilizer and dairy manure effects on corn yield. Soil Sci Soc Am J 56:148–154

Knezevic SZ, Datta A, Bruening C, Gogos G (2012) Propane-fueled flame weeding in corn, soybean, and sunflower. http://www.agpropane.com/uploadedFiles/Agriculture/Program_Safety_On_The_Farm/Flame%20Weeding%20Training%20Manual_08-27-12_final%20(2).pdf. Accessed 27 September 2013

Kruidhof HM, Bastiaans L, Kropff MJ (2008) Ecological weed management by cover cropping: effects on weed growth in autumn and weed establishment in spring. Weed Res 48:492–502

Lague C, Gill J, Peloquin G (2001) Thermal control in plant protection. In"Physical Control Methods in Plant Protection" (C. Vincent, B. Panneton, and F. Fleurat-Lessard, Eds.), pp. 35–46, Springer-Verlag, Berlin, Germany

Leroux GD, Douheret J, Lanouette M, Martel M (1995) Selectivity of propane flamer as a mean of weed control. Hort Sci 30:820–828

Leroux GD, Douheret J, Lanouette M (2001) Flame weeding in corn. In"Physical Control Methods in Plant Protection" (C. Vincent, B. Panneton, and F. Fleurat-Lessard, Eds.), pp. 47–60, Springer-Verlag, Berlin, Germany

Liebman M, Davis AS (2010) Managing Weeds in Organic Farming Systems: An Ecological Approach. In C. Francis, Organic Farming: The Ecological System (pp. 173–196). American Society of Agronomy

Lithourgidis AS, Matsi T, Barbayiannis N, Dordas CA (2007) Effect of liquid cattle manure on corn yield, composition, and soil properties. Agron J 99:1041–1047

Milberg P, Hallgren E (2004) Yield loss due to weeds in cereals and its large-scale variability in Sweden. Field Crops Res 86:199–209

Mulder TA, Doll JD (1993) Integrating reduced herbicide use with mechanical weeding in corn (*Zea mays*). Weed Technol 7:382–389

Neilson B (2012) The Integration of Propane Flaming and Mechanical Cultivation for Effective Weed Control in Agriculture. M.S. thesis, The University of Nebraska-Lincoln, Lincoln, NE, USA

Roth G (2013) Between the rows: organic corn production. Penn State Extension. At: http://extension.psu.edu/plants/crops/grains/corn/production/between-the-rows-organic-corn-production. Accessed 29 September 2013

Seifert S, Snipes CE (1996) Influence of flame cultivation on mortality of cotton (*Gossypium hirsutum*) pests and beneficial insects. Weed Technol 10:544–549

Statistical Analysis Systems (SAS) (2005) The GLIMMIX Procedure. Online Documentation. SAS Institute, Inc., Cary, NC, USA. Version 9.1

Stephenson KQ (1959) Mechanized Weed Control for Cotton Production in Arkansas. University of Arkansas Exp Station Report Series, 87, 16 pp., AR, USA

Sumption P, Firth C, Davies G (2004) Observation on agronomic challenges during conversion to organic field vegetable production. In: Hopkins A (ed), Organic farming: science and practice of profitable livestock and cropping. Proceedings of the BGS/AAB/COR conference. British Grassland Society, pp.176‑179

Ulloa SM, Datta A, Knezevic SZ (2010a) Growth stage influenced differential response of foxtail and pigweed species to broadcast flaming. Weed Technol 24:319–325

Ulloa SM, Datta A, Knezevic SZ (2010b) Tolerance of selected weed species to broadcast flaming at different growth stages. Crop Prot 29:1381–1388

Ulloa SM, Datta A, Bruening C, Neilson B, Miller J, Gogos G, Knezevic S Z (2011) Maize response to broadcast flaming at different growth stages: Effects on growth, yield and yield components. Eur J Agron 34:10–19

Wszelaki AL, Doohan DJ, Alexandrou A (2007) Weed control and crop quality in cabbage [*Brassica oleracea* (capitata group)] and tomato (*Lycopersicon lycopersicum*) using a propane flamer. Crop Prot 26:134–144

5.8. Figures

Figure 5.1. The 4-row flamer developed at the University of Nebraska performing parallel–hooded flaming (broadcast flaming) treatments in maize at six leaf–seven leaf stage. 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 over the land area, and to all four rows in the plot (broadcast flaming treatment). The 4-row full 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 the heat. Each hood was positioned over the intra-row space and covered two torches

Figure 5.2. The 4-row full flamer developed at the University of Nebraska performing banded flaming treatments in maize at six leaf–seven leaf stage. In the banded setup, torches were positioned at a 30° angle toward crop row so that flame only covered a band of 30 cm of intra-row space (banded flaming treatment)

Figure 5.3. The 4-row flamer-cultivator developed at the University of Nebraska performing flaming and cultivation treatments in maize at three leaf–four leaf stage. The flamer-cultivator was built by modifying Noble Row-Runner cultivator 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 to perform inter-row cultivation. 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. 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

Figure 5.4. Aggressive cultivation treatment in maize at six leaf–seven leaf stage with Buffalo type cultivator. The term “aggressive cultivation” describes a cultivation method that allows throwing soil into intra-row space, which creates a small ridge that buried the flamed weeds

5.9. Tables

Table 5.3. Maize planting, emergence, and harvest dates in field experiments at Concord, NE, USA in 2010, 2011, and 2012

Year	Date		
	Planting	Emergence	Harvest
2010	May 28	June 9	October 19
2011	May 5	May 28	October 10
2012	June 6	June 11	October 14

Table 5.4. Mean monthly temperature and precipitation recorded at Concord, NE, USA during the maize growing season in 2010, 2011, and 2012

Month	2010				2011				2012[a]			
	Temperature (°C)			Precipitation (mm)	Temperature (°C)			Precipitation (mm)	Temperature (°C)			Precipitation (mm)
	Min.	Max.	Mean		Min.	Max.	Mean		Min.	Max.	Mean	
May	7.5	21.1	14.3	53	8.2	20.5	14.4	225	10.6	25.3	17.9	157
June	15.0	27.0	21.0	326	14.7	26.0	20.3	131	16.0	29.0	22.5	38
July	17.0	28.4	22.7	264	20.2	30.5	25.3	59	19.2	33.9	26.5	1
August	16.8	28.5	22.7	127	16.3	27.7	22.0	148	14.3	29.6	21.9	42
September	9.8	23.0	16.4	66	8.1	22.1	15.1	19	8.4	26.5	17.5	15
October	3.5	19.5	11.5	13	4.1	19.1	11.6	40	1.5	14.9	8.2	38

[a] Three irrigations each of 80 mm water were applied 10 days apart starting from 3 August in 2012 due to severe drought condition

Table 5.5. List of weed management treatments with corresponding growth stages of maize in field experiments at Concord, NE, USA in 2010, 2011, and 2012

Weed management treatments		Operation performed	
		Growth stage[a]	
Treatment number	Abbreviation (V3–V4) – (V6–V7)	V3–V4	V6–V7
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

[a] Weed control treatments were applied at two growth stages of maize, that included V3–V4 (3-leaf–4-leaf) and V6–V7 (6-leaf–7-leaf)

Table 5.6. Crop growth stage and plant height, application date, time of day, and weather conditions at Concord, NE, USA during the maize growing season in 2010, 2011, and 2012

Year	Crop growth stage	Plant height (cm)	Application date	Time of day	Weather conditions		
					Air temperature (°C)	Relative humidity (%)	Wind direction-velocity (km h^{-1})
2010	V3–V4	13–15	June 24	10:00 AM	21	80	N-8
	V6–V7	55–65	August 2	1:00 PM	27	51	SE-20
2011	V3–V4	9–12	June 11	10:15 AM	25	76	SE-13
	V6–V7	39–50	June 29	2:00 PM	32	51	S-16
2012	V3–V4	13–16	June 21	11:00 AM	26	40	NW-8
	V6–V7	45–60	August 9	10:15 AM	23	50	NW-6

Table 5.7. Mean weed density with standard errors, average height, and species composition collected one day prior to initiation of the weed management treatment in field experiments at Concord, NE, USA in 2010, 2011, and 2012 (combined)

Weed management treatments	Density (plants m^{-2})	Average weed height (cm)	Species-specific contribution to weed community (%)[a]			
			SETVI	AMARE	ABUTH	CHEAL
1. Weed-free control	197 ± 70	2.0	69	0	1	30
2. Weedy season long	270 ± 32	1.7	88	1	7	4
3. Cultivation (V3–V4) fb cultivation (V6–V7)	263 ± 56	1.9	79	0	6	15
4. Cultivation (V3–V4) fb flame-cultivation (V6–V7)	192 ± 28	2.0	87	0	5	8
5. Cultivation (V3–V4) fb broadcast flaming (V6–V7)	285 ± 36	1.9	86	0	7	6
6. Flame-cultivation (V3–V4) fb cultivation (V6–V7)	258 ± 60	1.8	71	0	7	23
7. Flame-cultivation (V3–V4) fb flame-cultivation (V6–V7)	292 ± 43	1.9	75	2	3	20
8. Flame-cultivation (V3–V4) fb broadcast flaming (V6–V7)	323 ± 80	1.9	83	1	6	10
9. Broadcast flaming (V3–V4) fb cultivation (V6–V7)	242 ± 48	2.3	87	3	3	8
10. Broadcast flaming (V3–V4) fb flame-cultivation (V6–V7)	390 ± 87	1.7	82	0	6	12
11. Broadcast flaming (V3–V4) fb broadcast flaming (V6–V7)	250 ± 49	1.6	84	0	3	13
12. Banded flaming fb aggressive cultivation (V3–V4) fb banded flaming fb aggressive cultivation (V6–V7)	355 ± 46	2.0	87	0	4	9

[a] Weed species were presented using the Weed Science Society of America (WSSA)-approved computer codes. SETVI, *Setaria viridis* (L.) Beauv., AMARE, *Amaranthus retroflexus* L., ABUTH, *Abutilon theophrasti* Medik., CHEAL, *Chenopodium album* L.

Table 5.8. Significance levels in the three-way ANOVA of the effects of year (Y), manure (M), and weed management treatments (WMT) on crop injury (7 and 28 days after treatment-DAT), weed control (7 and 28 DAT), weed dry matter (WDM) at 60 DAT, yield components, and yield of maize in the field experiments at Concord, NE, USA in 2010, 2011 and 2012

Effect	Crop injury		Weed control		WDM ($g\ m^{-2}$)	Yield components				Yield ($t\ ha^{-1}$)
	7 DAT	28 DAT	7 DAT	28 DAT		Plants m^{-2}	Ears $plant^{-1}$	Seeds ear^{-1}	1000-seed weed (g)	
WMT	***	***	***	***	***	*	***	***	***	***
M	***	***	n.s.	n.s.	**	n.s.	n.s.	***	n.s.	***
Y	n.s.	***	n.s.	n.s.	***	n.s.	n.s.	***	*	***
WMT × M	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
WMT × Y	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	***	n.s.	**
M × Y	n.s.	n.s.	n.s.	n.s.	***	n.s.	n.s.	***	n.s.	***
WMT × M × Y	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

n.s. not significant differences
***P<0.001; **P<0.01; *P<0.05

Table 5.9. Maize injury (7 and 28 DAT), weed control (7 and 28 DAT), and weed dry matter (60 DAT) as affected by different weed management treatments in field experiments at Concord, NE, USA (2010, 2011, and 2012 mean values)

Weed management treatments	Crop injury		Weed control		Weed dry matter ($g\ m^{-2}$)
	7 DAT	28 DAT	7 DAT	28 DAT	
1. Weed-free control	0	0	100	100	0
2. Weedy season long	0	0	0	0	715
3. Cultivation (V3–V4) fb cultivation (V6–V7)	0	0	51	33	441
4. Cultivation (V3–V4) fb flame-cultivation (V6–V7)	17	3	73	59	292
5. Cultivation (V3–V4) fb broadcast flaming (V6–V7)	21	4	68	56	346
6. Flame-cultivation (V3–V4) fb cultivation (V6–V7)	12	3	75	56	252
7. Flame-cultivation (V3–V4) fb flame-cultivation (V6–V7)	27	3	91	88	114
8. Flame-cultivation (V3–V4) fb broadcast flaming (V6–V7)	25	5	86	75	174
9. Broadcast flaming (V3–V4) fb cultivation (V6–V7)	12	3	66	49	354
10. Broadcast flaming (V3–V4) fb flame-cultivation (V6–V7)	31	6	90	80	182
11. Broadcast flaming (V3–V4) fb broadcast flaming (V6–V7)	33	8	72	49	265
12. Banded flaming fb aggressive cultivation (V3–V4) fb banded flaming fb aggressive cultivation (V6–V7)	23	5	97	94	59
LSD (P=0.05)	4	2	4	6	39

Table 5.8. Yield components of maize (number of seeds ear^{-1}) as affected by different weed management treatments in field experiments at Concord, NE, USA (2010, 2011, and 2012 mean values)

Weed management treatments	2010		2011		2012	
	Manure	No-manure	Manure	No-manure	Manure	No-manure
1. Weed-free control	685	531	698	752	490	508
2. Weedy season long	461	367	305	159	263	321
3. Cultivation (V3–V4) fb cultivation (V6–V7)	543	417	663	361	282	410
4. Cultivation (V3–V4) fb flame-cultivation (V6–V7)	563	429	683	547	443	421
5. Cultivation (V3–V4) fb broadcast flaming (V6–V7)	556	424	658	485	486	459
6. Flame-cultivation (V3–V4) fb cultivation (V6–V7)	585	440	656	526	399	412
7. Flame-cultivation (V3–V4) fb flame-cultivation (V6–V7)	640	513	733	593	395	438
8. Flame-cultivation (V3–V4) fb broadcast flaming (V6–V7)	604	464	697	576	443	399
9. Broadcast flaming (V3–V4) fb cultivation (V6–V7)	557	427	596	340	361	372
10. Broadcast flaming (V3–V4) fb flame-cultivation (V6–V7)	598	473	694	588	443	399
11. Broadcast flaming (V3–V4) fb broadcast flaming (V6–V7)	484	425	619	445	367	394
12. Banded flaming fb aggressive cultivation (V3–V4) fb banded flaming fb aggressive cultivation (V6–V7)	655	506	749	614	395	433
LSD (P=0.05)	60	70	130	171	115	103

Table 5.10. Yield components of maize (plant m^{-2}, ears $plant^{-1}$, and 1000-seed weight) as affected by different weed management treatments in field experiments at Concord, NE, USA (2010, 2011, and 2012 mean values)

Weed management treatments	Plant m^{-2}	Ears $plant^{-1}$	1000-seed weight (g)
1. Weed-free control	4.57	1.01	261
2. Weedy season long	4.26	0.94	236
3. Cultivation (V3–V4) fb cultivation (V6–V7)	4.43	0.96	246
4. Cultivation (V3–V4) fb flame-cultivation (V6–V7)	4.69	0.95	253
5. Cultivation (V3–V4) fb broadcast flaming (V6–V7)	4.57	0.97	249
6. Flame-cultivation (V3–V4) fb cultivation (V6–V7)	4.63	0.98	256
7. Flame-cultivation (V3–V4) fb flame-cultivation (V6–V7)	4.85	0.98	252
8. Flame-cultivation (V3–V4) fb broadcast flaming (V6–V7)	4.66	0.98	243
9. Broadcast flaming (V3–V4) fb cultivation (V6–V7)	5.00	0.95	241
10. Broadcast flaming (V3–V4) fb flame-cultivation (V6–V7)	4.73	0.96	245
11. Broadcast flaming (V3–V4) fb broadcast flaming (V6–V7)	4.83	0.97	245
12. Banded flaming fb aggressive cultivation (V3–V4) fb banded flaming fb aggressive cultivation (V6–V7)	4.90	0.98	256
LSD (P=0.05)	0.40	0.03	11

Table 5.10. Yields of maize under different weed management treatments as affected by manure applications in field experiments at Concord, NE, USA (2010, 2011, and 2012)

Weed management treatments	Yield (t ha^{-1})						Overall ranking
	2010		2011		2012		
	Manure	No-manure	Manure	No-manure	Manure	No-manure	
1. Weed-free control	10.30	8.75	9.03	7.83	8.00	8.10	1
2. Weedy season long	5.50	3.82	3.10	1.53	2.13	1.57	12
3. Cultivation (V3–V4) fb cultivation (V6–V7)	6.90	5.75	7.27	4.93	3.97	3.87	11
4. Cultivation (V3–V4) fb flame-cultivation (V6–V7)	8.00	6.85	7.63	5.87	6.20	5.53	7
5. Cultivation (V3–V4) fb broadcast flaming (V6–V7)	7.47	6.28	7.03	4.97	5.27	5.20	9
6. Flame-cultivation (V3–V4) fb cultivation (V6–V7)	8.00	7.18	7.30	5.77	6.10	5.90	6
7. Flame-cultivation (V3–V4) fb flame-cultivation (V6–V7)	9.57	7.95	8.33	7.30	7.83	6.77	3
8. Flame-cultivation (V3–V4) fb broadcast flaming (V6–V7)	8.47	7.25	7.87	5.83	6.17	5.30	5
9. Broadcast flaming (V3–V4) fb cultivation (V6–V7)	7.80	6.55	6.27	4.50	4.37	3.87	10
10. Broadcast flaming (V3–V4) fb flame-cultivation (V6–V7)	8.90	7.62	7.80	6.53	7.03	6.70	4
11. Broadcast flaming (V3–V4) fb broadcast flaming (V6–V7)	8.13	6.85	7.23	5.37	5.33	5.53	8
12. Banded flaming fb aggressive cultivation (V3–V4) fb banded flaming fb aggressive cultivation (V6–V7)	9.93	8.18	8.33	7.57	7.90	7.67	2
LSD (P=0.05)	0.87	0.96	1.16	1.19	1.2	1.4	

CHAPTER 6. Weed control by flaming and cultivation in organic soybean - effects on yield and yield components

6.1. Abstract

Propane flaming in combination with cultivation is a potential alternative tool for weed control in organic soybean production. Field studies were conducted at the Haskell Agricultural Laboratory in 2010, 2011 and 2012 to determine the level of weed control and crop response to flaming and cultivation 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). Treatments were applied at the VC (unfolded cotyledon) and V4-V5 (4-leaf-5-leaf) growth stages. Propane doses were 20 and 45 kg/ha for the banded and broadcast flaming treatments, respectively. Data were collected for: visual ratings of crop injury and weed control level at 7 and 28 days after treatment (DAT), weed biomass at 60 DAT, crop yield and yield components. The combination of mechanical cultivation and banded flaming applied twice (at VC and V4-V5) provided highest level of weed control at 28 DAT (>80%) and highest yield. Cultivation twice provided only 41% weed control 28 DAT. Soybean plants recovered well after all flaming treatment, with the exception of broadcast flaming twice (28% crop injury at 28 DAT). Flaming injury, however, was not translated to significant loss in yield and broadcast flaming twice was one of the highest ranked weed control treatments. Combining flaming with cultivation has a potential to effectively control the weeds in organic soybean production.

Keywords: Organic crop production; Nonchemical weed control; Manure; Parallel and cross flaming; Crop injury.

6.2. Introduction

Weed management is an important challenge in all farming systems, but it is especially difficult in organic production without the use of chemical herbicides (Liebman and Davis, 2010). Favorable market opportunities for organic soybean products in the past decade (Delate et al., 2003) have given strong economic incentive for organic soybean producers to reduce the yield loss due to weed presence. Yet, multiple surveys of organic producers cite weed control as the foremost production-related problem in major agronomic crops (Cavingelli et al., 2008; Walz, 1999). This is likely the result of lacking the equivalent of inexpensive and nearly complete chemical weed control. Therefore, organic farmers usually relay on multiple weed suppression tactics, each of which is individually weak but cumulatively strong. Liebman and Gallandt (1997) characterized these techniques as the use of “many little hammers”, in contrast with the single “big hammer” that herbicides and transgenic crop technology provide in conventional agriculture.

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 (Gunsolus, 2011), are usually not effective enough to control weeds below the economic threshold. Thus, organic producers largely depend on mechanical cultivation and hand weeding for their weed control. Cultivation, however, is also often not effective enough as it leaves a strip of uncontrolled weeds that remain within 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 often too expensive (e.g., ranging from \$700 to \$1200 ha−1), time consuming and difficult to organize (Kruidhof et al., 2008). Hence, there is a need to reexamine existing and evaluate alternative methods that could be utilized for weed control in organic cropping systems (Kruidhof et al., 2008).

Knezevic and Ulloa (2007) reported that propane flaming is one of the most promising alternatives for weed control in organic cropping systems, and has potential for use on the conventional crops as well. Propane flaming leaves no chemical residues in plants, soil 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; Wszelaki et al., 2007). Based on previous research conducted to determine the response of various weed species to broadcast flaming, propane doses of 60 kg/ha were sufficient to provided 80% control of grasses and 90% control of broadleaf weed species commonly found in Nebraska (Ulloa et al., 2010a, 2010b). Ulloa et al. (2010a, 2010b) reported that grasses were harder to control because position of the growing point at the time of flaming was under the soil surface, thus protected from direct heat injury. For the same reason, flaming has the most potential to be used grass-like crops such as corn and sorghum (Ulloa et al,2010c, 2010d, 2010e; Ulloa et al., 2011a, 2011b), but it can also be used in soybean if conducted at appropriate growth stage (Ulloa et al, 2010f). Soybeans have been shown to be the most tolerant to flaming in the emergence stage when the cotyledons are closed around the growing point, but above ground (Ulloa et al, 2010f). After cotyledons are open, soybeans become much more susceptible to flaming, and growing point must be protected in order to avoid severe yield loss (Ulloa et al, 2010f). Response of various crops and weeds to flame weeding is well reported in the literature; however, vast majority of crop tolerance studies were conducted under weed free conditions, whereas the response of weeds was determined without presence of crop. Therefore, the response of weeds and crop growing together in real field situation needs to be evaluated.

Weed sensitivity and crop tolerance to flame weeding also depends on design of flaming equipment. Some studies that investigated technical aspects of selective flame weeding in soybean (e.g. torch type, angle and height, ground speed, etc.) recommend cross-flaming set up, where open torches are set perpendicular to the crop row and traveling direction (Ascard, 1995; Kepner et al., 1978; Lien et al., 1967; Vester, 1985). However, such torch set up provides only weed control in intra-row space, and changing torch configuration might be limiting when flaming is combined with cultivation into a single weed control operation (Leroux et al., 2000). On the other hand, when torches are positioned parallel to the crop row hoods can be employed to keep the heat close to the ground, which can protect crop canopy from heat damage and reduce the energy consumption up to 50% (Ascard, 1995; Bruening 2009). Practical use of parallel torch set up has been primarily used for non-selective preemergence weed control in vegetable production and slow germinating row crops such as carrots and beets (Ascard et al., 2007), while its use in corn and soybean has seldom been investigated. In order improve selective flame weeding in organic soybean, filed performance of parallel flame weeding techniques needs to be assessed.

The objective of this study was to determine the effectiveness of parallel-hooded flaming and mechanical cultivation alone and in combination for weed management in organic soybean grown under two manure regimes.

6.3. Materials and Methods

Study site and experimental set up

Field experiments were conducted in 2010, 2011 and 2012 at the Haskell Agricultural Laboratory of the University of Nebraska located near Concord in northeast Nebraska (42.37◦N, 96.68◦W) on certified organic field where soybean was grown in rotation with corn. Blue River organic soybean hybrids (2612034 in 2010, and 56M30 in 2011 and 2012) were planted in 76cm rows with a four-row planter in 15m by 3m plots, with seeding rate of 370,660 seed ha-1. Agronomic practices such as planting and harvest were conducted according to the local cropping practices (Table 6.1). Average monthly rainfall and temperatures data for the growing season at Concord, NE in 2010, 2011 and 2012 are given in Table 6.2. In 2010 and 2011 crop growth was completely dependent on precipitation, whereas in 2012 three 80 mm irrigations were applied 10 days apart from each other starting August 3 (Table 6.2).

Experimental design and treatments

The experiments were conducted using a split-plot design with three replications. The main-plot was manure regime (manure or no-manure) and the sub-plots were 12 different weed management treatments (WMT). A manure rate of about 110 t ha–1 was applied to manure blocks on 5 May, 4 April, and 25 April in 2010, 2011, and 2012, respectively. Manure was stockpiled for a year before it was utilized.

The WMT included: weed-free control, weedy season long control, and 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 6.3). Growth stages of soybean were based on leaf number that included VC (unfolded cotyledons) and V4-V5 (4-trifoliate-5-trifoliate), as described by 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 6.3). Weeds in the weed-free control plots were removed by hand weeding and hoeing as needed. Weed management treatments were applied at a constant speed (4.8 km h^{-1}) and propane pressure was adjusted in order to deliver 45 kg ha^{-1} for broadcast flaming and 20 kg ha^{-1} for banded flaming and flame-cultivation treatments (Knezevic et al. 2012). The treatment dates, time of day, and weather conditions for each application are presented in Table 6.4.

Equipment

Two flame weeding units (4-row full flamer and 4-row flamer/cultivator) previously developed at the University of Nebraska (Bruening 2009; Neilson, 2012), were utilized for conducting weed management treatments. 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 (Figure 5.1 and 5.2). In 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^o. 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 banded setup, torches were flipped sideways so that flame only covers a band of 30 cm of intra-row space (banded flaming treatment). Unit had a four specially designed 1.2m 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 V3-V4 growth stages, whereas hoods were ‘open’ during flaming at V6-V7 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 set up protected the upper portion of maize 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 (Figure 5.3). Its support structure was modified Noble Row-Runner cultivator that originally had 5 sweeps per gang. Two edge sweeps on each of the 4 gangs were replaced 60 cm long hoods, leaving three middle sweeps to for preforming inter-row cultivation as described by Neilson (2012). Each half of the hood covered one cylindrical torch angled back at 30^o and mounted 15 cm away from the crop row and parallel to the slope of the hood (Neilson, 2012). 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) between row coverage (i.e. flame/cultivation treatment). In preforming these two operations simultaneously cultivation always comes after flaming to allow rupture of cell walls and cause water loss, before cultivator sweeps pass through. When preforming cultivation only treatment, flaming torches were turned off.

In addition, flame/cultivation (treatment 12) was also applied in two separate operations (Table 6.4). Flaming was conducted first using 4-row full flamer with banded setup (banded flaming), and then followed by aggressive cultivation with a Buffalo type cultivator that has single, 50 cm wide sweep and set of hillers (Figure 5.4). We utilized the term “aggressive cultivation” as a way to describe a cultivation method that allowed throwing soil into intra-row space, which created a small ridge that buried flamed weeds.

Data collection

Density, composition and height of weed species were collected in each plot prior to initiation of the treatment (VC soybean stage). Counts were conducted from by placing 1 m^2 approximately 2 m from the bottom edge of the plot. From the same area at 60 days after treatment (DAT) weed biomass samples were hand harvested and dried at 50^{o}C for two 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% - 0 representing no weed control or no crop injury, and 100 representing complete weed control, or crop death.

Yield components and yields were also collected. Before 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% moisture content.

Statistical analysis

All data variables (visual crop injury and weed control ratings, weed dry matter, yield components, and yield) were subjected to analysis of variance (ANOVA) using the PROC ANOVA procedure of the Statistical Analysis Systems (SAS) to test for the significance ($P<0.05$) of years, treatments, and their interactions (SAS Institute, 2005). Means for the significant treatment effects were compared using Fisher's protected least significant difference (LSD) procedure at $P<0.05$.

6.4. Results

Characteristics of weed community

Weed species composition, density, and height were similar in all three years; thus, data were combined over years (Table 6.5). In general, 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 6.5). 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 composition of weed community to a greater extent, as occurrence of these species was < 1 % (data not shown). Overall weed density in this study ranged from 355 to 475 plants m–2, with weed height ranged from 1.5–2.8 cm prior to initiation of the treatment (Table 6.5).

Crop injury

Crop injury ratings at 7 and 28 DAT indicate that soybeans were able to recover after flaming treatment. For each WMT, visual ratings at late evaluation date (28 DAT) were significantly lower than at early evaluation dates (7 DAT). For example, treatment 8 (FC-BF) caused 43% crop injury at 7 DAT, while three weeks later (at 28 DAT) crop injury dropped to 13%. The magnitude of crop injury, however, varied with type of weed management practice. While cultivation caused no injury on soybean, higher injury rates were observed at 28 DAT (3-28%) when plants were flamed once or twice in the season. Visual ratings at 28 DAT also indicate that all WMT had <14% crop injury, with the exception of broadcast flaming conducted twice, where 28% crop injury was observed. It is important to mention that regardless of these observations correlation between crop injury and yield was highly insignificant ($r = 0.05$) suggesting that crop injury was not a major criteria in determining the effectiveness of WMT.

Weed control and weed biomass

Pearson correlation analyses reveal strong negative linear relationship (r = -0.79) between weed control levels at 28 DAT and weed biomass (Table 6.10); meaning that large portion of variation in weed biomass can be explained by visual weed control levels, and vice versa. Due to this high correlation significant year by WMT interaction for weed dry matter was omitted and data was combined over years to present its effects on WMT.

Results show that flame/cultivation was by far the most effective weed control practice, whereas cultivation alone provided the poorest weed control. Weed management treatments 7 (FC-FC) and 12 (FCa-FCa) were the only two treatments that had >80% weed control at 28 DAT and <100 g/m^2 of weed biomass (Table 6.7). Cultivation twice (treatment 3) was the worst treatment resulting with 23% weed control level at 28 DAT and weed dry matter of 357 g m^{-2}, which was only a minor improvement over weedy season long control that had 537 g m^{-2} of weed biomass (Table 6.7). All other WMT provided anywhere from 23-69% weed control level and 165-305 g m^{-2} of weed biomass (Table 6.7).

Yield components

Results of this study show no effect of WMT on plant m^{-2} and number of seeds pod^{-1}, while the effects on pods plant^{-1} and 1000 seed weights were highly significant (Table 6.6). While overall population (24-26 plants m^{-2}) and formation of seeds in pods (2.37-2.62 seeds pod^{-1}) were similar for all WMT (Table 6.8), correlation analysis shows that increase in weed control levels at 28 DAT caused linear increase in number of pods plant^{-1} (r = 0.54) and 1000 seed weight (r = 0.34) (Table 6.10). These results are suggesting that treatments that were more effective in controlling weeds had larger number of pods plant^{-1} and larger 1000 seed weights. For example, results from 2011 indicate that the most effective WMT (treatment 12) had 31 pods plant^{-1} and 1000 seed weights of 156 g; moderately effective WMT (treatment 8) had 25 pods plant^{-1} and 1000 seed weights of 149 g; while the least effective treatment (treatment 3) had 23 pods plant-1 and 1000 seed weights of 139 g (Table 6.8). Furthermore, pods plant^{-1} and 1000 seed weight had significant positive correlation with yield (0.71 and 0.47), suggesting that increase in number of pods plant^{-1} and 1000 seed weight caused linear increase in yield (Table 6.10). Therefore, differences observed in final yield are mainly due to joint effect that WMT had on pods plant^{-1} and 1000 seed weight.

Yield

Soybean yield varied from year to year mainly due to differences in weather conditions (Table 6.2, Table 6.6). Overall, highest yield was observed with higher total precipitation. For instance, when manure was applied soybean yield for weed free control treatments were 6.06, 3.86 and 2.56 t ha^{-1} in 2010, 2011 and 2012, respectively; which corresponded to decreasing trend in total yearly precipitation of from year to year: 849 mm in 2010, 622 mm in 2011, and 471 mm in 2012 (Table 6.2, Table 6.8).

Manure application had no influence on the effectiveness of WMT as year by WMT by manure interactions were insignificant for all evaluated variables (Table 6.6). Addition of manure, however, significantly reduced soybean yield in treatment 6, 9 and 11 by 0.52, 0.24, and 21 t ha^{-1}, respectively; causing significant WMT by manure interaction (Table 6.9, Table 6.6). All other WMT yielded statistically similar in both manure and no-manure treatments (Table 6.9).

Soybean yield increased as effectiveness of WMT increased, regardless of year and manure regime. Correlation analysis show that increase in weed control levels (r = 0.61), pods plant^{-1} (r = 0.71) and 1000 seed weight (r = 46) caused positive linear increase in grain yield (Table 6.10). Consequently, banded flaming followed by aggressive cultivation at VC and V4-V5 (FCa-FCa) was the most effective WMT yielding 5.26, 3.62 and 2.13 t ha^{-1} in 2010, 2011 and 2012, respectively; which was statistically similar to weed free control (Table 6.9). Flame-cultivation conducted twice (FC-FC) was the second best treatment resulting in 4.73, 3.39 and 2.11 t ha^{-1} yields, while broadcast flaming conducted twice yielded 4.35, 3.15 and 1.83 t ha^{-1} in 2010, 2011 and 2012, respectively (Table 6.9). Cultivation twice was the least effective WMT yielding in range from 0.34 to 3.22 t ha^{-1}.

6.5. Discussion

Results of this study show that manure addition did not influenced effectiveness of WMT and soybean yield. Previous reports on response of soybean to manure fertilization are very inconsistent. Study conducted by Schmidt et al. (2001) indicated that manure addition increased soybean yield at sites having lower available nitrogen and phosphorus, while in cases where site had a history of white mold, the application of manure was generally unfavorable. Effects of manure fertilization on soybean yield at this location (Concord, NE) need to be investigated.

All parameters that were critical in evaluating the effectiveness of WMT (weed control levels, pods plant^{-1}, 1000 seed weight, yield) indicated that banded flaming followed by aggressive cultivation applied twice in the season (at VC and V4-V5) was the best treatment; while the second best treatment was flame-cultivation twice. These results suggest that that 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 showed that two post-emergence flame-cultivations provided acceptable weed control with no yield reduction in maize [Zea mays (L.)] and cotton [Gossypium hirsutum (L.)] (Leroux et al. 1995; Seifert and Snipes, 1996). Larson (1960) suggested that when properly used flaming in combination with cultivation can be an effective tool in controlling most annual and some perennial weeds. It is also interesting to note that flame-cultivation was more effective when banded flaming was applied with aggressive cultivation using buffalo-type cultivator, as soil that was thrown to intra-row space reduced the ability of weeds (especially grassy species) to regrow after flaming treatment. This delay of regrowth provided just enough time for soybean plants to close up the canopy before the subsequent weed emergence. Additional studies are needed to test such 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 crop yield. This is mainly due to utilizing specially designed hoods that minimized crop injury by protecting most of soybean canopy from significant heat damage. Similarly, Stephenson (1959) 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. In our study broadcast flaming twice was one the most effective weed management treatments with best weed control and high yields. Based on previous research done by Knezevic et al. (2012), parallel-hooded flaming can be safely used in soybean if applied not more than two times in season and at VC (unfolded cotyledon) and/or after V4-V5 growth stage. Timing of flaming application, however, should be adjusted based on weed size and types of weed species present to maximize its efficiency (Ascard 1995; Ulloa et al. 2010a,b).

In conclusion, combining banded flaming and between row cultivation into a single operation was the most efficient weed control practice regardless of year, manure and application timing (growth stage of the crop). Downside 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 valuable weed management tool in hands of soybean organic farmers. 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 overall effectiveness of integrated weed control programs in both organic and conventional crops (Ascard 1995; Datta and Knezevic 2013; Leroux et al. 2001; Wszelaki et al. 2007).

6.6. Acknowledgements

This study was partially funded by the Propane Education and Research Council, USDA and the Nebraska Propane Association. The authors are also grateful for the help provided by Jon Scott, and many summer helpers.

6.7. References

Ulloa SM, Datta A, Knezevic SZ (2010b) Tolerance of selected weed species to broadcast flaming at different growth stages. Crop Prot 29:1381–1388

Ascard J (1995) Effects of flame weeding on weed species at different developmental stages. Weed Res 35:397–411

Ascard J, Hatcher PE, Melander B, Upadhyaya MK (2007) Thermal weed control. In: Upadhyaya MK and Blackshaw RE, eds. Non-chemical weed management. Principles, concepts and technology. Cabi, Wallingford/Cambridge: 155-175

Bruening CA (2009) Development of Propane Flaming Equipment for Thermal Weed Control in Agronomic Crops. M.S. thesis, The University of Nebraska-Lincoln, Lincoln, NE, USA

Cavingelli AM, Teasdale RJ, Conklin EA (2008). Long-term agronomic performance of organic and conventional field crops in the mid-Atlantic region. Agron J 100:785-794.

Delate K, Duffy M, Chase C, Holste A, Friedrich H, Wantate N (2003) An Economic Comparison of Organic and Conventional Grain Crops in a Long-Term Agroecological Research (LTAR) site in Iowa. The American Journal of Alternative Agriculture 18(2):59-69

Gunsolus J (2011) Delayed planting, crop rotation keys to weed control in organic corn, soybeans. St. Paul, MN: Ag News Wire - University of Minnesota Extention.

Kepner AR, Bainer R, Barger LE (1978) Principles of Farm Machinery. Westport, CT: AVI Publishing Company, Inc

Knezevic SZ, Ulloa SM (2007) Flaming: potential new tool for weed control in organically grown agronomic crops. J Agric Sci 52:95–104

Knezevic ZS, Datta A, Bruening C, Gogos G (2012). Propane-Fueled Flame Weeding in Corn, Soybean, and Sunflower. Retrieved March 14, 2013, from University of Nebraska - Lincoln and PERC extension publication: http://www.agpropane.com/ContentPageWithLeftNav.aspx?id=1916

Kruidhof HM, Bastiaans L, Kropff MJ (2008) Ecological weed management by cover cropping: effects on weed growth in autumn and weed establishment in spring. Weed Res 48:492–502

Larson HG, Fairbanks LG, Fenton GF (1960) What does it cost to use Farm Machinery. University of Agricultural Experiment Station Bulletin 417

Leroux GD, Douheret J, Lanouette M, Martel M (1995) Selectivity of propane flamer as a mean of weed control. Hertscience 30(4):820

Liebman M, Davis AS (2010) Managing Weeds in Organic Farming Systems: An Ecological Approach. In C. Francis, Organic Farming: The Ecological System: 173-196

Liebman M, Gallandt E (1997) Many little hammers: ecological approaches for management of crop-weed interactions. LE Jackson (ed.) Ecology in agriculture: 291-343

Lien MR, Liljedahl BJ, Robbins RP (1967) Five year's research in flame weeding. Proceedings Fourth Annual Symposium on Thermal Agriculture, Sponsored by Natural Gas Processors Association and National LP-Gas Association: 6-20

Mulder TA, Doll JD (1993) Integrating Reduced Herbicide Use with Mechanical Weeding in Corn (Zea mays). Weed Tech 7:382-389

Neilson B (2012) The Integration of Propane Flaming and Mechanical Cultivation For Effective Weed Control in Agriculture. MS thesis, The University of Nebraska-Lincoln, Lincoln, NE, USA

Nemming A (1994) Costs of flame cultivation. Acta Hort 372:205–212

Ritchie SW, Hanway JJ, Thompson HE, Benson GO (1997) How a soybean plant develops. Special Report 53 Iowa State University, Cooperative Extension Service, Ames, IA, USA

Schmidt JP, Lamb JA, Schmitt MA, Randall GW, Orf JH, Gollany HT (2001) Soybean varietal response to liquid swine manure application. Agron J 93: 358-363

Seifert S, Snipes CE (1996) Influence of Flame Cultivation on Mortality of Cotton (Gossypium hirsutum) Pests and Beneficial Insects. Weed Tech 10:544-549

Statistical Analysis Systems (SAS) (2005) The ANOVA Procedure. Online Documentation. SAS Institute, Inc., Cary, NC, USA. Version 9.1

Stephenson KQ (1959) Mechanized Weed Control for Cotton Production in Arkansas. University of Arkansas Exp Station Report Series 87: 16

Ulloa SM, Datta A, Knezevic, SZ (2010a) Growth stage influenced differential response of foxtail and pigweed species to broadcast flaming. Weed Tech 24:319–325

Ulloa SM, Datta A, Knezevic, SZ (2010b) Tolerance of selected weed species to broadcast flaming at different growth stages. Crop Prot 29:1381–1388

Ulloa SM, Datta A, Knezevic, SZ (2010c) Growth stage impacts tolerance of winter wheat (Triticum aestivum L.) to broadcast flaming. Crop Prot.29, 1130–1135

Ulloa SM, Datta A, Knezevic, SZ (2011b) Growth stage influenced sorghum response to broadcast flaming: Effects on yield and its components. Agron J 103:7–12

Ulloa SM, Datta A, Bruening C, Neilson B, Miller J, Gogos G, Knezevic SZ (2011a) Maize response to broadcast flaming at different growth stages: Effects on growth, yield and yield components. Eur J Agron 34:10–19

Ulloa SM, Datta A, Cavalieri SD, Lesnik M, Knezevic SZ (2010e) Popcorn (Zea mays L. var. everta) yield and yield components as influenced by the timing of broadcast flaming. Crop Prot 29:1496–1501

Ulloa SM, Datta A, Malidza G, Leskovsek R, Knezevic SZ (2010d) Timing and propane dose of broadcast flaming to control weed population influenced yield of sweet maize (Zea mays L. var. rugosa). Field Crops Res 118:282–288

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

Vester J (1985) New experience with flame cultivation for weed control. In: Castile C. (ed) Flame Cultivation for Weed Control. Proceedings of the International Meeting (pp. 10-20), Namur, Belgium: C.R.A.B.E. Opprebais

Walz E (1999) Final Results of the Third Biennial National Organic Farmers' Survey. Organic Farming Research Foundation, Santa Cruz, CA, USA

Wszelaki AL, Doohan DJ, Alexandrou A (2007) Weed control and crop quality in cabbage [Brassica oleracea (capitata group)] and tomato (Lycopersicon lycopersicum) using a propane flamer. Crop Prot 26:134–144

6.8. Tables

Table 6.11. Soybean planting, emergence, and harvest dates in field experiments at Concord, NE, USA in 2010, 2011, and 2012

Year	Date		
	Planting	Emergence	Harvest
2010	Jun 10	Jun 10	Oct 10
2011	Jun 11	May 11	Sep 11
2012	Jun 12	Jun 12	Oct 12

Table 6.12. Mean monthly temperature and precipitation recorded at Concord, NE, USA during the maize growing season in 2010, 2011, and 2012

Month	2010				2011				2012[a]			
	Temperature (°C)			Precipitation (mm)	Temperature (°C)			Precipitation (mm)	Temperature (°C)			Precipitation (mm)
	Min.	Max.	Mean		Min.	Max.	Mean		Min.	Max.	Mean	
May	7.5	21.1	14.3	53	8.2	20.5	14.4	225	10.6	25.3	17.9	157
June	15.0	27.0	21.0	326	14.7	26.0	20.3	131	16.0	29.0	22.5	38
July	17.0	28.4	22.7	264	20.2	30.5	25.3	59	19.2	33.9	26.5	1
August	16.8	28.5	22.7	127	16.3	27.7	22.0	148	14.3	29.6	21.9	42
September	9.8	23.0	16.4	66	8.1	22.1	15.1	19	8.4	26.5	17.5	15
October	3.5	19.5	11.5	13	4.1	19.1	11.6	40	1.5	14.9	8.2	38

[a] Three irrigations each of 80 mm water were applied 10 days apart starting from 3 August in 2012 due to severe drought condition

Table 6.3. List of weed management treatments with corresponding growth stages of maize in field experiments at Concord, NE, USA in 2010, 2011, and 2012

Weed management treatments		Operation performed	
		Growth stage[a]	
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

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

Table 6.13. Crop growth stage, application date, time of day, and weather conditions at Concord, NE, USA during the maize growing season in 2010, 2011, and 2012

Year	Crop growth stage	Application date	Time of day	Weather conditions		
				Air temperature (°C)	Relative humidity (%)	Wind direction-velocity (km h^{-1})
2010	VC	June 25	10:00 AM	24	86	SE-10
	V5	August 21	1:00 PM	27	84	SE-14
2011	VC	June 10	10:15 AM	16	88	NW-13
	V5	August 6	2:00 PM	31	45	E-3
2012	VC	June 21	11:00 AM	26	40	NW-8
	V4-V5	August 9	10:15 AM	23	50	NW-6

Table 6.14. Mean weed density with standard errors, average height, and species composition collected one day prior to initiation of the weed management treatment in field experiments at Concord, NE, USA in 2010, 2011, and 2012 (combined)

Weed management treatments	Density (plants m^{-2})	Average weed height (cm)	Species-specific contribution to weed community (%)[a]			
			SETVI	AMARE	ABUTH	CHEAL
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

[a] Weed species were presented using the Weed Science Society of America (WSSA)-approved computer codes. SETVI, *Setaria viridis* (L.) Beauv., AMARE, *Amaranthus retroflexus* L., ABUTH, *Abutilon theophrasti* Medik., CHEAL, *Chenopodium album* L.

Table 6.15. Significance levels in the three-way ANOVA of the effects of year (Y), manure (M), and weed management treatments (WMT) on crop injury (7 and 28 days after treatment-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, USA in 2010, 2011 and 2012

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

n.s. not significant differences
****P*<0.001; ***P*<0.01; **P*<0.05

Table 6.16. Soybean injury (7 and 28 DAT), weed control (7 and 28 DAT), and weed dry matter (60 DAT) as affected by different weed management treatments in field experiments at Concord, NE, USA (2010, 2011, and 2012 mean values)

Weed management treatments	Crop injury		Weed control		Weed dry matter ($g\ m^{-2}$)
	7 DAT	28 DAT	7 DAT	28 DAT	
1. Weed-free control	0	0	100	100	0
2. Weedy season long	0	0	0	0	537
3. Cultivation (VC) fb cultivation (V4–V5)	0	0	40	23	357
4. Cultivation (VC) fb flame-cultivation (V4–V5)	28	9	59	41	271
5. Cultivation (VC) fb broadcast flaming (V4–V5)	41	12	35	19	305
6. Flame-cultivation (VC) fb cultivation (V4–V5)	5	3	76	62	214
7. Flame-cultivation (VC) fb flame-cultivation (V4–V5)	27	6	84	80	82
8. Flame-cultivation (VC) fb broadcast flaming (V4–V5)	43	14	76	59	204
9. Broadcast flaming (VC) fb cultivation (V4–V5)	9	4	51	27	264
10. Broadcast flaming (VC) fb flame-cultivation (V4–V5)	35	14	76	69	165
11. Broadcast flaming (VC) fb broadcast flaming (V4–V5)	49	28	71	68	165
12. Banded flaming fb aggressive cultivation (VC) fb banded flaming fb aggressive cultivation (V4-V5)	31	9	90	82	64
LSD (P=0.05)	3	2	5	5	47

Table 6.8. Yield components of maize (plant m^{-2}, seeds pod^{-1}, pods $plant^{-1}$, and 1000 seed weight) as affected by different weed management treatments in field experiments at Concord, NE, USA (2010, 2011, and 2012)

Weed management treatments	Plants m^{-2}	Seeds pod^{-1}	Plant m^{-1}			1000 seed weight (g)		
			2010	2011	2012	2010	2011	2012
1. Weed-free control	24	2.52	43	29	33	136	157	121
2. Weedy season long	25	2.37	11	16	5	121	135	90
3. Cultivation (VC) fb cultivation (V4–V5)	26	2.55	26	23	15	122	139	104
4. Cultivation (VC) fb flame-cultivation (V4–V5)	25	2.47	18	16	14	121	142	109
5. Cultivation (VC) fb broadcast flaming (V4–V5)	24	2.56	26	24	21	122	142	112
6. Flame-cultivation (VC) fb cultivation (V4–V5)	25	2.53	24	25	16	124	145	112
7. Flame-cultivation (VC) fb flame-cultivation (V4–V5)	24	2.48	32	28	26	130	155	117
8. Flame-cultivation (VC) fb broadcast flaming (V4–V5)	25	2.59	28	25	21	124	149	114
9. Broadcast flaming (VC) fb cultivation (V4–V5)	25	2.60	30	26	17	132	140	113
10. Broadcast flaming (VC) fb flame-cultivation (V4–V5)	26	2.53	26	24	18	128	155	117
11. Broadcast flaming (VC) fb broadcast flaming (V4–V5)	24	2.51	28	24	18	127	152	117
12. Banded flaming fb aggressive cultivation (VC) fb banded flaming fb aggressive cultivation (V4-V5)	25	2.62	34	31	25	132	156	118
LSD (P=0.05)	2.1	0.33	6.7	6.0	5.0	4.3	9.4	8.9

Table 6.9. Yields of soybean under different weed management treatments as affected by manure applications in field experiments at Concord, NE, USA (2010, 2011, and 2012)

Weed management treatments	Yield (t ha^{-1})						Overall ranking
	2010		2011		2012		
	Manure	No-manure	Manure	No-manure	Manure	No-manure	
1. Weed-free control	6.06	5.78	3.86	3.92	2.56	2.20	1
2. Weedy season long	0.45	1.02	1.00	1.52	0.18	0.26	12
3. Cultivation (VC) fb cultivation (V4–V5)	2.51	3.22	2.06	1.58	0.34	0.79	11
4. Cultivation (VC) fb flame-cultivation (V4–V5)	2.64	3.81	1.91	2.74	1.32	1.36	8
5. Cultivation (VC) fb broadcast flaming (V4–V5)	2.64	3.35	2.02	2.22	1.22	1.43	10
6. Flame-cultivation (VC) fb cultivation (V4–V5)	3.03	3.69	2.41	2.87	1.32	1.77	7
7. Flame-cultivation (VC) fb flame-cultivation (V4–V5)	4.73	4.73	3.34	3.45	2.03	2.19	3
8. Flame-cultivation (VC) fb broadcast flaming (V4–V5)	3.60	3.85	2.25	2.58	1.40	1.87	6
9. Broadcast flaming (VC) fb cultivation (V4–V5)	2.49	3.76	2.29	2.45	1.19	1.46	9
10. Broadcast flaming (VC) fb flame-cultivation (V4–V5)	4.14	4.24	2.99	3.17	1.96	2.11	5
11. Broadcast flaming (VC) fb broadcast flaming (V4–V5)	4.22	4.49	3.05	3.25	1.76	1.91	4
12. Banded flaming fb aggressive cultivation (VC) fb banded flaming fb aggressive cultivation (V4-V5)	5.44	5.09	3.61	3.63	2.12	2.14	2
LSD (P=0.05)	1.00	0.98	0.68	0.63	0.46	0.35	

Table 6.10. 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, USA (2010, 2011, and 2012)

	yield (t/ha)	Crop injury 28 DAT (%)	Weed control 28 DAT (%)	Weed dry matter 60 DAT (g)	Plants m^{-2}	Pods $plant^{-1}$	Seeds pod^{-1}
crop injury 28 DAT (%)	0.05						
weed control 28 DAT (%)	0.61*	0.07					
weed dry matter 60 DAT (g)	-0.39*	-0.09	-0.79*				
plants m^{-2}	0.03	-0.03	-0.07	0.10			
pods $plant^{-1}$	0.71*	-0.17*	0.54*	-0.41*	-0.08		
seeds pod^{-1}	0.01	0.01	0.08	-0.14*	-0.01	0.13*	
1000 seed weight (g)	0.46*	0.04	0.34*	-0.18*	-0.06	0.43*	-0.1

*significant at 10% levels of probability

CHAPTER 7. General Conclusions

7.1. Conclusions for objective 1:

Describe dose–response curves for propane when flaming selected weed species at different growth stages (Chapter 2.)

- Response to broadcast flaming varied among species and growth stages.
- Common lambsquarters at the 5-leaf, tansy mustard at 9-leaf and flowering and henbit at flowering stage were effectively controlled (90% control) with propane doses between 54 and 62 kg ha^{-1}.
- Higher propane doses (>80 kg ha^{-1}) were necessary to obtain 90% control of common lambsquarters at later growth stage (11-leaf) and early growth stage of henbit (9-leaf), while 90% control of cutleaf evening primrose, field pennycress, and dandelion was not achieved with highest propane does (90 kg ha^{-1}) utilized in the study.
- Propane flaming has a potential to be used as PRE broadcast tool for early spring weed control

7.2. Conclusions for objective 2:

Determine corn and soybean tolerance to single and repeated flaming by utilizing the equipment designed to selectively flame weeds in row crops with torches positioned parallel to the crop row (Chapters 3. and 4.)

- Four-row flamer with its hood technology showed a great potential in minimizing crop injury when conducted after V5 in soybean and after V4 in corn, protecting the growing point and sparing the major portion of the leaves from any heat damage

- Both corn and soybean were able to tolerate up two flaming treatments with propane dose of 45 g ha^{-1} without any yield reduction. For best results, soybeans should be flamed at VC and V5, while timing of flaming in corn can be adjusted based on the weed size and the types of weed species present

7.3. Conclusions for objective 3:

Determine the effectiveness of flaming and cultivation for weed control management under two manure levels in organic corn and soybean (Chapters 5. and 6.)

- Manure application increased yield of corn in years when there no drought. In soybean, no effect of manure was observed
- Combining flaming and cultivation was single, the most effective weed control practice in both corn and soybean. When applied twice in the season, treatment yielded statistically similar to weed-free control making a significant improvement over existing, most commonly used "cultivation twice practice"
- Broadcast flaming could be employed to provide satisfactory weed control when conditions are too wet to cultivate
- Flaming should be combined with cultivation and other non-chemical weed management strategies to increase overall effectiveness of integrated weed control programs in both organic and conventional crops