MECHANICAL AND THERMAL WEED CONTROL IN ORGANIC CROPS

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The undersigned, appointed by the dean of the Graduate School,

have examined the thesis entitled

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And hereby certify that, in their opinion, it is worthy of acceptance.

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CHAPTER I

Literature Review

Introduction

Manufactured pesticides and fertilizers are widely utilized in conventional agriculture, often adversely impacting environmental and community health (Pimentel, 2005). In 2010, 109,495 cases of pesticide exposure were reported to poison control centers (Roberts and Reigart, 2013). Because of the concerns related to conventional agricultural production, organic agriculture has become popular among consumers (Knowler and Bradshaw, 2007; Scherr and McNeely, 2008; Willer et al., 2010) and has been found to be less detrimental to the environment than conventional production systems (Crowder and Reganold, 2015).

Northbourne (2003) states that organic farming can be an important component of natural ecology since customers are looking for more environmentally-friendly products. According to Mannion (1995), organic farming is an agriculture system that focuses on the production of goods while addressing environmental protection. Scofield (1986) emphasizes that organic farming integrates many components of agricultural sustainability.

Organic agriculture uses methods that avoid synthetic materials, such as pesticides, antibiotics, and genetically modified organisms (GMOs). Organic growers generally believe they are preserving natural resources and biodiversity and decreasing the risk of cancer by using only natural substances (Kristiansen and Merfield, 2006).

Standards of certification

Organic certification gives farmers the authorization to sell and distribute their products as certified organic and verifies that farms that grow and commercialize organic products are following USDA National Organic Program rules. Producers marketing organic goods over $5,000 per year must certify using an accredited certifying agency in order to sell as organic. Farms producing less than $5,000 a year of organic products and that sell only directly to consumers do not need to become certified, but still have to follow the national guidelines from the USDA to sell their product as organic (Baier, 2012; Coleman, 2012). The four different categories of organic production are crops, wild crops, livestock, and processed products (Baier, 2012; Coffey and Baier, 2012; Coleman, 2012).

To become certified organic, a producer must go through several steps. The first step of this process is to implement organic practices on his/her property and to apply to a certifying agency. A certifying agency will then process the application and inspect the farm operation to ensure that the farmer is following all USDA organic regulations. A certificate from the certifying agency will be delivered to the applicant by the end of the process, allowing the farmer to commercialize organic products using the USDA approved label. An annual review and inspection are necessary to maintain the USDA organic certification (Baier, 2012; Coffey and Baier, 2012; Coleman, 2012). There is a transitional period of 36 months when converting conventional land to organic. During the transition, organic practices must be utilized but the product cannot be sold as organic until the transition period is over (Baier, 2012; Coffey and Baier, 2012; Coleman, 2012).

Principles

The idea of organic farming was developed using important principles of sustainability such as biodiversity and natural plant nutrition (Kuepper and Gegner, 2004). The main idea behind the principle of biodiversity is to enable interactions between plants and beneficial organisms (Kratochwil, 2013). Biodiversity can also be built when different production systems are interconnected, for example, crop production and livestock, thus leading to greater sustainability (Kuepper and Gegner, 2004).

Plant nutrition in organic farming focuses on the recycling of nutrients to reduce the use of externally-sourced fertilizers (Stockdale et al., 2002). Organic advocates believe that conventional farming contributes to pest outbreaks by altering food web structure and communities from the introduction of synthetic pesticides and fertilizers that can affect non-target organisms. Organic farming promotes balanced pest control among natural enemies, lessening the risk of ecological damage (Crowder et al., 2010; Decker et al., 1994; Sullivan et al., 1991)

Practices for organic farming

Organic producers rely on many different techniques to increase yields such as crop rotation, composting, cover crops and tillage for weed control. Crop rotation can help reduce soil degradation while increasing soil organic matter in the soil (Christensen et al., 2012). Crop rotation can decrease weed and disease pressure and improve crop growth through release of various organic acids and plant growth regulating compounds in the rhizosphere (Power and Follett, 1987). In a crop rotation system, a cover crop can also be used to provide nutrients for subsequent crops and to suppress weeds.

Cover crops are used to cover the soil and also to increase water infiltration and soil moisture, decreasing drought stress. Cover crops can help reduce soil compaction and erosion while improving soil structure and increasing the efficiency of nutrient cycling (Bergtold et al., 2012; O'Connell et al., 2015; Reeves, 1994). Yield reductions can potentially occur when growing cover crops because of decreased soil water availability for the following crop if rainfall is low. In areas with high annual precipitation or where irrigation is used, cover crops do not generally lead to soil moisture reductions (Unger and Vigil, 1998).

Composted animal manure is also an important fertility source in organic production. In organic compost production, controlled and aerobic conditions must be used. Compost can be used as a type of fertilizer because it can provide the macronutrients for plant growth such as nitrogen, phosphorus, and potassium (Goulding et al., 2008). Compost nutrient concentration can be influenced greatly by the type of manure used and the storage conditions that it was produced with. For instance, poultry manure has lower N:P ratios when compared to cattle manure and compost stored under shelter generally has higher N levels than compost exposed to rain (Nelson and Janke, 2007). Long-term application of poultry manure can lead to environmental degradation due to the high levels of P that are applied when adequate N is supplied for crop growth (Chang and Entz, 1996; Eghball and Power, 1994).

Organic producers are also highly dependent on tillage for weed control. Tillage leads to physical and chemical changes in the soil that can affect soil organic matter levels as well as water infiltration. Tillage can cause soil erosion and accelerate soil carbon loss due to breakdown of soil aggregates. While tillage can adversely affect soil microorganism populations (Reicosky and Allmaras, 2003; Roger-Estrade et al., 2010), it generally has a positive effect on reduction of weed density (Wilson, 1993).

Organic crop production

In 2014, about 1% of the total arable land in the world (47.3 million hectares) was managed using organic practices by more than 2.3 million producers (Willer and Lernoud, 2016). Oceania has the greatest land area in organic production (17.4 million ha), followed by Europe (11.7 million ha) and Latin America (6.9 million ha). The top three countries for organic production are Australia, Argentina, and the United States. From 2013 to 2014, the total organic area in the world increased by 0.5 million hectares. Europe and North American are responsible for greater than 90% of global purchases of organic products and lead demand for organic food (Sahota, 2010; Willer and Lernoud, 2016; Willer et al., 2010).

North America and U.S organic crop production

North America has more than 12,000 organic farms (almost 3.1 million ha) that represent approximately 0.06% of the total arable land and 7% of total agricultural organic land in the world. In the U.S., 1.6 million hectares were certified organic in 2005 and organic production generated more than $20 billion in revenues in 2007 (Dimitri and Greene, 2000; Dimitri and Oberholtzer, 2009; Willer and Lernoud, 2016; Willer et al., 2010).

An increase in consumer demand and the opening for organic products in conventional big retailers are the major reasons for organic market growth. Organic foods now occupy important marketing space in the most important U.S. food retailers. Market demand was responsible for a 586% increase of organic food sales in from 1997 to 2008.

Supermarkets and other food retailers have continued introducing organic products on their shelves and companies continue to introduce products made from organic crops (Willer and Lernoud, 2016; Willer et al., 2011).

Overall, organic crops generally yield less than conventionally produced crops with reductions ranging from 8 to 25% (Clark et al., 1999; Dimitri and Oberholtzer, 2009; Lockeretz, 1989; Seufert et al., 2012). On the other hand, Delate et al. (2003) states that organic corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merril] planted in a long rotation can yield the same as conventional crops under similar environmental conditions.

Organic weed management

Weed monitoring

The definition of a weed is an undesired plant that is interfering with crop growth and development (Aldrich, 1984; Zimdahl, 2013). To be considered a weed, the undesired plant has to interfere with the growth of desirable plants and have the characteristics of persistence and perniciousness (Ross and Carole, 1985).

Conventional farmers can rely on cultural, chemical and physical techniques to control weeds, while organic growers can usually use cultural and mechanical approaches only. These techniques ares subdivided into prevention and control measures. Crop rotation, cover crop and tillage are some examples of prevention methods, while cultivation, thermal weed control, and mowing are some examples of control methods (Bàrberi, 2002; Radosevich et al., 1997).

Methods to prevent weeds in organic systems

Crop rotation

Crop rotation is considered an important technique to control weeds (Cardina et al., 2002; Froud-Williams, 1988). Populations of broadleaf and grass weeds such as common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), and giant foxtail (*Setaria faberi* Herrm) were reduced 88, 29 and 80% respectively in a corn-oats (*Avena sativa* L.)-hay rotation system (Cardina et al., 2002). Crop rotation can decrease weed population because the crop planted can differ radically from previous crops in one or more factors, such as competitiveness with weeds, planting and harvesting date, growth habit, or crop production practices such as mowing pastures. These factors can inhibit the growth and abundance of weeds in areas where crop rotation is practiced (Froud-Williams, 1988; Liebman et al., 1990).

Cover crop

Cover crops are used to minimize soil erosion and nutrient losses, and to suppress weeds (Flach, 1990; Teasdale, 1993; White et al., 1989). The use of cover crops can also reduce seed germination because of allelopathic effects and because of changes in soil temperature, moisture, and plant available light (Barnes et al., 1987).

Cereal rye is one the main cover crops cultivated in the U.S. because it can survive throughout the winter and produce enough biomass to last throughout the summer (Wilkins and Bellinder, 1996). Stoskopf (1985) states that cereal rye leaves the highest amount of biomass residue when compared to other cereal grains and reaches maturity before legume cover crops, allowing adequate time for the following crop to be planted.

Cereal rye cover crops also have the ability to retain more nutrients from manure applications and to inhibit emergence and growth of many weeds. Cereal rye inhibited growth of common ragweed (*Ambrosia artemisiifolia* L.) by 45%, green foxtail (*Setaria viridis* (L.) Beauv) by 85%, and redroot pigweed, common lambsquarters and common purslane (*Portulaca oleracea* L.) by 100%. However, it had no effect on the emergence of yellow foxtail (*Setaria glauca* (L.) Beauv) (Shilling et al., 1985). Cereal rye can suppress germination of some species, including weeds, due to the release of allelochemicals (White et al., 1989). Rye planted before corn can cause poor corn growth and establishment. This could also be due to nitrogen immobilization from rye residue breakdown more than to allelopathy (Barnes et al., 1987; Hartzler, 2014; Shilling et al., 1986; White et al., 1989).

Some researchers believe that the cover crop should be terminated at least two weeks prior to planting a summer crop to allow the cash crop to have enough water available at planting time (Hargrove and Frye, 1987; Kornecki et al., 2009). Cover crops can be terminated by mechanical methods, such as roller-crimping, cultivation and disking, using herbicides, or if the growing season is long enough, letting it terminate by itself (Teasdale et al., 2007; Teasdale et al., 1991). In organic no-till, the summer crop is usually planted the same day that the cover crop is terminated (Mirsky et al., 2009).

Cereal rye in organic no-till can be can be terminated using a roller-crimper at Zadoks growth stage 61 (first anthers visible) or later (Mirsky et al., 2009). If crimping is performed at the correct time, the termination rate for rye is above 95% (Ashford and Reeves, 2003; Kornecki et al., 2006). The main use for the roller-crimper is to injure and to accelerate senescence of the cover crop. It is used mainly in agriculture systems where the use of herbicides is not allowed, such as in organic crop production (Kornecki et al., 2009). Hair pinning of cover crop residue during crop planting can lead to decreased germination of the cash crop. Hair pinning is when the cover crop residue is pulled into the planting furrow, leading to decreased seed to soil contact of the subsequent crop (Kornecki et al., 2009).

Tillage

Tillage is used to control weeds, to stimulate seed germination and to increase nutrient transformations and availability for the crop. However, if tillage is overused it can increase soil carbon loss and greenhouse gas emissions and cause soil erosion (Ferrero et al., 1999; Shrestha, 2006). Because mechanical tillage has to be performed as needed in organic production, potential delays due to wet soils, farm size, and labor availability can occur (Gunsolus, 1990; Lovely et al., 1958; McGarry, 1988). In the United States, traditional tillage is responsible for soil losses of 8,619 kg ha^{-1} $year^{-1}$, compared to soil loss in no-till of 328 kg ha^{-1} $year^{-1}$ (Aber and Melillo, 2001; Robertson et al., 2000).

Methods to control weeds in organic systems

Cultivation

Cultivators perform better when soils are dry enough to avoid compaction. If rainfall occurs around the time of cultivation, weeds may recover and survive. (Curran, 2004; Hamilton and Baldwin, 2006). Cultivation is an important technique for weed control for organic farmers (Murphy et al., 1996). Cultivation will have the best results if performed when weeds are close to 2.5 cm tall and when the cash crop will not have the risk to be covered by the movement of the soil during the operation. It is not recommended to perform cultivation if corn or soybean are below the two-leaf stage (Curran, 2004).

Depending on the crop height and growth stage, cultivation equipment can damage the crop foliage and root system, reducing yields later in the season (Hamilton and Baldwin, 2006). Cultivation has to be performed as a continuation of a weed management plan to try to catch weeds that escaped from the previous weed control techniques such as tillage or cover cropping (Hamilton and Baldwin, 2006).

Flaming

The heat generated by propane flame can reach temperatures up to 1990 ºC and desiccate plant leaves and damage cell walls (Diver, 2002; Pelletier et al., 1995). To be lethal, leaf tissue must be exposed to temperatures ranging from 55 to 70 ºC for a time period ranging from 65 to 130 microseconds (Knezevic, 2017).

Overall, grass weeds are more resistant to flaming when compared to broadleaf weeds because of the location of the growing point when this technique is performed (Ulloa et al., 2010b). In early stages, the growing point in grasses is below the topsoil surface and protected from the heat, allowing the weed to regrow following a flame treatment. The growing point in broadleaves is above the soil surface and exposed to the flaming (Ascard, 1995; Knezevic, 2017; Ulloa et al., 2010b).

Some grass weeds including green foxtail, yellow foxtail and barnyardgrass (*Echinochloa crus-galli* (L.) Beuav) can be controlled over 80% with flaming, while various broadleaf species, such as redroot pigweed, common waterhemp (*Amaranthus* *rudis* Sauer), velvetleaf (*Abutilon theophrasti* Medic), ivyleaf morning glory [*Ipomoea hederacea* (L.) Jacq], and common lambsquarters up to 25 cm tall can be controlled up to 90% when applying 60–80 kg ha^{-1} of propane (Knezevic, 2017; Ulloa et al., 2010a; Ulloa et al., 2010b). Flaming is recommended on corn between emergence and V1 leaf stage for broadcast flaming and between V1-V10 leaf-stage for banded flame weeding, while soybean can receive broadcast flaming between crop emergence and the V1 leaf stage, and between V4-V5 trifoliate-stage for banded flaming weeding (Knezevic et al., 2012; Ulloa et al., 2011). Flaming has to be used with caution since it can cause a fire if applied in areas with high amounts of crop residue.

Hot water

Hot water can be used to control weeds where chemicals are not allowed and when farmers want to integrate weed control techniques. Ninety percent control of white mustard (*Sinapis alba* L.) at the two-leaf stage can be achieved using hot water spray at approximately 110 ºC, with a travel speed of the equipment at 1.3 km/h, and at the six-leaf stage when the travel speed is 0.5 km/h (Hansson and Ascard, 2002). Because older plants have more tolerance to heat than younger plants, tractor speed has to be reduced allowing the machine to deliver more water to achieve the same level of control when weeds are older than the two-leaf stage (Hansson and Ascard, 2002; Hansson and Mattsson, 2003; Sutcliffe, 1977).

Although plant size interferes with the efficacy of hot water, environmental factors have a more variable effect. Air temperature has minimal influence on the control of weeds when using hot water (Hansson and Mattsson, 2003). However, rainfall increases the requirement of hot water when compared with plants treated during dry periods. To control 90% of wet white mustard plants requires a 21% energy increase over control of dry plants (Hansson and Mattsson, 2003). Hot water treatment performed after a period of at least three days without rain can increase weed control, reducing the amount of water required (Hansson and Mattsson, 2003). The use of a wetting agent called Biowett® added in hot water can reduce plant fresh weight an average of 27% when compared to hot water applied without the wetting agent. (Hansson and Mattsson, 2002).

Hot water can be an alternative to tillage for weed control on small areas, but since the equipment requires large amounts of water and energy, it may not be practical when performing on large scale operations. Hot water can be detrimental to beneficial soil microorganisms and insects at the time of the application, but it may control some pathogens and nematodes (Ascard et al., 2007; Hansson and Mattsson, 2002).

Between-row mowing

Mowing is mainly used to reduce weed growth by defoliation and to prevent the production of seeds. Mowing will increase soil temperature and light penetration because of the reduction of plant biomass, changing the local microenvironment (Donald, 2006a; Donald, 2006b). Mowing is currently used to control weeds around organic fields, to manage cover crops, in pastures and also in right-of-ways. However, the use of mowing for between-row weed control is rare (Donald, 2000; Lampkin, 1990; Smith, 1995).

Mowing can control broadleaves better than grass weeds because the growing point of a broadleaf is above ground. (Donald, 2006b). It is possible to control emerged broadleaves such as waterhemp and common ragweed, with one-time mowing only, while multiple mowings are necessary to control giant foxtail (Donald, 2000; Donald, 2006b).

The search for healthy food and the increase in the purchasing power of consumers are driving the increased demand for organic foods. While organic crop production has been growing substantially, the techniques available to help farmers control pests, especially weeds, have been not following this same trend. Organic farmers still have to rely heavily on cultivation to control weeds and while this is an important tool, it can negatively impact the soil by decreasing the level of organic matter and increasing the risk of soil erosion. The lack of data on alternative weed control methods in organic systems is the main reason why more research in this area is extremely needed. In this study, we compare the primary weed control methods of cultivation and flaming in tilled systems to secondary weed control using hot water spray and between-row mowing in organic no-till systems.

Objectives

- Evaluate organic weed management systems (flaming, hot water, between-row mowing, and cultivation) within a corn/soybean rotation.
- Estimate the amount of time (seconds) required to effectively control small broadleaf and grass weeds using hot water spray.

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CHAPTER II

Efficacy of Weed Control Techniques in Organic Corn and Soybean

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Abstract

Effective weed control is one of the most yield-limiting factors in organic corn and soybean production. Additionally, the amount of tillage needed to control weeds in organic practice is often criticized for its negative impacts on soil quality. This research was conducted in central Missouri from 2016-2017 to compare cultivation, flame application, between-row mowing, and hot water spray for in-season weed control in organic corn and soybeans. Between-row mowing and hot water application were paired with no-tillage and a crimped winter cover crop of cereal rye (*Secale cereale* L.). When weeds reached 10.2 cm, weed control practices were implemented and repeated as necessary until canopy closure. Grass and broadleaf weed biomass between crop rows was determined at multiple dates throughout the 2016 and 2017 seasons and in-row weed levels were determined at the final collection date for each crop each year.

Broadleaf weed biomass at the end of the soybean season in 2016 was lower in the two treatments utilizing no-till and cover crops as primary weed control and hot water and mowing as secondary control. Soybean yield was adversely affected by flaming but not significantly different for the cultivation, mowing and hot water treatments. In 2017, soybean had less between-row grass biomass in the cultivation and flaming treatments than in hot water and mowing, but broadleaf levels were the same in the mowed treatment as the cultivated and flamed treatments. In 2016, grass biomass was lower in the no-till treatments between corn rows and higher in the crop rows than the other two treatments. Weed control treatments led to no significant differences in corn yield in 2016 and higher yields in the no-till treatments in 2017. In-row weed levels were significantly higher in corn in 2017 for the hot water treatment. Hot water at the levels applied in this research was not an effective weed control method. The crimped cover crop used in the no-till treatments limited weed growth in early-season corn and soybean and when coupled with between-row mowing is a potential alternative to cultivation in organic crop production. Flaming is also a potential alternative to cultivation in corn production.

Keywords: sustainable agriculture, no-till, flame, hot water, between-row mowing

Introduction

Conventional crop production practices rely heavily on synthetic fertilizers and pesticides to control weeds, insects, and diseases while increasing crop yields, which significantly impacts public health and the environment (Pimentel, 2005). In 2010, 109,495 cases of pesticide exposure were reported to poison control centers in the United States (Roberts and Reigart, 2013). Concerns related to conventional production systems have been increasing over the years, making organic products more popular among consumers (Knowler and Bradshaw, 2007; Scherr and McNeely, 2008; Willer et al., 2010). Global market demand for organic food has reached $81.6 billion. The United States is the primary consumer of organic products, with annual sales topping $37 billion. (Willer and Lernoud, 2017).

This increased demand for organic food impacts farmers. In 2017, 2.4 million farmers produced organic crops worldwide in an area estimated at 50.9 million hectares (1.1% of total agricultural land), and from 2014-2016, 6.5 million hectares of farmland were converted to organic production (Willer and Lernoud, 2017).

Since organic agriculture does not allow the use of synthetic pesticides and fertilizers (Kristiansen and Merfield, 2006), and weeds are a major factor responsible for crop losses in agriculture (Oerke and Dehne, 2004), organic producers must use alternative methods to control weeds. Organic farmers often rely on tillage to control weeds (Bond and Grundy, 2001) but the mechanical disturbance caused by tillage can cause rapid mineralization of organic carbon leading to its loss as CO_2 and can destroy soil structure, leading to lower levels of water infiltration and plant available water (Karlen et al., 1994; Reicosky and Allmaras, 2003). Other practices have been developed to help to control weeds in organic crop production. Flaming is one technique that has been used to control weeds in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr] as an alternative to cultivation. Propane flames can reach temperatures up to 1990 ºC and desiccate plant leaves and damage cell walls (Diver, 2002; Pelletier et al., 1995). To be lethal, leaf tissue must be exposed to temperatures ranging from 55 to 70 ºC for 65 to 130 microseconds (Knezevic, 2017). Grass species are more tolerant to flaming than broadleaf species because of the location of the growing point below the soil surface at early growth stages (Ulloa et al., 2010). This makes corn a desirable crop for weed control with propane flame. The growing point in broadleaf species is above ground and exposed directly to flames, making broadleaf weeds more susceptible to flaming, but also making it more likely to damage soybean when using flaming (Ascard, 1995; Knezevic, 2017; Ulloa et al., 2010).

For weed control in organic no-till systems, techniques such as between-row mowing and hot water application can be used in place of flaming and cultivation to avoid residue fire and soil and residue disturbance. In organic no-till, cover crops are planted to suppress weeds through competition and exclusion of light on the soil surface and can be terminated using a roller-crimper. When crimped at Zadock's 61 growth stage, the vascular tissue of cover crops will be destroyed by the roller-crimper and the residue will remain flat on the soil surface (Mischler et al., 2010).

Between-row mowing is used to reduce weed growth by defoliation and to prevent the production of seeds. It is currently used to control weeds at the edges of organic fields, to manage cover crops, and in pastures. (Donald, 2000; Lampkin, 1990; Smith, 1995). Mowing can control broadleaves better than grass weeds because the growing point of a broadleaf is above-ground while a grass weed growing point is below-ground at early stages. (Donald, 2006). It is possible to control emerged broadleaf weeds such as waterhemp (*Amaranthus rudis* Sauer), common cocklebur (*Xanthium strumarium* L.) and common ragweed *(Ambrosia artemisiifolia* L.), with one-time mowing only, while multiple mowings are necessary to control giant foxtail (*Setaria faberi* Herrm) (Donald, 2000). Soybean and corn yields showed no significant differences between treatments performed with repeated use of mowing, hoeing, and rototiller, with soybean and corn yields averaging 2000 and 7000 kg ha^{-1} respectively (Donald, 2006).

Hot water application can also be a useful tool for weed control. Although injuries caused by heat can be reversible at the initial stages of weed growth, accumulated heat can cause thermal death as a result of denaturation of proteins and the melting of the lipids of the plant cells (Daniell et al., 1969). White mustard (*Sinapis alba* L.) can be controlled more than 90% using hot water spray at approximately 110 ºC, at both two-leaf and six-leaf stages with a travel speed ranging from 0.5 to 1.3 km ha^{-1} (Hansson and Ascard, 2002). Plants larger than the two-leaf stage are more tolerant to heat than younger plants and more water is necessary to achieve the same level of control when weeds are older than the two-leaf stage (Hansson and Ascard, 2002; Hansson and Mattsson, 2003; Sutcliffe, 1977). In addition to weed control, hot water can also control some pathogens and nematodes. Some challenges of hot water application include a high demand for water and energy, making its use less practical for large-scale operations (Ascard et al., 2007; Hansson and Mattsson, 2002).

Few studies have examined alternatives to mechanical tillage for use in organic corn and soybean production systems. Negative impacts from tillage necessitate developments of alternative methods of weed control. The objective of this research was to improve techniques for weed control while protecting crop yields within an organic corn/soybean rotation. The weed management treatments of propane flame, between-row cultivation, hot water spray, and between-row mowing were evaluated for weed control.

Material and methods

Research was conducted on a 1.17 ha area at the Bradford Research Center, a University of Missouri research farm located in Columbia, MO (38.8929 O N, 92.2010 O W). The predominant soil series at the research site is a Mexico silt loam (pH of 6.7 with 3.8 % organic matter). The field received organic certification through Quality Certification Services (QCS, Gainesville, FL), and has been in organic production for five years.

The study site was prepared for initiation of the experiment in the fall of 2015. The site was mowed with a 4.6 m John Deere Bush Hog (John Deere, Moline, IL). Organic compost from poultry manure (3-2-2) (Early Bird Composting California, MO) was applied with a New Holland 155 spreader (New Holland Ag., New Holland, PA) at 3.6 mT ha^{-1}. The site was then disked with a True-Tandem disk harrow 375 with 61 cm blades and 23 cm spacing (Case IH, Racine, WI) twice to incorporate the compost. After harvest in 2016, crop residue was mowed and food waste compost (1-1-1) (Bluebird Compost, Fulton,. MO) was spread at a rate of 18 mT ha^{-1}, then incorporated using a disk with a harrow.

The crop rotation was corn-soybean-wheat (*Triticum aestivum* L.). Experimental plots measured 6.1 x 9.1 m. A cover crop mix was planted on 20 October 2015 and consisted of cereal rye (*Secale cereale* L.) (123.3 kg ha^{-1}), Austrian winter pea (*Pisum* *sativum* L. ssp.) (10.1 kg ha^{-1}), crimson clover (*Trifolium incarnatum* L.) (11.2 kg ha^{-1}), and Essex rapeseed (*Brassica napus*) (3.0 kg ha^{-1}) and 4 October 2016 consisting of cereal rye (123.3 kg ha^{-1}) before soybeans; and cereal rye at (123.3 kg ha^{-1}) and Austrian winter pea (10.1 kg ha^{-1}), before corn with a Tye no-till drill (Tye CO. Lockney, TX), at 19 cm row spacing. Due to the fact that essex rapessed and crimson clover were being resistant to crimping, a change in the cover crop mix was necessary to avoid cover crop regrowth during the cash crop season. Wheat was planted at 67.2 kg ha-1 at 19 cm row spacing and was followed after harvest by either a double-crop soybean or a summer cover crop treatment. Those plots were not utilized in this research study. Crop production was in the site for the past 14 years.

Cover crops stand were terminated on 15 March 2016 and 2 April 2017 with a brush hog mower (John Deere, Moline, IL) for cultivated and flamed treatments and with a roller-crimper (I&J Mfg., Gap, PA) the same day as cash crop planting for the no-till with hot water or between-row mowing treatments.

On 5 May 2016 and 30 May 2017, organic corn hybrid Master's Choice 5300 was planted at a seeding rate of 45,700 seeds ha^{-1} for no-till plot treatments and 33,500 seeds ha^{-1} for tilled plot treatments with a four-row planter (John Deere, Moline, IL). Corn was planted into the standing winter cover crop for all no-till treatment plots. The cover crop was terminated by crimping with three passes of the crimper immediately after planting.The seeding rate for no-till corn was increased to assure an acceptable corn stand. Row spacing was 76 cm, resulting in eight-row plots. The corn was replanted in both years due to poor stands. On 25 May 2016 and on 7 June 2017 replanting of corn in the no-till plots was necessary due to only a 30% stand emerging from the crimped cover crop.

Nitrogen in the form of Chilean sodium nitrate ($NaNO_3$,) (16-0-0) was hand applied to V4 stage corn on no-till treatment plots on 20 June 2016 and 21 June 2017 at 56.0 kg ha^{-1}. The National Organic Program (NOP) considers non-synthetic $NaNO_3$ a restricted substance. Article 7 CFR section 205.602(g) of NOP's National List states $NaNO_3$ can only be applied for 20% of a crop nitrogen requirement in organic farming (SAREP, 2002). The application rates for 2016-2017 followed these guidelines based on measurements from a chlorophyll SPAD 502 meter (Spectrum Technologies Inc., Aurora, IL). The crimped cover crop plots and non-cover crop plots each had 30 randomly selected V5 growth stage corn plants analyzed for chlorophyll concentration, and $NaNO_3$ was applied as per NOP regulation.

On 13 May 2016 and 7 June 2017, soybean (Emerge E3782S, maturity 3.7) was planted at a rate of 165,000 seeds ha^{-1} for till plots and 192,000 seeds ha^{-1} for no-till treatments in 2016 and 2017 with a four-row planter (John Deere, Moline, IL). Soybean was planted into the standing winter cover crop for all no-till treatments. The cover crop was terminated by crimping immediately after soybean planting. The seeding rate for no-till soybean was increased to assure an acceptable crop stand. Row spacing was 76 cm, providing eight-row treatment plots. Because soybeans are symbiotic nitrogen fixers, the only nutrients applied were those in the initial fall compost amendment before cover crop planting.

Grass and broadleaf weed biomass was collected between crop rows prior to each weed control treatment and in crop rows at the end of the season in two randomized locations in each plot using a 0.09 m^2 quadratic frame. Weed treatments were first performed when weed seedlings were 10.2 cm high and repeated as necessary until the crop was too tall for safe clearing of tractor mounted implements (Table 2.1). Soybean plants were smaller in stature and received approximately two more applications per treatment than the corn plants in 2016. However, the exception is the propane flame (Red Dragon, Flame Engineering Inc, LaCrosse, KS) weed suppression treatment. Due to the soybean plant's small seedling stature and susceptibility to high heat, flame treatments had to be delayed until soybean plants were 25.4 cm tall. As a result of the delayed flame treatment, between-row cultivation was used in 2016 on soybean flame treatment plots until plants were of an acceptable height. Crop shields directed propane flames away from soybean seedlings. The flame treatment plots still experienced soybean stand loss in 2016 (0%-30%) with the shield-outfitted implement. In 2017, we followed the University of Nebraska guidelines for flame application on soybeans, which recommends the propane flamer be used only during emergence, at cotyledon stage and when the plant is at V4-V5 stage (Knezevic et al., 2012), using between-row cultivation when weed control was necessary during growth stages susceptible to flaming. The propane flame was applied in both corn and soybean at 35 PSI with a tractor speed of 6.4 kilometers/hour (km/h); flames reached up to 1093º C.

A custom built machine with a hot water sprayer (Largo Industries, Decaturville, TN) was mounted on a three-point hitch behind the tractor. Due to a water source with high calcium levels, water was routed through a filter (Pentair®) and water softener (Morton®) before filling a 227 L tank. From the tank, the water was piped to a diesel-powered heater (hot water high-pressure sprayer modified for this use) and then through high-pressure lines and a spray boom with three hooded units, each with two nozzles (Teejet® 6508). The area of each hood was 1.02 x 0.55 m and the machine was designed to apply a topical spray of water at 150°C at a rate of 765 liters/hour. Hot water treatment was not applied as frequently in 2016 as the other treatments because the dense crimped cover crop supplied the needed early-season weed management. Furthermore, equipment malfunctions delayed hot water treatment. Although these were remedied quickly, the growth rate of corn allowed only one hot water treatment application in 2016. The second weed management treatment with a cover crop, between-row mowing, was done with a self-propelled push mower (DR Trimmer, Vergennes, VT) and was also less frequently applied in 2016 due to good weed control from the crimped cover crop. The conventional organic row crop weed management practice, between-row cultivation, was done with a Danish S-tine four-row cultivator (Harriston, Minto, ND).

Corn was harvested on 30 September 2016 and 10 October 2017 from two center rows with a Kincaid research combine, (Kincaid Equip. Mfg., Haven KS). Soybean was harvested using the two middle rows on 4 October 2016 and 3 October 2017 with a 2-row Wintersteiger research combine (Wintersteiger Inc., Salt Lake City, UT).

To identify which weeds were present in this research area and to estimate the amount of seeds in the seed bank, a total of 15 soil samples were collected on October 23, 2015, and on October 4, 2016, using a 7.6 cm standard soil auger in 15 different points of the field. From each sample, a subsample of 100 g of soil was suspended in a solution of 10 g sodium hexametaphosphate and 2.5 g sodium bicarbonate in 0.5 L of distilled water to disperse clays. The bottle containing the soil suspension was shaken at 150 rpm for 5 minutes. Soil particles were removed with an 80-mesh sieve and the remaining seeds and organic debris were collected over cheesecloth and air dried. Dry samples were processed individually using a microscope and forceps to separate and identify weed seeds. Seeds were counted and classified to plant species using appropriate guides (Bryson and DeFelice, 2010; Buhler and Hoffman, 1999).

The 30-year average precipitation for Boone County is 1,083.0 mm. In 2016, 927.8 mm were recorded and in 2017 the amount of rain was 837.7 mm until November of 2017. The greatest precipitation amounts in 2016 were recorded from May to September, with a total accumulation of 646.66 mm, while in 2017 the greatest precipitation amounts were recorded from April to July, with a total accumulation of 528.09 mm for that period.

The experimental design for this study was a randomized complete block design with separate areas for corn, wheat, and soybeans. Data were analyzed using SAS Enterprise Guide 9.4 statistical software (SAS Inst., 2013). Treatment and replication were considered random effects whereas crop type was considered fixed. Statistical significance was at $P \leq 0.05$. When treatment effects were significant, means were separated using Fisher's least significant difference (LSD).

Results and discussion

Weed biomass

The biomass of grass and broadleaf weeds collected in 2016 and 2017 in corn and soybean plots was used as the main tool to measure weed control treatment performance. The grasses present were giant foxtail (*Setaria faberi* Herrm.), yellow foxtail (*S. glauca* (Poir. Roemer & J.A. Schultes.) and large crabrass (*Digitaria sanguinalis* L.) while the broadleaf weeds were common cocklebur (*Xanthium strumarium* L.), waterhemp

(*Amaranthus rudis* Sauer.), common purslane (*Portulaca oleracea* L.) and carpetweed (*Mollugo verticillata* L.).

Weed biomass was primarily composed of grasses in 2016 and varied widely among treatments. In 2016, at 18 days after planting (DAP) and at 25 and 32 DAP (Figure 2.1, 2.2, 2.3) of soybean, the amount of broadleaf and grass weeds collected were higher in the tilled plots where cultivation and flaming were performed than in no-till plots where hot water and mowing treatments where used. The use of a crimped cover crop delayed initial weed emergence leading to the appearance that hot water and mowing were more effective than tillage or flaming. Weed suppression by cover crops was dissipating by 59 DAP, resulting in increased weed biomass in hot water and mowing treatments (Figure 2.4 and 2.5). At 46 DAP (Figure 2.4) the plots where cultivation was performed showed the lowest amount of grass biomass, with a 91% decrease compared to mowing, but the biomass of broadleaves was higher when compared to the other treatments. At 59 DAP (Figure 2.5), hot water had the lowest amount of weed control for both grasses and broadleaves. The amount of grass biomass found where hot water was performed was 3.7-fold higher when compared to cultivation and 2.8-fold higher when compared to flaming. There was four times more weeds in the hot water treatments than where flaming was used and 22-fold more when compared to cultivation. Weed biomass at the end of the season (141 DAP) showed the cumulative impact of each weed management approach (Figure 2.6). Weed biomass was collected between crop rows when management practices were implemented, and within crop rows where weed suppression was primarily a result of crop competitiveness. Both in-row and between-row results showed that grass weeds represented about 93% of the total biomass harvested late in the season, while 82% of weeds were found in the rows, showing that in-row weed biomass was not differentially affected by the control technique used. A lower amount of broadleaf biomass in the rows was found in no-till plots where hot water and mowing were performed throughout the season (figure 2.6), showing that cover crops used in organic no-till can significantly reduce weed populations when coupled with secondary between-row weed control .

When weed control treatments were performed at 9 DAP (Figure 2.7) in soybean in 2017, weed biomass was 5-fold higher in mowed plots than in the cultivated treatments. In 2017, cover crop growth before soybeans was less than in 2016 and provided less early season weed control. Cover crop biomass in 2016 was 8420 kg ha^{-1} and in 2017 was 6740 kg ha^{-1}. Flaming treatments had the highest amount of broadleaves at 9 DAP, up to 4-fold higher compared to mowing. At 54 DAP (Figure 2.8), 62% of the total grass weed biomass was in plots where the hot water treatment was used. No significant difference was seen between treatments when controlling broadleaf weeds. At 78 DAP (Figure 2.9), no differences between treatments for broadleaf weed control was found, but grass biomass in the hot water treatment was 5.8 times higher than flaming. At 87 DAP (Figure 2.10), when the last data were collected on soybeans in 2017, 65% of grasses and 83% of broadleaves were found in the rows. Grass weeds represented about 67% of the total amount of weed biomass. Cultivation and flaming had significantly less between-row grass biomass than hot water and mowing and significantly less between-row broadleaves than hot water. Mowing controlled broadleaves as well as flaming and cultivation.

In 2016, only cultivation and flaming were performed on corn at 19 DAP (Figure 2.11) with no significant differences between treatments. Because the crimped cover crop present in the hot water and mowing treatments prevented early-season weeds from emerging, secondary weed control was not needed for the first month of growth. At 33 DAP (Figure 2.12) the cover crops on no-till plots were still responsible for the low amounts of weed biomass on hot water and mowing plots. Flaming treatments showed the highest amount of grass weed biomass; 20-fold higher when compared to mowing. At 41 DAP (Figure 2.13), flaming still had the highest amount of grass weed biomass, up to 70-fold higher when compared to mowing. At 54 DAP (Figure 2.14) weed control treatments were performed only on hot water and mowing plots because few between-row weeds had grown in cultivation and flaming treatments since the previous treatments were performed. At 133 DAP (Figure 2.15) grass weeds represented about 82% of the total weed biomass collected, with 61% of the total grass biomass present in the crop rows. At the end of the season in 2016, no-till treatments using hot water and mowing as secondary weed control controlled more between-row grasses than cultivation or flaming in corn. Flaming and hot water had greater in-row grass biomass than cultivation and mowing while in-row and between-row broadleaves were not significantly different between treatments.

In 2017 corn plots, cultivation had the highest grass biomass at 18 DAP, 3.5-fold higher when compared to hot water, while no difference was found on broadleaves across treatments (Figure 2.16). At 30 DAP there were no significant differences between treatments for both grass and broadleaf biomass (Figure 2.17). The final data collected at 95 DAP showed that 72% of the total weed biomass harvest was composed of grasses

(Figure 2.18). Weed biomass from in the crop rows was 75% grass and 80% broadleaves at the end of the season. Hot water had significantly higher biomass levels of between-row grasses than the other three treatments while in-row grasses and broadleaves were not significantly different between the four treatments.

Throughout both seasons, the crimped cover crop present on the no-till plots was likely responsible for in-row weed reduction because of the weed-limiting effect of a cover crop mulch (Moore et al., 1994). Cover crops such as cereal rye can suppress weeds through allelopathy, competition for resources, and suppression of germination (Clark et al., 1994; Creamer et al., 1996; Galloway and Weston, 1996). In a previous experiment using cowpea (*Vigna unguiculata)* as a cover crop, weed dry weights averaged 79% less when compared to the amount of weed dry weights collected in bare soil plots (Hutchinson and McGiffen, 2000). An experiment comparing different cover crops showed that weed biomass reduction was similar with rye and crimson clover (*Trifolium incarnatum*) treatments ranging between 19 and 95% less weed biomass than a conventional tillage treatment without cover (Yenish et al., 1996).

It was determined through a separate experiment that all of the weed control in the hot water treatments was due to the crimped cover crop rather than from the hot water. Hot water applied at the lowest tractor speed was inadequate to cause significant weed damage. These results are presented in chapter three.

Flaming performed during the mid-season on corn plots in 2016 was least effective and resulted in the highest amount of weed biomass among the treatments. Studies show that shorter weeds (up to 6 cm and 6 leaves) are easier to control with flaming than taller weeds (up to 50 cm tall, with 7 or more leaves) (Datta and Knezevic, 2013). Since taller weeds that are more tolerant to flaming are more common during the middle of the growing season, (Ulloa et al., 2010), flaming showed less efficacy in controlling these weeds. Additionally, grasses are more difficult to control with flaming than broadleaf species (Ulloa et al., 2010) because of the physical position of the grass growing point below soil surfaceat the time of flaming (Knezevic and Ulloa, 2007). Recent research shows that applying banded flaming followed by cultivation can provide over 90% weed control, while the use of flaming alone conducted twice as the same operation can provide about 88% weed control at the V3 and V6 corn growth stages (Stepanovic et al., 2016).

Crop yield

The cumulative impact of weeds on crop yield varied between treatments and years (Table 2.2). In 2016, weed control treatments performed on corn resulted in no significant differences in yields. Flaming treatments resulted in significantly lower yields in soybean because flaming was performed as needed throughout the season until canopy closure, damaging the soybeans and reducing yields. Previous research showed that flaming can be performed on soybeans only between VE-VC and V4-V5 growth stages without yield reductions (Knezevic et al., 2012). In 2017, flaming treatments were not done on soybean until the V5 stage. At that point, most weeds had grown too large for control.

In 2017, between-row mowing and hot water applications on corn had significantly higher yields compared to cultivation and flaming treatments. It was observed that the cover crop residue in the no-till plots reduced early season in-row weeds, likely contributing to improved yields. The lowest soybean yield in 2017 was with the hot water treatments. Cultivation and flaming treatments had the highest soybean yields in 2017 (Table 2.2). Mowing was only conducted three times and grasses grew significantly tall enough between treatments to affect soybean yield. More frequent mowing may lead to improved yields.

Weed seed bank

The amount of weed seeds in the soil was determined in 2016 and 2017 (Table 2.3). In 2016, common chickweed represented 17% of the total of seeds found, followed by large crabgrass (15%), giant foxtail (10%), and waterhemp (3%). Grasses represented 52% and broadleaves 48% of the total of weeds in 2016. In 2017, waterhemp seeds represented 25% of the total of seeds found, followed by giant foxtail (20%) and yellow foxtail (18%). In 2017, the soil seed bank consisted of 47% broadleaves and 53% grasses.

Conclusions

The cover crops used in this study provided residues that were effective in the no-till treatments to significantly suppress weeds of both early season and in-row weeds. There are viable alternatives to cultivation for organic weed management, such as mowing and flaming, but improvements in weed control may be possible by integrating these techniques with cover crops to optimize efficacy. Flaming works well as weed control in organic corn production but may damage soybean plants when flaming is applied directly to soybean leaves after the cotyledon stage. Hot water will not be effective until spray rates are better adjusted and equipment design is improved. Between-row mowing coupled with a cover crop controlled broadleaves and in-row grasses as well as flaming and cultivation in both corn and soybean. Future research should focus on controlling weeds in the rows to reduce crop competition and increase yields.

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	2016		2017	
Weed Treatment	Corn	Soybean	Corn	Soybean
Cultivation	24-May, 7-Jun, 14-Jun	1-Jun, 7-Jun, 29-Jun, 11-Jul	Jun-16, June-28	11- Jun, 30-Jul, 24-Aug
Flaming	23-May, 7-Jun, 14-Jun	1-Jun, 7-Jun, 16-Jun, 29-Jun, 11-Jul	Jun-16, June-28	11- Jun, 30-Jul, 24- Aug
Hot water	29-Jun	29-Jun, 21-Jul	Jun-16, June-28	11- Jun, 30-Jul, 24- Aug
Mowing	14-Jun, 29-Jun, 8-Jul	14-Jun, 29-Jun, 8-Jul, 26-Jul	Jun-16, June-28	11- Jun, 30-Jul, 24- Aug

Table 2.1. List of weed control treatments for two-year organic soybean and corn trials in central Missouri.

Table 2.2. Mean yield of organic corn and soybean from 2016-2017 as impacted by weed management practices. Values followed by a different lowercase letter within each column are significantly different (using Fisher's protected LSD) at α=0.05.

	2016		2017	
Weed Treatment	Corn ($kg.ha^{-1}$)	Soybean ($kg.ha^{-1}$)	Corn ($kg.ha^{-1}$)	Soybean ($kg.ha^{-1}$)
Cultivation	7,351.6 ns	1,637.5 ab	5,767.9 bc	2,690.0 a
Flaming	6,642.9 ns	1,121.7 b	4,642.5 c	2,421.0 ab
Hot water	6,685.0 ns	1,759.3 a	7,016.4 ab	1,759.3 c
Mowing	7,442.6 ns	2,148.6 a	8,117.4 a	2,255.6 b

Table 2.3. Mean of weed seeds found (number.ha^{-1}) found in soil from the research area in 2015 and 2016 prior the cover crop planting.

	2015	2016
Weed species	Number. ha^{-1}	Number. ha^{-1}
Barnyardgrass (*Echinochloa crus-galli* (L.) Beauv)	37,345	-
Common chickweed (*Stellaria media* (L.) Vill)	165,815	67,222
Common purslane (*Portulaca oleracea* L.)	-	44,815
Common sunflower (*Helianthus annuus* L.)	-	22,407
Downy brome (*Bromus tectorum* L.)	22,407	-
Fall panicum (*Panicum dichotomiflorum* Michx)	59,753	-
Field pennycress (*Thlaspi arvense* L.)	67,222	
Giant foxtail (*Setaria faberi* Herrm)	101,852	96,032
Large crabgrass (*Digitaria sanguinalis* (L.) Scop.)	146,667	61,620
Pennsylvania smartweed (*Polygonum pensylvanicum* L.)	131,243	-
Shattercane (*Sorghum bicolor* (L.) Moench.)	-	22,407
Smooth crabgrass (*Digitaria ischaemum* (Schreb. ex Schweig.)	116,519	-
Waterhemp (*Amaranthus rudis* Sauer.)	30,810	141,339
Wild cucumber (*Echinocystis lobata* Michx.)	22,407	-
Yellow foxtail (*Setaria glauca* L.)	22,407	112,037
Yellow wood sorrel (*Oxalis stricta* L.)	56,019	-

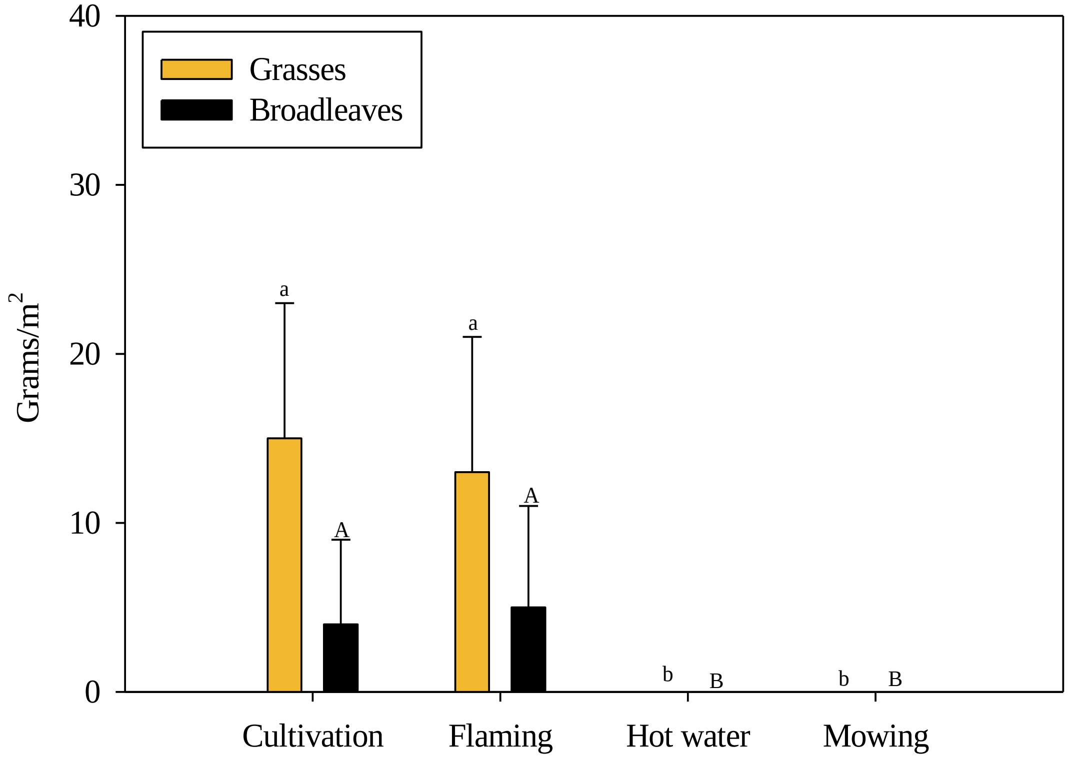

Figure 2.1. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in soybean (between-row) in response to cultivation, flaming, hot water and mowing at 18 days after planting in 2016. Means within plant type with the same upper case or lower case letters are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

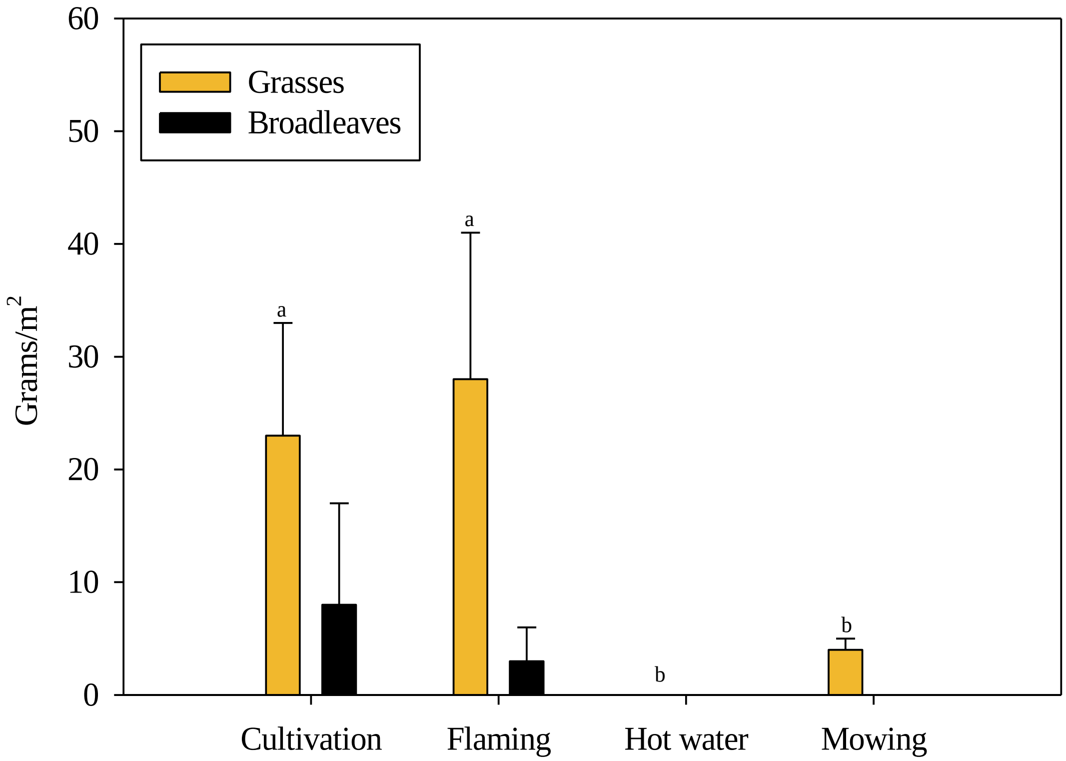

Figure 2.2. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in soybean (between-row) in response to cultivation, flaming, hot water and mowing at 25 days after planting in 2016. Means within plant type with the same letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

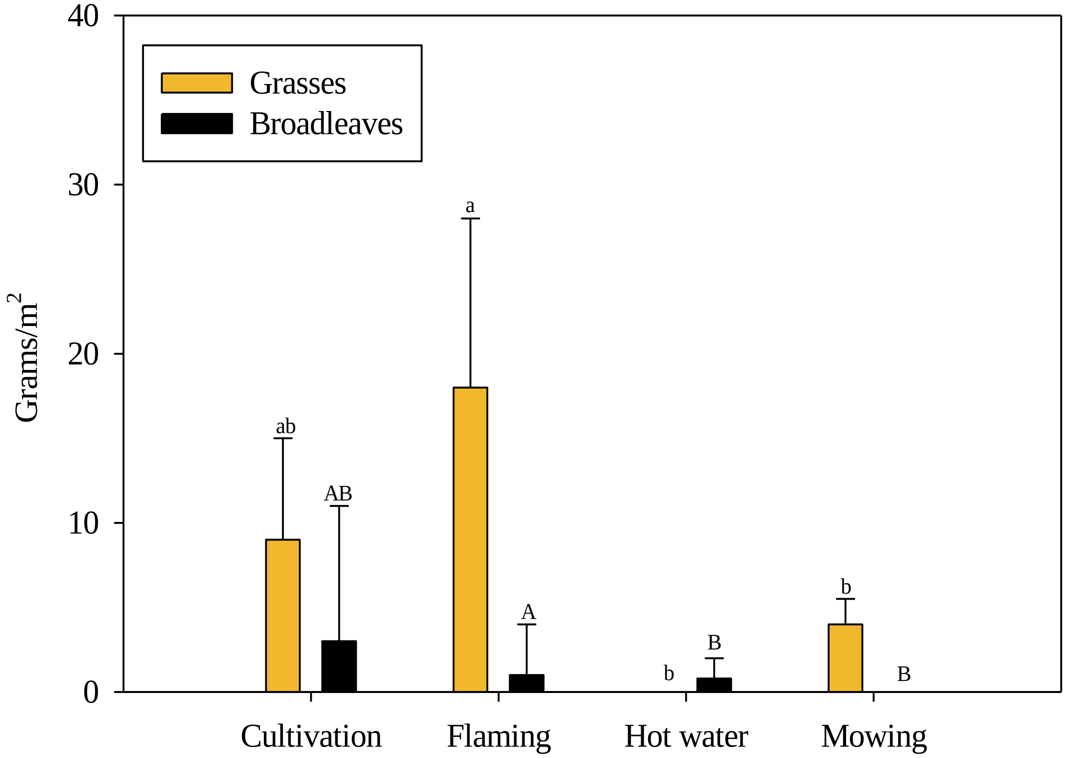

Figure 2.3. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in soybean (between-row) in response to cultivation, flaming, hot water and mowing at 32 days after planting in 2016. Means within plant type with the same lower case or upper case letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

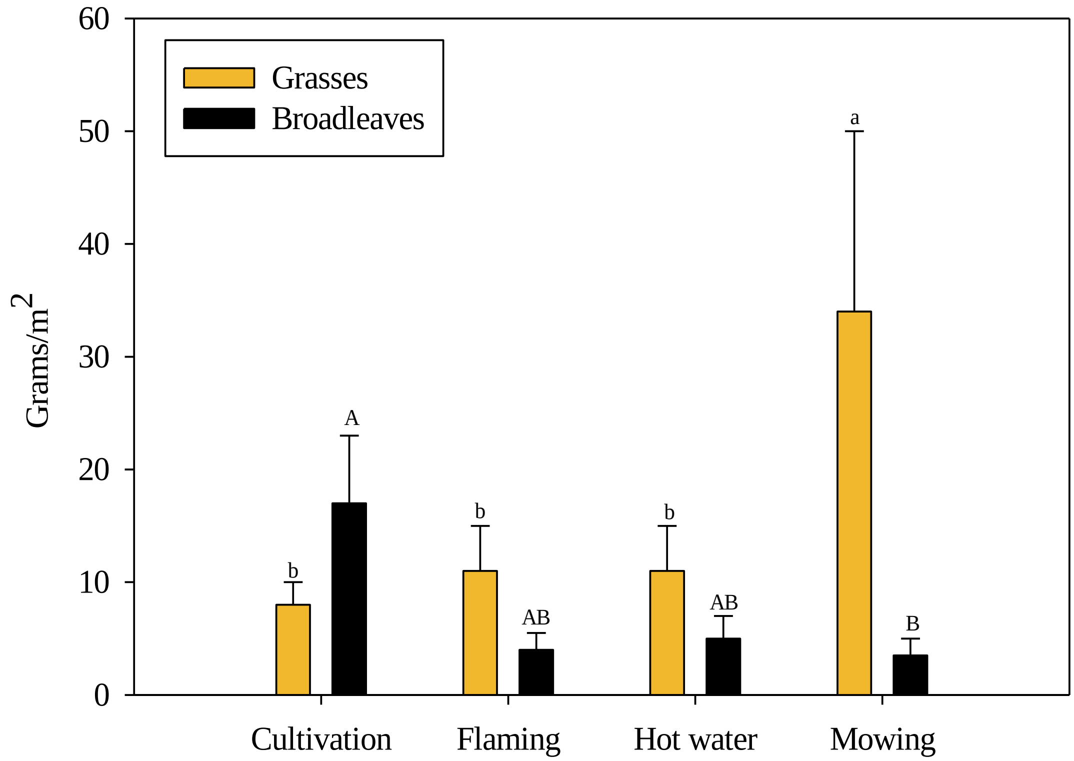

Figure 2.4. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in soybean (between-row) in response to cultivation, flaming, hot water and mowing at 46 days after planting in 2016. Means within plant type with the same lower case or upper case letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

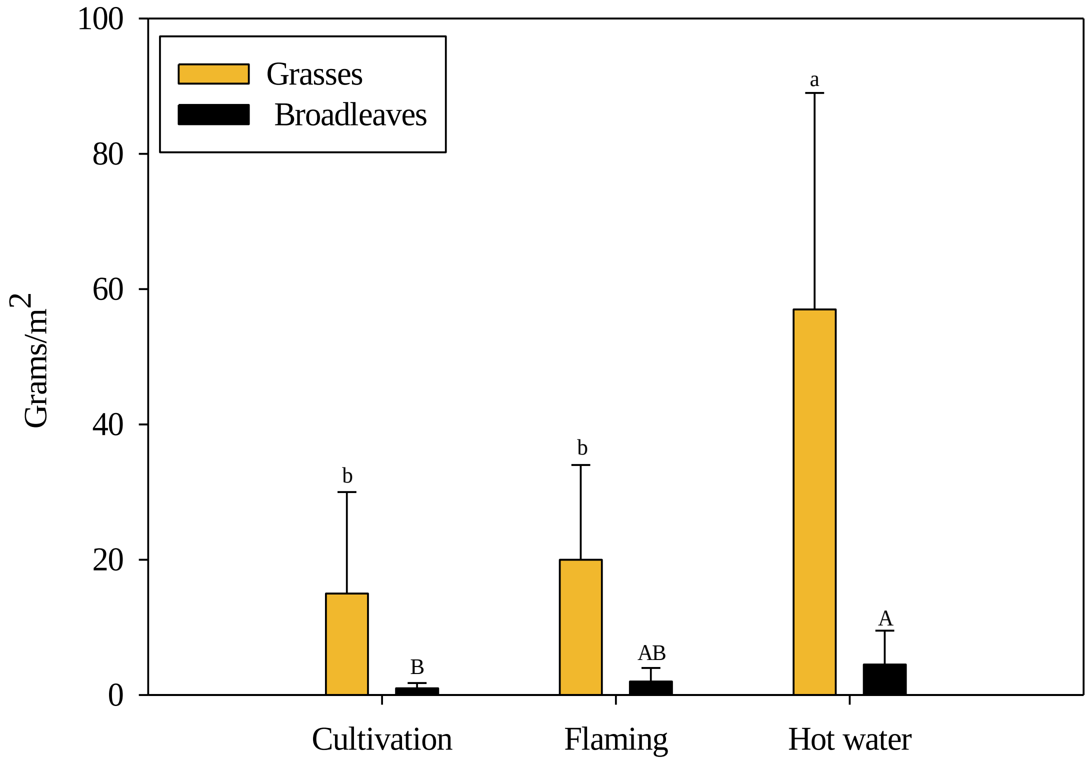

Figure 2.5. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in soybean (between-row) in response to cultivation, flaming and hot water at 59 days after planting in 2016. Means within plant type with the same lower case or upper case letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

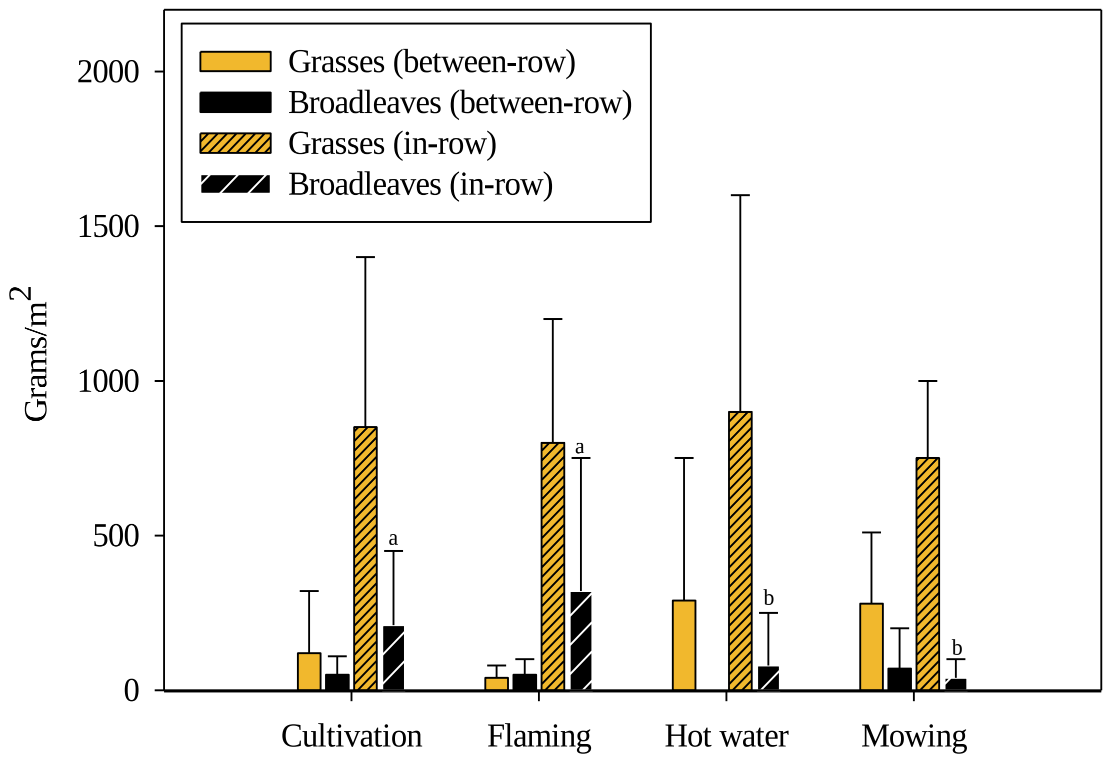

Figure 2.6. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in soybean (between-row and in-row) in response to cultivation, flaming, hot water and mowing at 141 days after planting in 2016. Means within plant type with the same letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

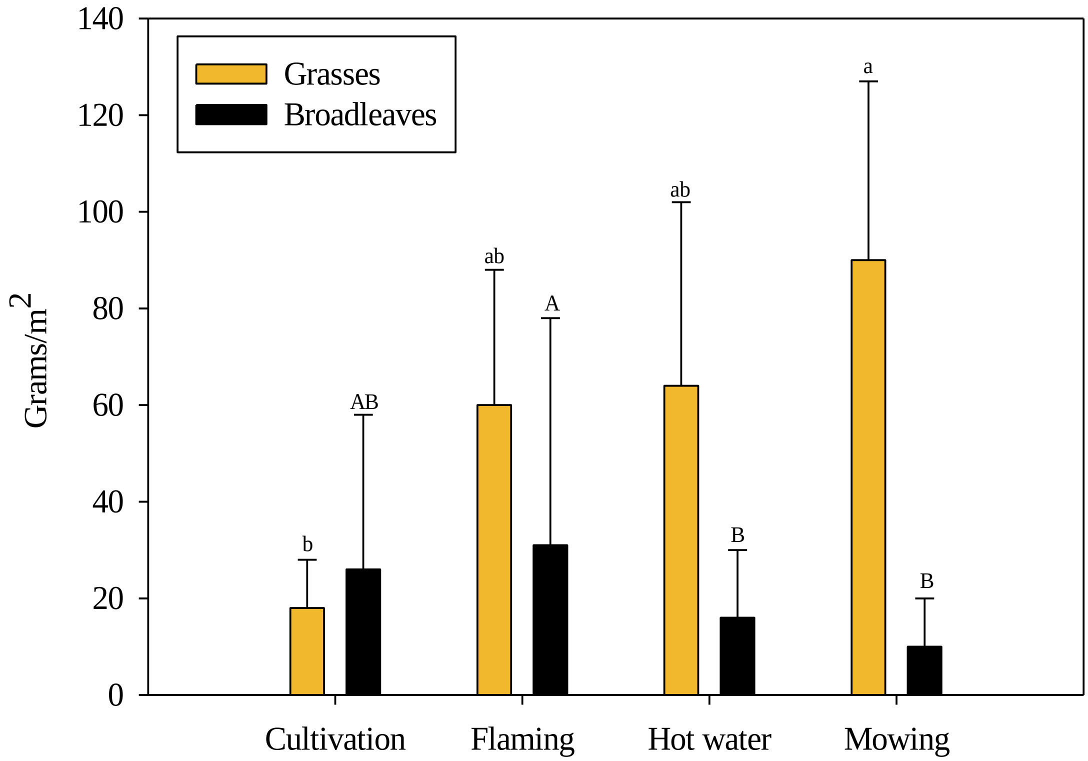

Figure 2.7. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in soybean (between-row and in-row) in response to cultivation, flaming, hot water and mowing at 9 days after planting in 2017. Means within plant type with the same lower case or upper case letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

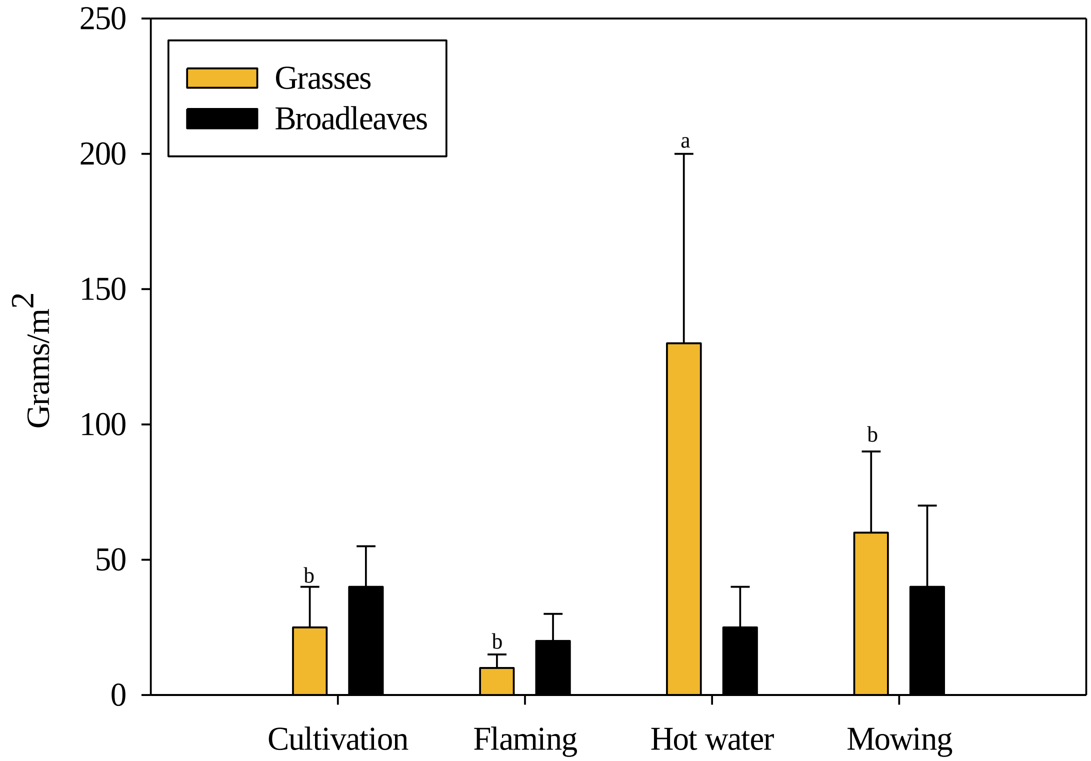

Figure 2.8. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in soybean (between-row and in-row) in response to cultivation, flaming, hot water and mowing at 54 days after planting in 2017. Means within plant type with the same letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

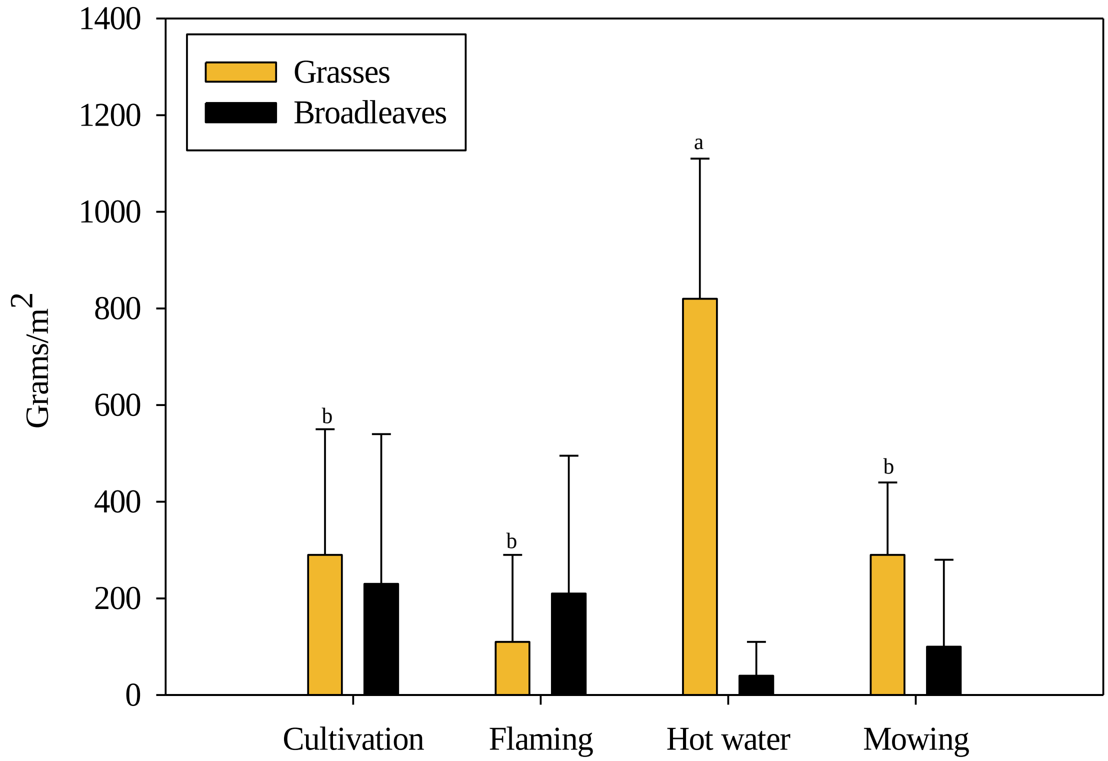

Figure 2.9. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in soybean (between-row and in-row) in response to cultivation, flaming, hot water and mowing at 78 days after planting in 2017. Means within plant type with the same letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation**.**

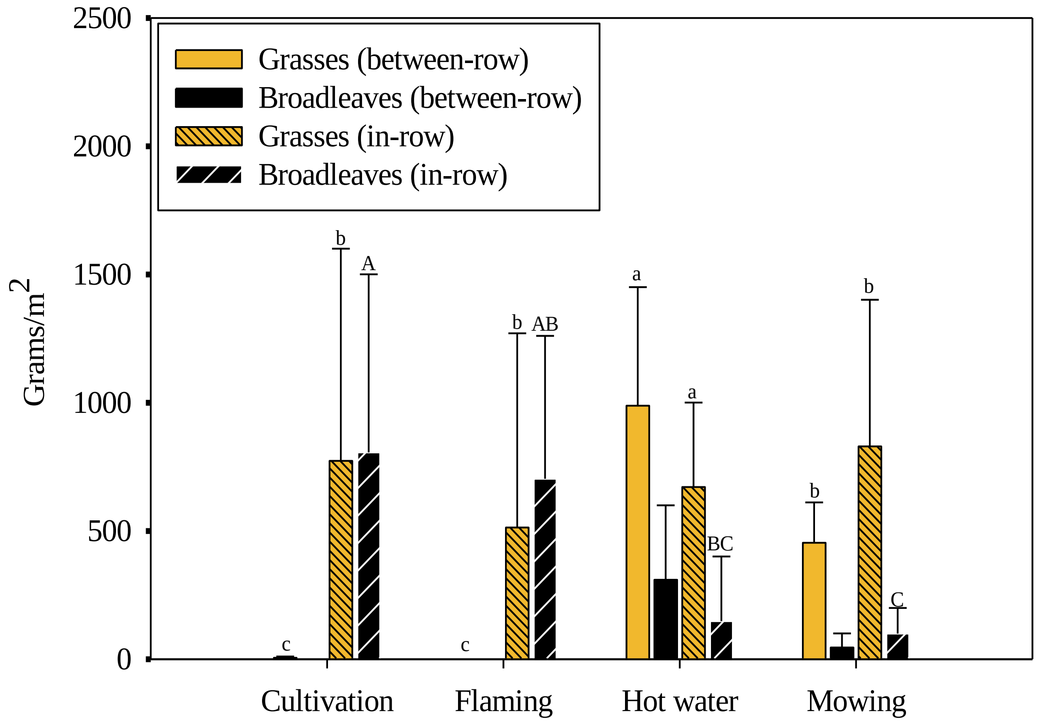

Figure 2.10. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in soybean (between-row and in-row) in response to cultivation, flaming, hot water and mowing at 87 days after planting in 2017. Means within plant type with the same lower case or upper case letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

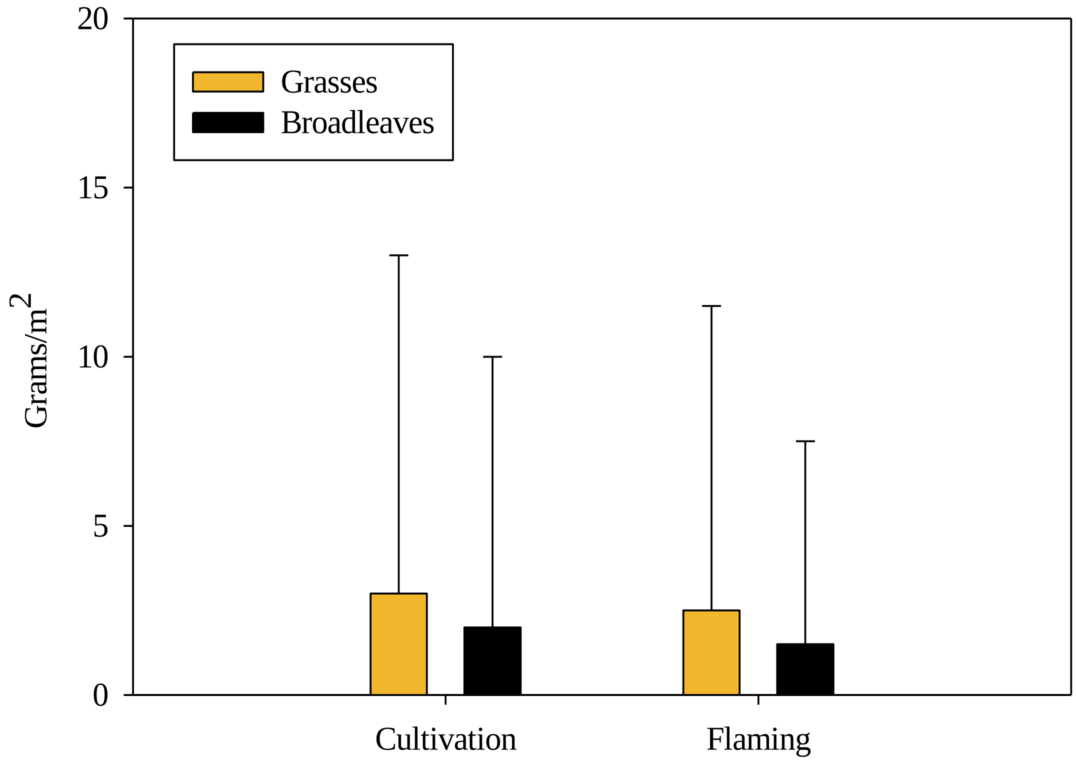

Figure 2.11. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in corn (between-row) in response to cultivation and flaming at 19 days after planting in 2016. Vertical bars indicate the standard deviation.

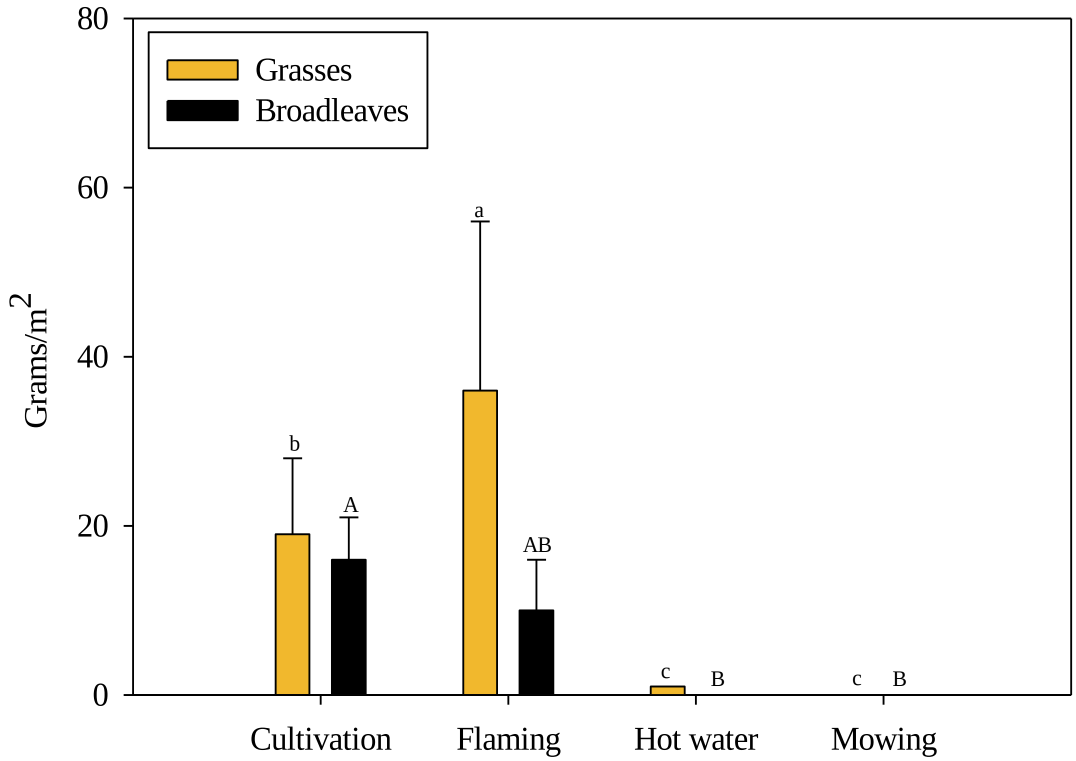

Figure 2.12. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in corn (between-row) in response to cultivation, flaming, hot water and mowing at 33 days after planting in 2016. Means within plant type with the same lower case or upper case letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

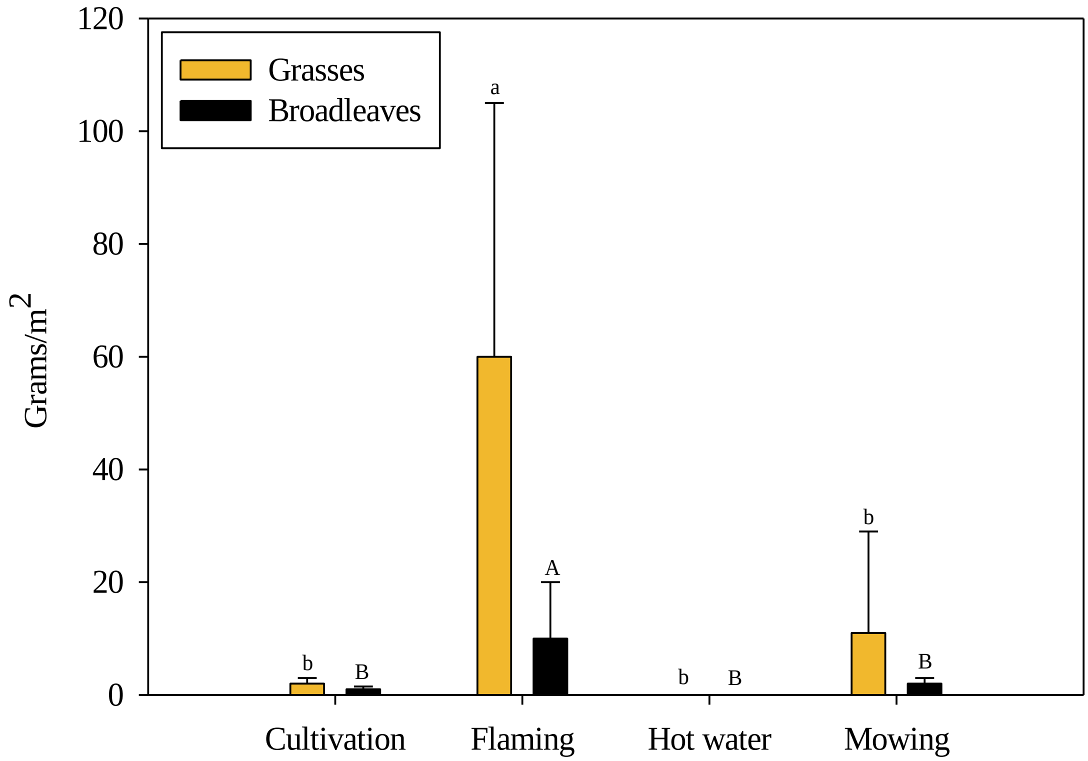

Figure 2.13. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in corn (between-row) in response to cultivation, flaming, hot water and mowing at 41 DAP in 2016. Means within plant type with the same lower case or upper case letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

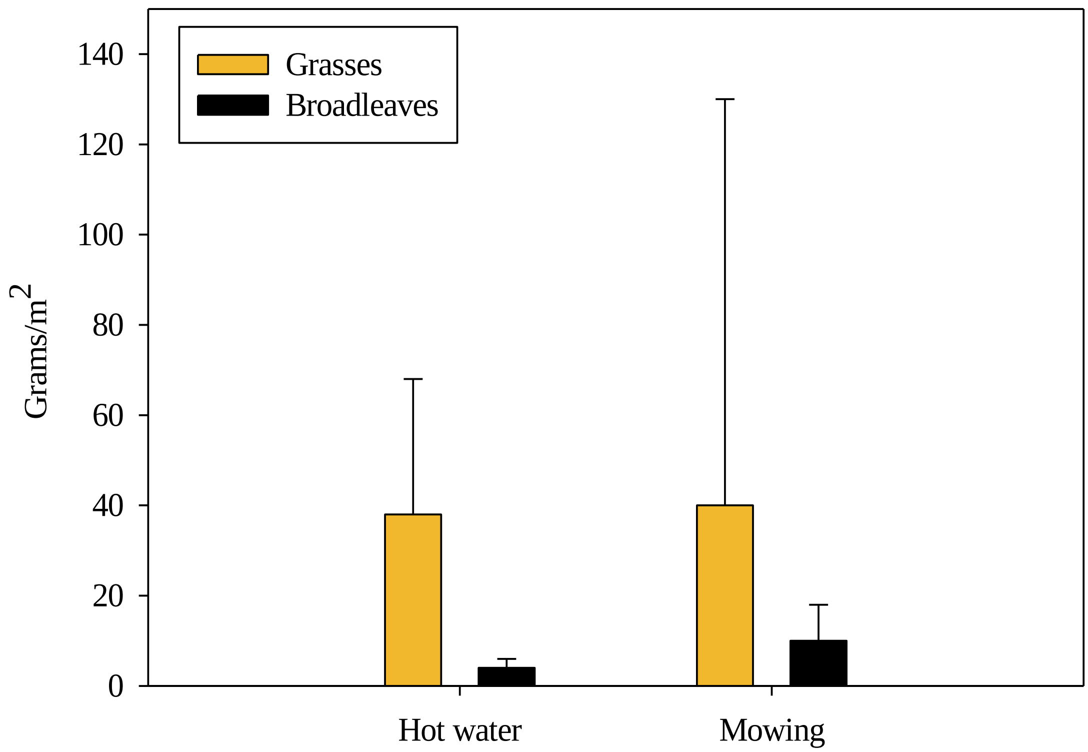

Figure 2.14. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in corn (between-row) in response to hot water and mowing at 54 days after planting in 2016. Vertical bars indicate the standard deviation.

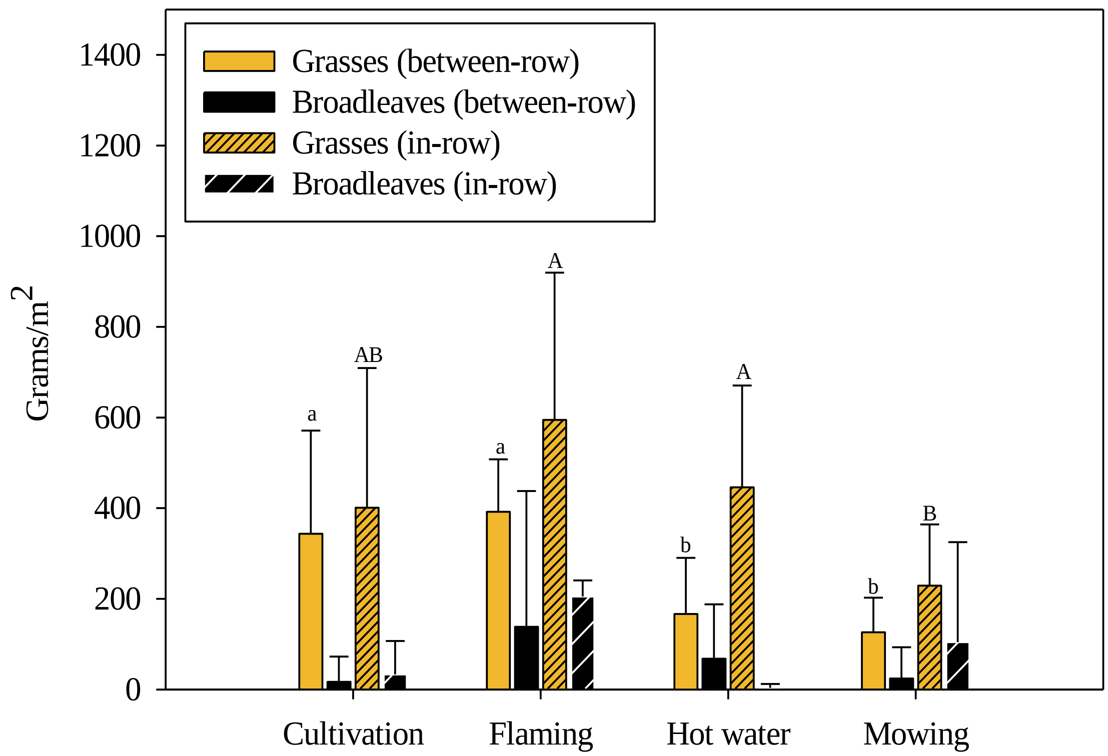

Figure 2.15. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in corn (between-row and in-row) in response to cultivation, flaming, hot water and mowing at 133 days after planting in 2016. Means within plant type with the same lower case or upper case letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

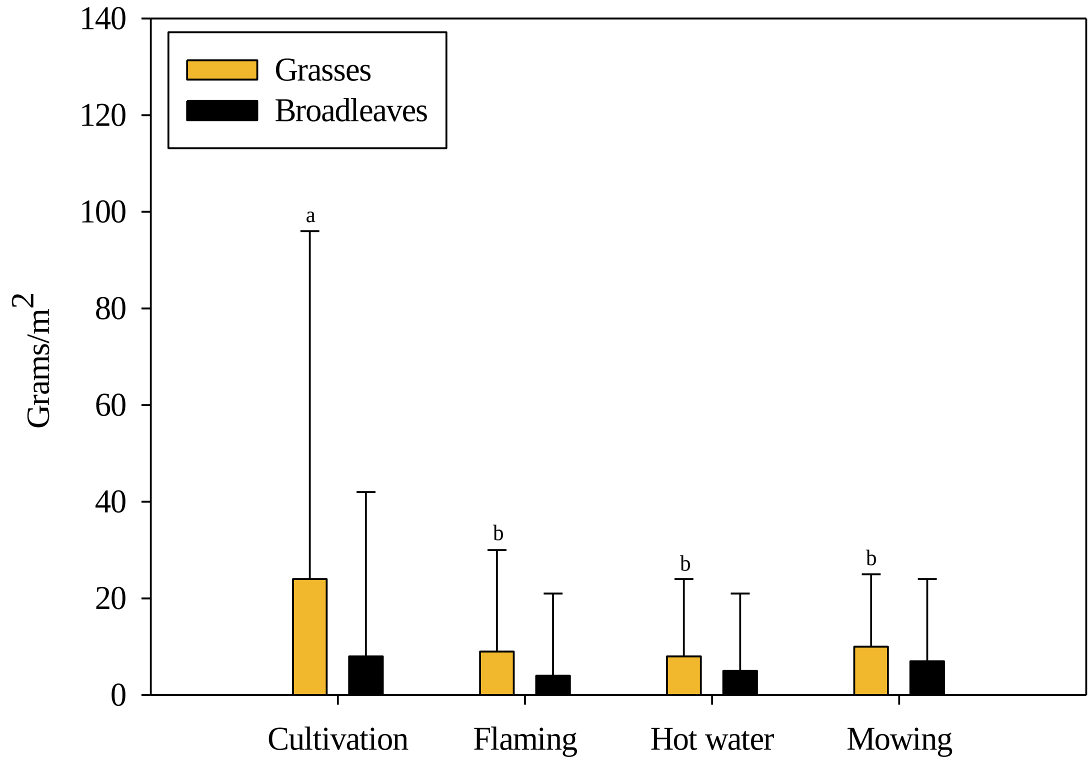

Figure 2.16. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in corn (between-row) in response to cultivation, flaming, hot water and mowing at 18 days after planting in 2017. Means within plant type with the same letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

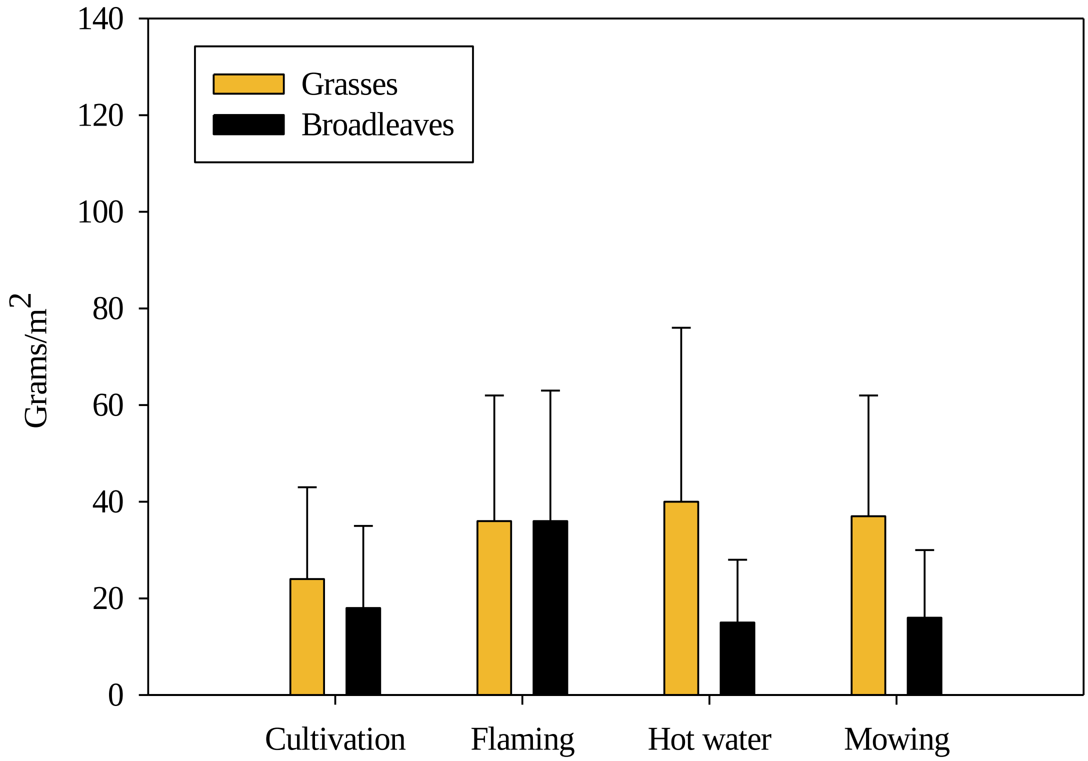

Figure 2.17.Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in corn (between-row) in response to cultivation, flaming, hot water and mowing at 30 days after planting in 2017. Vertical bars indicate the standard deviation.

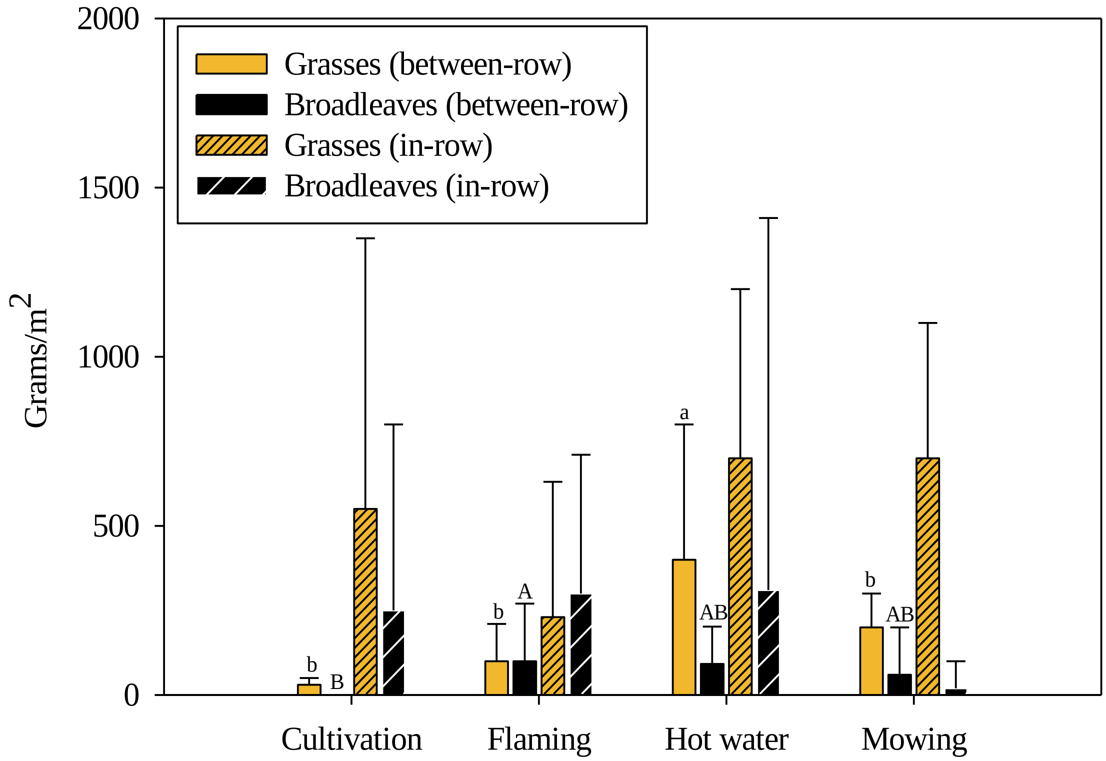

Figure 2.18. Mean weed biomass of grass and broadleaf weeds collected 1 day after treatments were performed in corn (between-row and in-row) in response to cultivation, flaming, hot water and mowing at 95 days after planting in 2017. Means within plant type with the same letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

CHAPTER III

Weed Control Using Hot Water

RICARDO COSTA SILVA, KERRY CLARK, and REID J. SMEDA

Abstract

Using hot water to control weeds in organic production can be effective but there is a lack of information regarding basic functionality of this technique. The goal of this research was to estimate the amount of time (seconds) and water volume required (L/ha^{-1}) to effectively control small broadleaf and grass weeds. In central Missouri, an area was prepared with a field cultivator to control existing weeds and to allow new ones to germinate. The experimental design was a randomized complete block with five repetitions and 11 treatments of five second intervals ranging from 0 to 45 seconds of exposure time. Plot size was 1.5 x 1.8 m and a 0.09 m^2 quadratic frame was used to collect weed biomass and to rate percentage of injury in each plot. A custom built hot water sprayer was used to spray weeds up to 13 cm in height. This study was repeated at five different times in the same area during the summer of 2017. Results showed that greater than 84% of grass weeds and 93% of broadleaf weeds were controlled when hot water was applied for at least five seconds at the rate of 6,235 L/ha^{-1}. At this application rate, grass weed biomass was reduced about 88%, while broadleaf weed biomass was reduced approximately 95% when compared to the control treatment of no hot water application. Hot water can be an alternative for weed control in small areas with high value crops.

Keywords: thermal method, organic weed control, organic crop production .

Introduction

Although controlling weeds in organic crop production systems is cited by farmers as their greatest challenge (Place et al., 2009) and despite the fact that higher amounts of weeds are found in organic fields when compared to conventional fields (Hyvönen et al., 2003), relatively little research has focused on organic weed management compared to conventional crop production (Bàrberi, 2002).

Tillage is used as an important tool to control weeds, but it also can increase the loss of nutrients in the soil through erosion and organic carbon mineralization (Lal, 2004; Soane et al., 2012). Since physical, chemical, and biological soil properties are greatly influenced by tillage (Gilley and Doran, 1997) it is necessary to find alternative techniques to control weeds that cause less soil disturbance. Thermal weed control practices such as flaming and hot water application can become useful tools for weed control in organic production (Hansson and Ascard, 2002).

An alternative to tillage for weed control is the use of heat to burn off undesirable vegetation. Flaming combustible using liquids or gases was used on railroad rights-of-way, however, the risk of fire was too high to sustain this method (Berling, 1992). A safe alternative is heating water and direct application on weeds. Since hot water weed control eliminates the risk of fire hazards, it can be an alternative to flame weeding in areas where its use is not suitable (Hansson and Ascard, 2002). The size of the plant being controlled by hot water and environmental factors, such as drought and rain can affect the control of weeds, while air temperature has minimal influence on weed control when using hot water (Hansson and Mattsson, 2003).

Hot water can be an alternative to tillage for weed control on small areas, but since the equipment requires large amounts of water and energy, may not be practical when performing on large scale operations. Hot water can be detrimental to beneficial soil microorganisms and insects at the time of the application, but on the other hand may control some pathogens and nematodes (Ascard et al., 2007; Hansson and Mattsson, 2002).

A previous study comparing energy-dose with water flow showed that at a low-energy dose (455 kJ m^{-2}), treatment with a higher water flow (1.7 l min^{-1} per nozzle) can significantly decrease white mustard (*Sinapis alba* L.) fresh weight compared to lower water flow (1.2 l min^{-1} per nozzle). On the other hand, there was no significant effect of different water flows at the high-energy (755 kJ m^{-2}) dose (Hansson and Mattsson, 2002).

The practice of using hot water for weed control can impact existing vegetation as well as seeds. The injuries caused by heat can be reversible at the initial stages, while accumulated heat can cause thermal death as a result of denaturation of proteins and denaturation of the lipids of the plant cells (Daniell et al., 1969). Steaming the soil prior to planting to a soil depth of 2.5 cm for 6-9 minutes raises the temperature to more than 70^{o} C, which can kill viable weeds seeds. Weed species, such as groundsel (*Senecio vulgaris* L.), common chickweed (*Stellaria media* L.) and annual bluegrass (*Poa annua* L.), showed up to 70% of plant biomass reduction lasting for as long as 4 months after the treatment was performed (Boedker and Noye, 1994). Heating is effective to control viable weed seeds when using mulching and compost since most viable weed seeds can lose germination capacity when temperatures reach approximately 60^{o} C. (Davies et al., 1993; Grundy et al., 1998). At 57^{o} C and higher, 90% of the leaves of soybean (*Glycine* *max* (L.) Merr.) and *Elodea* ssp. showed signs of cell death, such as bleached chloroplasts and irreversible plasmolysis (Daniell et al., 1969).

Efficacy of hot water application is dependent on the stage of the plant when treated. Three times more energy was required to control white mustard at the six-leaf stage when compared to application at the two-leaf stage (Hansson and Mattsson, 2002). Hot water should not be applied during rain or when plants are wet to avoid energy losses. The use of insulated shields with nozzles and coarse droplets can prolong the time of exposure and improve weed control effect up to about 30% when compared to fine droplets (Hansson and Ascard, 2002).

There is a lack of information on the amount of time and water volume necessary to effectively control small grasses and broadleaves in agricultural areas. The goal of this study was to estimate the amount of time (seconds) and water volume required to effectively control broadleaf and grass weeds in conventional tilled areas.

Material and methods

The field study was conducted at Bradford Research and Extension Center, a University of Missouri research farm located in Columbia, MO (38.8929 O N, 92.2010 O W). The predominant soil series at the research site is a Mexico silt loam (pH of 6.7 with 3.8 % organic matter). Prior to initializing treatments, a field cultivator was used to remove existing weeds and facilitate germination of new weeds.

The experimental design was a randomized complete block with five repetitions and 11 treatments. Individual plot size was 1.5x1.8 m. A custom built machine (Figure 3.1) with a hot water sprayer (Largo Industries, Decaturville, TN) was mounted on a three-point hitch behind the tractor. To eliminate calcium buildup, the water input was routed through a filter (Pentair®) and water softener (Morton®) then into a 227 L water storage tank. From the tank, the water was piped to a diesel-powered heater (hot water high-pressure sprayer modified for this use) and then through high-pressure lines and a spray boom that has three hooded units with two nozzles in each hood (Teejet® 6508 and 200 Mesh Brass TeeJet® Tip Strainer). The size of each hood was 1.02 by 0.55 m and the machine was designed to apply a topical spray of water at 150°C at a rate of 765 liters/hour onto the weed leaf surface.

This study was repeated at five different times during the summer of 2017. All treatments were carried out when the air temperature ranged between 25 to 30 °C and the plant foliage was dry. Treatments consisted of time of exposure of plants to hot water spray and included: 0 seconds (untreated control); 1.3 seconds (1,647 L/ha^{-1}); which is equivalent of the speed of the lowest gear on the tractor (John Deere 6410, Moline, IL);5 seconds (6,235 L/ha^{-1}); 10 seconds (12,529 L/ha^{-1}); 15 seconds (18,765 L/ha^{-1}); 20 seconds (25,000 L/ha^{-1}); 25 seconds (31,23510 L/ha^{-1}); 30 seconds (37,529 L/ha^{-1}); 35 seconds (43,765 L/ha^{-1}); 40 seconds (50,000 L/ha^{-1}) and 45 seconds (56,235 L/ha^{-1}) (Table 3.1). Application of hot water on target weed species was designed to optimize coverage. During hot water application, the hoods were 3.8 cm above the ground and the spray nozzles were 30.5 cm above the ground level.

Grass and broadleaf weeds were evaluated at heights from 8 to 13 cm. Damage was visually evaluated at 7 days after treatments using a rating scale of 0 (no visual damage) to 100 (plant death). At 7 days after treatment broadleaves and grasses were collected by severing shoots at the ground level from plants in a 0.09 m^2 area using a quadrant and their biomass was determined through weighing after dried at 45º C for 48 h. The grasses present were giant foxtail (*Setaria faberi* Herrm.), yellow foxtail (*S. glauca* (Poir. Roemer & J.A. Schultes.) and large crabrass (*Digitaria sanguinalis* L.) while the broadleaf weeds were common cocklebur (*Xanthium strumarium* L.), waterhemp (*Amaranthus rudis* Sauer.), common purslane (*Portulaca oleracea* L.) and carpetweed (*Mollugo verticillata* L.).

Data were analyzed using proc mixed in SAS (Enterprise Guide 9.4 statistical software SAS Inst., 2013). Treatment and replication were considered random effects whereas weed type was considered fixed effect in the model. Mean separation was carried out using Fisher's least significant difference (LSD). Statistical significance was at $P \leq 0.05$.

Results and discussion

Hot water application at five seconds and greater resulted in rapid development of plant injury. The control treatment where no hot water was applied had the highest biomass of grass weeds compared to the other treatments (Figure 3.2). An application volume of 1,647 L/ha^{-1} at 1.3 sec, used in the experiment, showed 19% injury in grasses (Table 3.2), and a 60% reduction of grass biomass when compared to control treatments (Figure 3.2). An application volume of 6,235 L/ha^{-1} at 5 sec injured 84% of grass (Table 3.2), and showed no significant differences when compared to treatments ranging from 6,235 L/ha^{-1} to 56,235 L/ha^{-1} of hot water applied. Grass biomass was decreased 88% when compared to the control treatment. Hot water applied at the volumes ranging from 6,235 L/ha^{-1} to 56,235 L/ha^{-1}, showed grasses injury levels varying between 82 and 100% with no significant differences in results (Table 3.2). Hot water can effectively control grasses up to 13 centimeters if applied at a rate of 6,235 L/ha^{-1}. These results confirm previous research showing that longer exposure time and higher water flow may increase weed control effects of hot water application (Hansson and Mattsson, 2002). Hot water application had little to no effect on yellow nutsedge (*Cyperus esculentus* L.).

In broadleaves, an application volume of 1,647 L/ha^{-1} caused 17% injury (Table 3.3), and a 60% reduction in broadleaf biomass when compared to the control treatment (Figure 3.3). Application rates ranging from 6,235 to 56,235 L/ha^{-1} led to greater than 90% injury in broadleaves and up to 95% biomass reduction when compared to the control treatment. Hot water can effectively control broadleaves up to 13 cm if applied for 5 seconds at a rate of 6,235 L/ha^{-1}.

These results show that the broadleaf weeds present at this site were more susceptible than grasses to hot water spray at 6,235 and 12,529 L/ha^{-1} application rates. In general, monocotyledonous weeds are more resistant than dicotyledonous weeds to thermal treatment (Parish, 1990). This tolerance depends mainly on the location of the growth meristems; but other factors, such as leaf and stem trichome structures and the level of moisture content increase the heat tolerance of grassy weeds when compared to small broadleaves (Lalor and Buchele, 1970).

Future experiments should focus on testing the amount of time between 1.3 and 5 seconds needed to attain adequate weed control to determine the possibility of reducing the amount of water applied without decreasing the level of control. Modifications to the sprayer should be attempted to determine if different spray nozzles or the height of the nozzles might affect the water volume needed for adequate weed control. Additionally, temperature of the water exiting the spray nozzles as it contacts the leaf surface needs to be determined. Currently, water temperature is heated to150º C in the diesel-powered heater but considerable heat loss may occur as the water travels to the spray nozzles.

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Table 3.1. Hot water applied (L/ha^{-1}) for each time of exposure (treatment) of plants to hot water.

Time	Volume (milliliters)	Rate (L/ha^{-1})
0	0	0
1.3	278	1,647
5	1,060	6,235
10	2,130	12,529
15	3,190	18,765
20	4,250	25,000
25	5,310	31,235
30	6,380	37,529
35	7,440	43,765
40	8,500	50,000
45	9,560	56,235

Table 3.2. Visual control of grasses s at 7 DAP at Columbia, MO in 2017. A rating of 0% indicated no weed control and a rating of 100% indicated complete weed control. Means within injury level (%) with the same letter are not significantly different using Fisher's Protected LSD at p=0.05.

Time (seconds)	Rate (L/ha^{-1})	Injury level (%)
0	0	0 a
1.3	1,647	19 b
5	6,235	84 c
10	12,529	82 c
15	18,765	91 c
20	25,000	92 c
25	31,235	88 c
30	37,529	87 c
35	43,765	88 c
40	50,000	94 c
45	56,235	100 c

Table 3.3. Visual control of broadleaves at 7 DAP at Columbia, MO in 2017. A rating of 0% indicated no weed control and a rating of 100% indicated complete weed control Means within injury level (%) with the same letter same letter are not significantly different using Fisher's Protected LSD at p=0.05.

Time (seconds)	Rate (L/ha^{-1})	Injury level (%)
0	0	4 a
1.3	1,647	17 b
5	6,235	93 c
10	12,529	93 c
15	18,765	95 c
20	25,000	96 c
25	31,235	92 c
30	37,529	94 c
35	43,765	97 c
40	50,000	95 c
45	56,235	96 c


Figure 3.1. Hot water sprayer

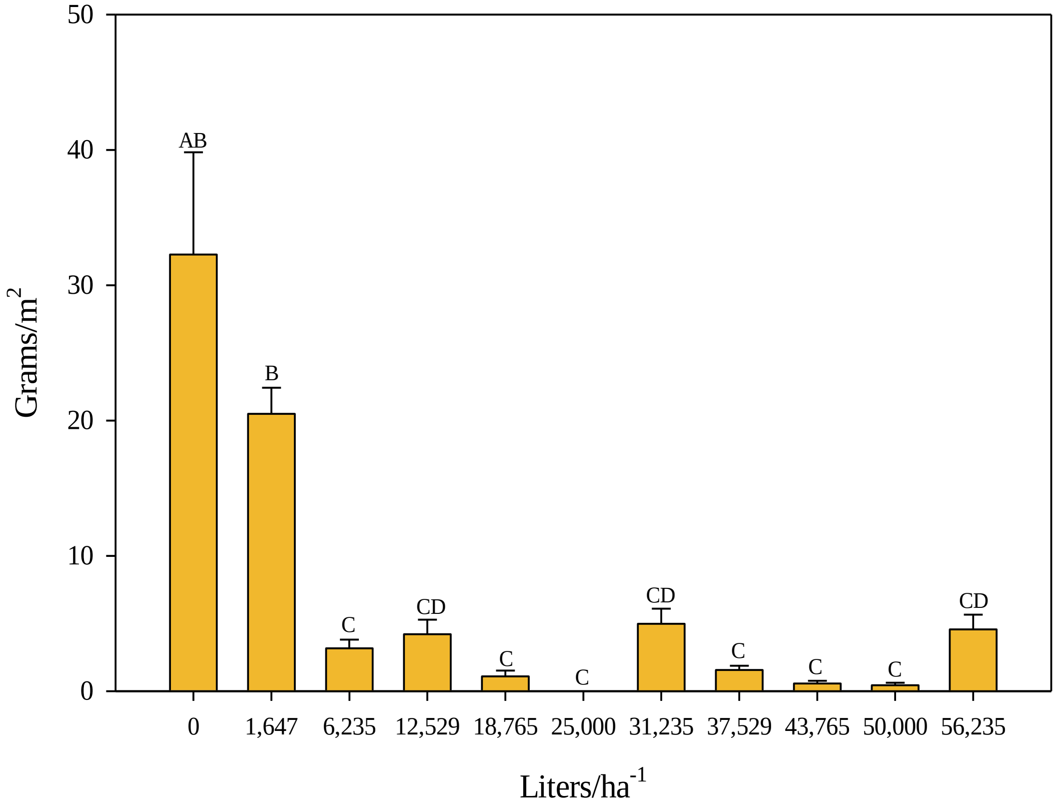

Figure 3.2. Biomass of grasses in response to hot water at 7 days after treatment (DAT). Means within treatment with the same letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.

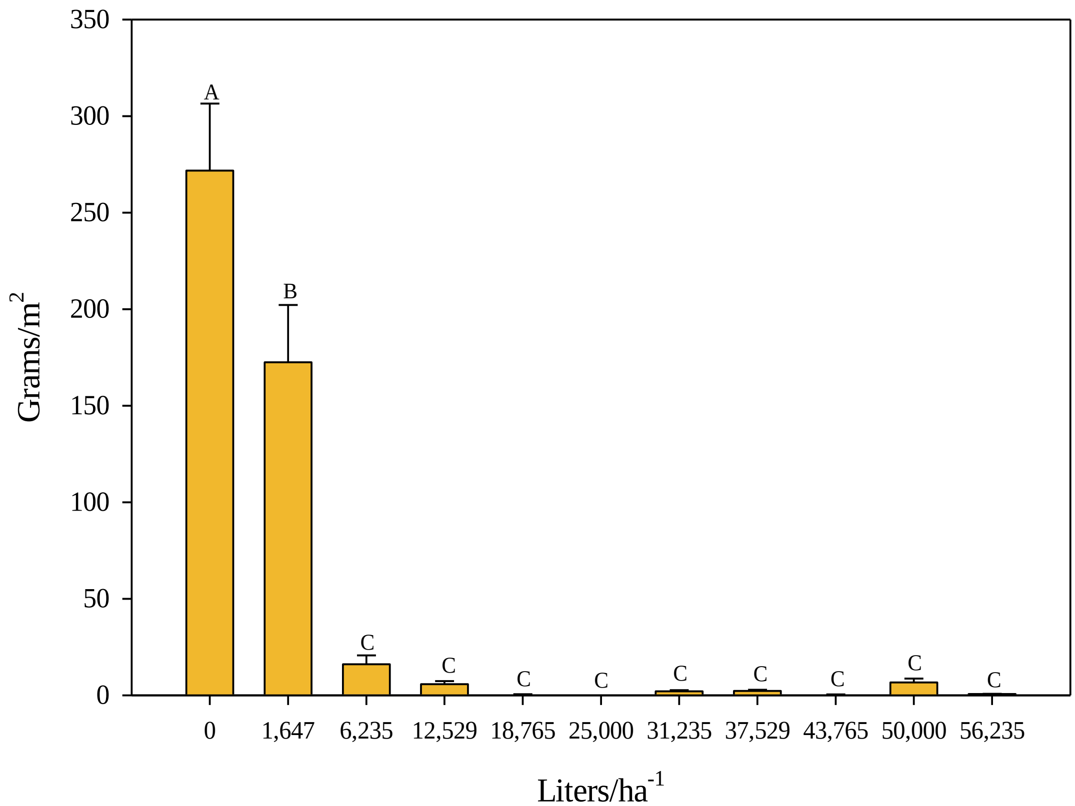

Figure 3.3 Biomass of broadleaves in response to hot water at 7 days after treatment (DAT). Means within treatment with the same letter are not significantly different using Fisher's Protected LSD at p=0.05. Vertical bars indicate the standard deviation.