Propane-Fueled Flame Weeding in Corn, Soybean, and Sunflower

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Executive Summary

Propane-fueled flame weeding provides multiple advantages over chemical and mechanical weed management methods and is effective in both conventional and organic crop production systems. During flame weeding, propane-fueled burners expose weed plant tissues to high levels of heat that rapidly change the internal temperature of plant cells and cause plant cells to rupture. The resulting loss of water and denaturing of proteins drastically reduce the weed's ability to survive, which then kills the plant. Because propane is nontoxic and does not contaminate ground water, it is an acceptable non-chemical weed control option in organic production and can be used in other locations where herbicide use is undesirable, such as in cities, parks, and other urban settings.

To provide a comprehensive overview of propane-fueled flame weeding, this guide consists of the following chapters:

1. **Background: The Need for Alternative Weed Control Methods**
2. **Introduction to Propane-Fueled Flame Weeding**
3. **How Propane-Fueled Flame Weeding Works**
4. **Flame Weeding Equipment Components and Configurations**
5. **Recommended Propane Dosage at Different Weed Growth Stages**
6. **Crop Tolerance To Post-Emergent Flame Weeding**

Key Tips for Propane-Fueled Flame Weeding

- ❍ Apply 10–12 gallons of propane per acre when using non-selective broadcast flame weeding to treat the entire crop row.
- ❍ Apply 4–5 gallons of propane per acre when using banded flame weeding (12-inch band flamed over the crop row). Lower propane doses can be effective when using a custom-designed hood.
- ❍ Limit post-emergence flame weeding application to two flaming operations per season on a single crop.
- ❍ Wait at least one hour after rain or heavy dew before conducting flame weeding treatment.
- ❍ Treat broadleaf weeds at earlier growth stages (i.e., heights of 1–3 inches, typically with one to six leaves) to reduce the required propane dosage for effective treatment.
- ❍ Improve the effectiveness of grass species control by performing a second flame weeding treatment within 7–10 days of the first treatment.
- ❍ Conduct aggressive cultivation within a few hours of flaming to achieve significant grass control. To do so, adjust the cultivator shanks so they push soil on top of the flamed grass, burying it.

1. Background: The Need for Alternative Weed Control Methods

1.1. Principles of Integrated Weed Management

Integrated Weed Management combines various preventative, cultural, genetic, mechanical, biological, and chemical weed control practices into a single program. While no single control measure is likely to provide complete weed control, the systematic implementation of the various components of integrated weed management can make significant contributions to weed control efforts.

An integrated weed management approach advocates the use of all available weed control options, including the following:

- Selection of a well adapted crop variety or hybrid with good early season vigor and appropriate disease and pest resistance (i.e., plant breeding).
- Appropriate planting patterns and optimal plant density.
- Precise timing, strategic placement, and appropriate quantity of nutrient application.
- Appropriate crop rotation, tillage practices, and cover crops.
- Suitable choice of mechanical, biological, and chemical weed control methods.
- Alternative weed control tools (e.g., flaming, steaming, infrared radiation, and sand blasting).

1.2. Dependence on Chemical Weed Control

Currently, many North American agronomic cropping systems are based on genetically modified crops (e.g., Roundup Ready and Liberty-Link), which rely heavily on the use of herbicides, especially glyphosate, the active ingredient in Roundup herbicide. The repeated use of chemicals may expand the number of herbicide-resistant weeds, increase the cost of herbicides, and contaminate surface and ground water. Increased public awareness of the effects of pesticides has led many countries to develop policies that mandate the reduction of herbicide use and incentivize the overall reduction of chemicals used for weed control as a means to lessen their environmental effects.

1.3. Weed Management in Organic Farming

The number of organic crop acres in the United States is expanding rapidly, mainly due to more robust consumer demand for food grown without chemicals and an attractive income potential for organic producers (Derksen et al., 2002). Sales of organic products have increased by more than 20 percent each year for the past decade, which makes the organic industry the fastest growing segment of U.S. agriculture. The area of certified organic cropland increased by more than 300 percent from 1992 to 2005, with total organic cropland growing from 403,573 acres (163,320 hectares) to 1,724,005 acres (697,680 hectares) during this time period (Greene, 2009). Despite this growth, current certified organic land only accounts for about 0.5 percent of total U.S. farmland production.

Organic farmers rank weed control as the number one problem that limits crop production (Walz, 1999). Controlling weeds without synthetic herbicides, as stipulated by the rules of organic agriculture, is challenging and requires the use of many techniques and strategies to achieve economically acceptable weed control and crop yields. A few herbicides are approved for use in organic production, but they are costly and their non-selectivity can lead to crop injury. Therefore, organic producers rely extensively on mechanical cultivation and hand weeding for their weed control, both of which have limitations. The challenges associated with weed management in organic farming necessitate the use of systems-oriented integrated weed management approaches that better incorporate alternative weed control tactics.

2. Introduction to Propane-Fueled Flame Weeding

2.1. Alternative Weed Control: Propane-Fueled Flame Weeding

Weeds are a major problem in both conventional and organic crop production systems. To address this issue, weed scientists worldwide are studying alternative weed control practices based on integrated weed management principles to help reduce herbicide dependence and provide organic farmers with an effective weed management method. Scientists have recently renewed their interest in flame weeding, especially due to the latest advances in flame technology (Bruening et al., 2009).

A propane-fueled flame weeding system uses a propane-fueled burner to expose weed plant tissues to rapid heat. Because propane is nontoxic and does not contaminate ground water, it is an acceptable non-chemical weed control option in organic production. This method of weed control has also received increased interest for integration in conventional cropping systems (Bond and Grundy, 2001) and can be used in other locations where herbicide use is undesirable, such as in cities, parks, and other urban settings.

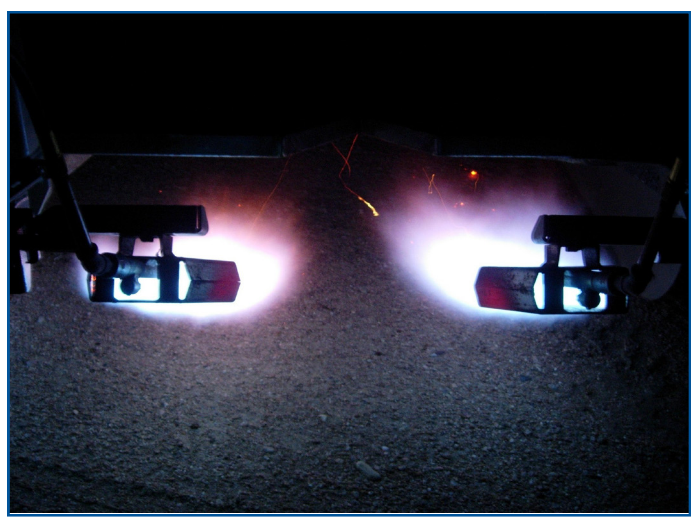


Figure 1: Flame with visible thermal energy

2.2. Benefits of Propane-Fueled Flame Weeding

Propane-fueled flame weeding is an increasingly attractive weed control method because it provides multiple advantages over chemical and mechanical weed management methods used in both conventional and organic farming operations. Compared with the use of chemical herbicides in conventional crop systems, flame weeding does not leave chemical residues in or on plants, soil, air, or water. Flame weeding does not pose safety risks to people in the surrounding area because it avoids drift hazards associated with chemical treatments; and unlike herbicides, flame weeding offers a treatment option that weeds cannot develop resistance against. However, flame weeding systems, most of which are designed to treat between four and eight rows at a time, are much smaller than chemical sprayers (Ascard et al., 2007). As a result, the flame weeding process is somewhat slow in comparison with chemical treatment.

Propane-fueled flame weeding has benefits over mechanical and hand weeding methods as well. The process of mechanical cultivation can bring new weed seeds to the surface, which can necessitate repeated cultivation later in the season. Because flame weeding does not disturb soil structure, the method can prevent new weed flushes that can occur after tilling and can reduce the potential for soil erosion. Unlike with mechanical cultivation methods, flame weeding can be used when soil is wet. It can also reduce the need for hand weeding in organic growing systems, which can be costly (ranging from $100 to $300 per acre [$300 to $800 per hectare]), time consuming, and difficult to organize.

Compared with alternate weed management methods, propane-fueled flame weeding does have some disadvantages. Its application can create a fire hazard in fields with heavy crop residue and has the potential to injure healthy crops in addition to weeds. As a result, it is critical to properly schedule flame weeding to ensure the safety of crops, personnel, and equipment. Additionally, as with all types of equipment that use hydrocarbon-based fuels, propane-fueled flame weeders produce some combustion byproducts. However, these byproducts contribute fewer greenhouse gases to the atmosphere than byproducts from other fuels such as diesel or gasoline (Ascard et al., 2007). Propane emits 19 percent fewer greenhouse gases than diesel and 18 percent fewer greenhouse gas emissions than gasoline per unit of energy (assuming complete combustion) (Energetics Incorporated, 2009). Additionally, carbon dioxide emissions from a banded flaming treatment combined with a mechanical cultivation treatment (two independent passes through the field) are about 8 percent lower than the emissions from the chemical production and application of a standard glyphosate treatment (Ulloa et al. 2011).

3. How Propane-Fueled Flame Weeding Works

3.1. A Closer Look: Flame Weeding at the Cell Level

Flame weeding systems control weeds by applying direct heat to plants, which rapidly changes the internal temperature of plant cells. This rapid temperature change expands the cell's contents—95 percent of which is water—causing the cell walls to rupture. This primary cause of cellular death is followed by the evaporation of the water that is released when the cell walls burst, which rapidly dries out the affected plant tissue. Direct heat injury also causes cell proteins to denature, which results in cell desiccation and ultimately the loss of cell function (Lague et al., 2001). The loss of water and denaturing of proteins drastically reduce the weed's competitive ability to survive and eventually kill the plant.

During the flame weeding process, propane-fueled burners can generate combustion temperatures as high as 3,400 degrees Fahrenheit (1,900 degrees Celsius) (Ascard et al., 2007), well above the temperature required for proteins to denature. Depending on the exposure time, protein denaturation may start at 113 degrees Fahrenheit (45 degrees Celsius). Temperatures in the range of 203–212 degrees Fahrenheit (95–100 degrees Celsius) have been lethal to weed leaves and stems when applied for at least 0.1 seconds.

3.2. Assessing Flame Weeding Effectiveness: A Rapid Field Test

The effectiveness of flame weeding treatment can be easily assessed in the field by conducting a simple fingerprint test a few minutes after treatment. To conduct the test, after properly shutting down the flame weeding system, the operator can inspect the plants by placing a treated weed leaf between his or her thumb and index finger. If a darkened impression is visible after firmly pressing on the leaf surface, as shown in Figure 2, it is evidence of water leakage from ruptured cell walls.

Figure 2: The fingerprint test demonstrates whether plant tissue has died during treatment

4. Flame Weeding Equipment Components and Configurations

4.1. Basic Flame Weeding Equipment Components

All propane-fueled flame weeding equipment must have several equipment components to carry out a successful flaming treatment. The following basic components are illustrated in Figure 3:

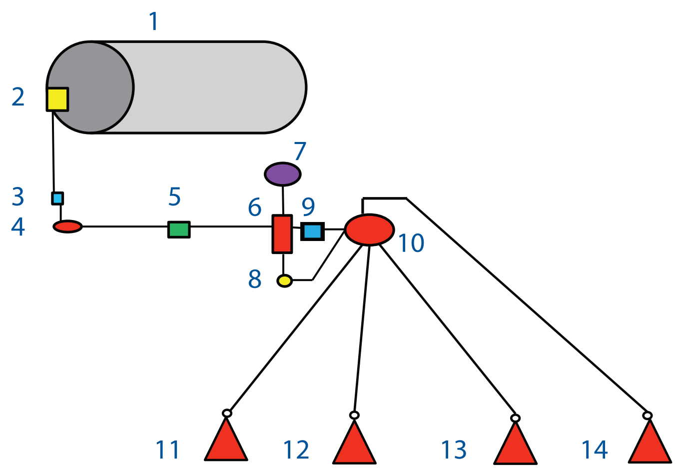
- **Supply Tank:** A propane supply tank (Part 1) provides the propane for combustion. The capacity of propane tanks in flame weed control systems can range from 1 gallon to greater than 500 gallons based on system size and customer need. Depending on the type of flame weeding system, the tank will need either a liquid or vapor source valve (Part 2).

- **Supply Network:** The supply network is a combination of parts that control propane flow and distribution (Parts 3–10). Manual and/or electronic valves control the propane flow from the supply tank to a pressure regulator, which reduces the pressure of the propane from the supply tank (typically ranging from 100 to 160 pounds per square inch depending on tank temperature) to the operating pressure (typically ranging from 10 to 60 pounds per square inch). Additional valves provide further control over the propane flow, and manifolds distribute the propane to the torches. Propane-compatible hard piping and flexible hose rated for the required pressure carry the propane from the tank, through the required components (e.g., pressure regulator), and to the torches.

- **Torch:** The torch (also known as the burner) is the point of propane combustion (Parts 11–14). Propane mixes with air inside the torch housing, and the combustion reaction begins once an ignition source is present. Torches are classified by their housing shape—generally flat or tubular—and whether they accept propane in the liquid or vapor state.

- **Frame:** The frame is the support structure for the propane supply tank, supply network, and propane torches. It provides the means to configure the torches in the desired torch-crop

Figure 3: Diagram of basic flame weeding system components



Part#	Description
1	Propane Tank
2	Excess Flow Safety Tank Valve
3	Master Solenoid Valve
4	Fuel Strainer/Filter
5	Regulator (10-100 PSI)
6	Brass Manifold
7	Pressure Gauge (0-100 PSI)
8	Needle Valve for Pilot Adjustment
9	Pilot Solenoid Valve
10	Brass Manifold
11	Torch
12	Torch
13	Torch
14	Torch

orientation. The frame is commonly a large metal structure that can be attached to a tractor; in the case of handheld flame weeding equipment, the human body is considered the frame.

- **Mobilizer:** The mode of mobilization of a flame weeding system depends on the type of system. A large row-crop unit requires a tractor or other vehicle, while a smaller garden unit is either pushed, pulled, or carried by the operator.

4.2. Equipment Safety Features

In addition to these basic equipment components, propane-fueled flame weeding systems may contain several other features that improve efficiency or protect crops or the operator. These additional features include the following:

- **Flame Hoods and Shields:** Hoods over the torch flames and shields on the sides of the torches can better direct the heat to the weeds, increasing fuel efficiency. This feature is especially helpful if treating weeds in windy conditions.

- **Emergency Shutdown Switch:** All propane-fueled flame weeding systems should be equipped with an emergency shutdown switch that can be activated in the event of a malfunctioning burner.

- **Remote Monitoring and Ignition:** A system that remotely ignites and monitors the status of the torches (i.e., ignited or extinguished) can significantly increase system efficiency and effectiveness and protect the system operator from the heat generated by the torches. Such a system is also useful for extinguishing the torches at the end of the field (e.g., at buffer rows or strips) and then re-igniting the torches when the operator is ready for the next pass.

Check with the equipment manufacturer or supplier to learn more about the features of their propane-fueled flame weeding equipment.

4.3. Examples of Flame Weeding Systems

A number of flame weeding systems are commercially available, ranging from small, handheld systems that can be used to control weeds in residential gardens to multi-row, tractor-pulled systems for use on large farms. In addition to the commercially available options, many farmers and mechanics choose to design custom flame weeding systems that meet their economic and crop configuration requirements.

Figure 4: Four-row flame weeding system developed by the University of Nebraska, Lincoln and Agricultural Flaming Innovations, Nebraska

4.3.1. Tractor-Pulled Commercial Flame Weeding Systems

There are several commercial flame weeding systems available for use in agronomic crops (Figure 4). These systems are typically designed to treat weeds in multiple crop rows at one time. As a result, they are often pulled behind a tractor or other vehicle.

4.3.2. Handheld Flame Weeding Equipment

Small flame weeding systems that can be carried by the operator are also commercially available. These systems are configured in the form of a cane, with the propane supply tank towed or carried in a backpack by the operator. They typically cost about the same as other handheld landscaping equipment, such as string trimmers.

4.4. Selective and Non-Selective Flame Weeding

Flame weeding treatments can be non-selective or selective to crop plants. During non-selective flame weeding treatments, everything in the treatment path—weeds and crops—is fully exposed to heat. Therefore, non-selective treatments are effective for controlling seedlings of early emerging weeds. This type of treatment is most commonly used during pre-emergence of the crop and at early crop growth stages when the crop is still able to recover from any treatment damage. Selective flame weeding treatments are done after the crop has emerged and aim to treat weeds while minimizing crop injury. This selectivity is usually achieved through torch configuration and/or the addition of various hoods.

Selective and non-selective treatments can be conducted as banded or full flaming operations. Banded flame weeding treatments are centered on the crop row and only treat widths of about 12 inches (i.e., 6 inches to the left and right of the row). In contrast, full flaming operations treat the full row width (e.g., 30 inches). The decreased treatment area of banded flaming lessens the required amount of propane but also necessitates additional cultivation of the inter-row area for more effective weed control.

5. Recommended Propane Dosage at Different Weed Growth Stages

5.1. Calibrating the Propane Dosage

All flame weeding systems must be calibrated to deliver a dose of propane that will provide the required amount of heat to kill weeds. The propane application dose, typically reported as propane gallons per acre (GPA), is regulated by a combination of propane operating pressure and application speed. For example, at a driving speed of about 4 miles per hour (6.4 kilometers per hour), propane doses can range from about 2 GPA to 20 GPA (about 10–100 kilograms per hectare) depending on the operating pressure and the specific torch being used. According to the University of Nebraska, banded flame weeding treatments require about 4–5 GPA, and full flaming treatments generally require propane doses of 10–12 GPA when treating weeds at their recommended growth stage.

The proper calibration of any flame weeding equipment requires specifications for both the propane flow rate and the operating pressure for the torch being used. The nozzle orifice size of the torch is the critical specification that can alter this relationship. Given a fixed operating pressure, there is a direct correlation between nozzle orifice size and propane flow rate: a larger orifice yields a greater flow rate. As a result, flow rate and operating pressure tables must include information about the torch/nozzle combination to be comprehensive and fully defined.

Keeping these specifications in mind, Table 1 demonstrates how various application speeds and propane pressure combinations achieve different propane doses (Knezevic et al., 2007). These varying dosages were determined using torches from a flame weeding research unit at the University of Nebraska, Lincoln. The data in Table 1 is specific to this equipment and cannot be applied to the use of all flame weeding torches. To properly calibrate a specific system, please request calibration information, including flow rate, operating pressure, and application speeds, from the equipment manufacturer that made the torches for your flame weeding equipment.

Table 1: Propane dosages in gallons per acre (GPA) as a function of propane pressure (PSI) and application speed (MPH)

Propane Pressure (PSI)	Speed (MPH)					
	1	2	4	6	8	10
10	10.2 GPA	5.1 GPA	2.6 GPA	1.7 GPA	1.3 GPA	1.0 GPA
20	18.2 GPA	9.1 GPA	4.5 GPA	3.0 GPA	2.3 GPA	1.8 GPA
30	26.1 GPA	13.0 GPA	6.5 GPA	4.4 GPA	3.3 GPA	2.6 GPA
40	34.0 GPA	17.0 GPA	8.5 GPA	5.7 GPA	4.2 GPA	3.4 GPA
50	42.0 GPA	21.0 GPA	10.5 GPA	7.0 GPA	5.2 GPA	4.2 GPA
60	50.0 GPA	25.0 GPA	12.5 GPA	8.3 GPA	6.2 GPA	5.0 GPA

5.2. Tolerance of Different Weed Species to Flame Weeding at Various Growth Stages

The required propane dosage for successful flame weeding treatment depends on the growth stage of the weed. In general, smaller weeds at heights of 1–3 inches (typically with one to six leaves) are much easier to control with propane-fueled flame weeding and require a lower propane dosage for successful treatment than larger weeds that are 3–20 inches tall and have seven or more leaves. Plant tissue is thin and delicate at early vegetative stages, which increases plant sensitivity to heat and prevents the weeds from recovering after heat damage.

Using non-hooded torches for broadcast flame weeding, the University of Nebraska, Lincoln conducted tests to determine the recommended propane dosage required to achieve 90 percent control of different weed species, which is comparable to the control achieved by chemical herbicides. While 90 percent control was used as the baseline during testing, 80 percent weed control is considered acceptable in organic farming operations because of the lower efficiency of available organic weed control methods. Table 2 provides recommended propane dosages when using broadcast flame weeding at various growth stages of common weeds, and Figure 5–19 demonstrate the effects of flame weeding on these weed species.

As shown in Table 2, common waterhemp, redroot pigweed, field bindweed, kochia, ivyleaf morningglory, velvetleaf, Venice mallow, common ragweed, common lambsquarters, tansy mustard, and henbit were effectively controlled (i.e., 90 percent control) with propane dosages that averaged about 10 gallons per acre (~50 kilograms per hectare) at early growth stages. When flamed at 14-leaf growth stages, these weeds were controlled with propane dosages that averaged about 15 gallons per acre (~75 kilograms per hectare).

Green foxtail, yellow foxtail, and barnyardgrass were controlled to 80 percent with average propane doses of about 9 gallons per acre (~42 kilograms per hectare) at early growth stages and 12 gallons per acre (~57 kilograms per hectare) at 7-leaf growth stages. Higher dosages of propane were required to reach 90 percent control of these species in comparison with the broadleaf species. General trends (based on the University of Nebraska, Lincoln testing and other available research) about the differences between treating broadleaf weeds and grasses with flame weed control are provided in the following sections.

Table 2: List of broadleaf and grass weed species, their growth stages with corresponding heights, and various dosages of propane needed to obtain 80 percent and 90 percent weed control with broadcast flame weeding

Weed species	Growth stage	Approximate weed height (inches)	Propane dose (gallons per acre)		Treatment Images
			80% Control	90% Control	
Common waterhemp *(Amaranthus rudis)*	3-leaf (V3)	2″	6 GPA	8 GPA	Figures 5a and 5b
	5-leaf (V5)	4″	7 GPA	10 GPA	
	Flowering	15″	7 GPA	10 GPA	
Redroot pigweed *(Amaranthus retroflexus)*	3-leaf (V3)	2″	10 GPA	15 GPA	Figures 6a and 6b
	5-leaf (V5)	4″	10 GPA	14 GPA	
	Flowering	18″	12 GPA	18 GPA	
Field bindweed *(Convolvulus arvensis)*	8-leaf (V8)	2″	6 GPA	8 GPA	Figures 7a and 7b
	10-leaf (V10)	4″	5 GPA	7 GPA	
	40-leaf (V40)	13″	7 GPA	12 GPA	
Kochia *(Kochia scoparia)*	6-leaf (V6)	1″	8 GPA	10 GPA	Figures 8a and 8b
	10-leaf (V10)	3″	6 GPA	8 GPA	
	Flowering	18″	10 GPA	15 GPA	
Ivyleaf morningglory *(Ipomoea hederacea)*	10-leaf (V10)	3″	8 GPA	12 GPA	Figures 9a and 9b
	14-leaf (V14)	4″	10 GPA	13 GPA	Figures 10a and 10b
	Flowering	16″	10 GPA	14 GPA	
Velvetleaf *(Abutilon theophrasti)*	5-leaf (V5)	2″	6 GPA	9 GPA	Figures 11a and 11b
	7-leaf (V7)	7″	8 GPA	12 GPA	
	16-leaf (V16)	39″	12 GPA	21 GPA	
Venice mallow *(Hibiscus trionum)*	3-leaf (V3)	2″	7 GPA	11 GPA	Figures 12a and 12b
	5-leaf (V5)	4″	7 GPA	11 GPA	
	Flowering	20″	8 GPA	15 GPA	

Weed species	Growth stage	Approximate weed height (inches)	Propane dose (gallons per acre)		Treatment Images
			80% Control	90% Control	
Common ragweed *(Ambrosia artemisiifolia)*	4-leaf (V4)	1″	3 GPA	4 GPA	Figures 13a and 13b
	14-leaf (V14)	8″	5 GPA	6 GPA	
	26-leaf (V26)	31″	10 GPA	14 GPA	
Common lambsquarters *(Chenopodium album)*	5-leaf (V5)	2″	8 GPA	10 GPA	Figures 14a and 14b
	11-leaf (V11)	5″	12 GPA	15 GPA	
Tansy mustard *(Descurainia pinnata)*	9-leaf (V9)	5″	8 GPA	10 GPA	Figures 15a and 15b
	Flowering	13″	10 GPA	12 GPA	
Henbit *(Lamium amplexicaule)*	9-leaf (V9)	6″	13 GPA	15 GPA	Figures 16a and 16b
	Flowering	12″	8 GPA	10 GPA	
Green foxtail *(Setaria viridis)*	5-leaf (V5)	2″	12 GPA	18 GPA	Figures 17a and 17b
	7-leaf (V7)	5″	12 GPA	19 GPA	
	Flowering	26″	22 GPA	30 GPA	
Yellow foxtail *(Setaria pumila)*	2-leaf (V2)	2″	9 GPA	15 GPA	Figures 18a and 18b
	4-leaf (V4)	4″	11 GPA	18 GPA	
	Flowering	19″	17 GPA	28 GPA	
Barnyardgrass *(Echinochloa crus-galli)*	4-leaf (V4)	2″	7 GPA	10 GPA	Figures 19a and 19b
	7-leaf (V7)	7″	9 GPA	16 GPA	
	Flowering	33″	16 GPA	27 GPA	

Note: Propane doses for banded flame weeding are 50 percent to 70 percent lower than the broadcast flaming rates provided in this table.
Source: Ulloa et al. (2010a, b) and Knezevic et al., unpublished data.

5.2.1. Broadleaf Weeds

Generally, when a propane dose of 10 gallons per acre (50 kilograms per hectare) is applied properly using broadcast flame weeding with non-hooded torches, it can control 90 percent of most broadleaf weeds at early growth stages (up to 7 inches tall) (Ulloa et al., 2010a, b). This propane dosage completely desiccates the leaves of annual broadleaf species within a few days of flame weeding, leaving no opportunity for plant regrowth. At earlier growth stages, a reduced propane dosage can be successful, but as plant size increases, weeds are more tolerant to heat and require higher propane dosages for successful treatment.

Broadleaf weeds that have cotyledons, such as wild sunflower and cocklebur, can survive flame weeding treatments at their cotyledon stage. To increase the effectiveness of treatment, it is recommended that these weeds not be treated until two to four leaves have developed.

5.2.2. Grasses

Grasses are harder to control than broadleaf species. While a dose of 10 gallons of propane per acre can typically control 90 percent of broadleaf weeds using broadcast flame weeding with non-hooded torches, it can only provide about 80 percent control of grass species in the form of short-term suppression when flamed at their early vegetative growth stages (two to seven leaves) (Ulloa et al., 2010a, b). This variation in effectiveness is likely due to the physical position of the growing point of grasses at the time of flaming. Because the growing point in grass species during early growth stages is below the soil surface, it is protected from the flame. In contrast, the growing point in broadleaf species is above the ground.

While the leaves of grassy species turn white shortly after flaming, leaving an appearance of a dead plant, within a week or two plants begin to recover with the growth of new leaves. Control of grass species can be improved by performing a second flame weeding treatment within 7–10 days of the first treatment. If an additional flame weeding treatment is not feasible, aggressive cultivation (i.e., cultivator shanks adjusted to push soil on top of the flamed grass) within a few hours of flaming can help prevent grass regrowth.

5.2.3. Perennial Weeds

Some perennial and biannual weeds (including dandelion and Canada, Musk, and Plumless thistle) are extremely sensitive to heat, and their aboveground tissue and biomass can be easily killed. For example, the University of Nebraska, Lincoln study suggested that a propane rate of 3 gallons per acre turned leaves of Canada thistles completely black within 24 hours after flame weeding. However, because flaming is unable to penetrate deep into the soil to destroy the root structures of perennial weeds, these plants regrew a few weeks later. To control these weeds throughout the season, flame weeding must be repeated several times during the season. Repeated flaming over several years can deplete the nutrients from the root and result in a complete kill of the plant.

5.3. The Impact of Moisture on the Effectiveness of Flame Weeding

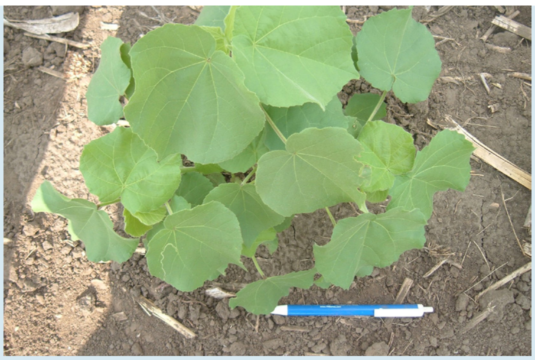
Any kind of moisture, including heavy dew and rain droplets on weed leaves, can reduce the effectiveness of flame weeding treatments or require higher propane doses to be successful. When weeds are wet, a portion of the heat applied to the weed leaves is used to evaporate the surface water from the leaf, which reduces the amount of heat that reaches the interior plant tissue. If this interior plant tissue is not sufficiently heated to the point that the cell walls burst and cause the plant to dry out, the weed can survive the flame weeding treatment. Despite this potential barrier, flame weeding treatments can be effective one hour after it has stopped raining.

While the presence of moisture can decrease the effectiveness of flame weeding treatments, it can also increase the safety of the operation. Moisture can both reduce the potential for crop injury and soak the crop residue present on the field, reducing the risk of fire. For this reason, it is often recommended that farmers irrigate fields with half an inch of water before flame weeding treatments. Light irrigation can also promote the early emergence of weed species that can then be controlled with non-selective broadcast flame weeding. Organic vegetable producers commonly irrigate prepared seedbeds to stimulate weed germination, and then use flame weeding to kill weed seedlings before planting the crop or before crop emergence.

Figures 5a–19b: Common weed species' response to propane-fueled broadcast flame weeding treatment

Before Flame Weeding	10 Days After Flame Weeding
	
Figure 5a: Common waterhemp at the 10-leaf (V10) stage	**Figure 5b:** Common waterhemp flamed with 10 gallons of propane per acre at the 10-leaf (V10) stage
	
Figure 6a: Redroot pigweed at the 10-leaf (V10) stage	**Figure 6b:** Redroot pigweed flamed with 10 gallons of propane per acre at the 10-leaf (V10) stage

Before Flame Weeding	10 Days After Flame Weeding
 **Figure 7a:** Field bindweed at the 10-leaf (V10) stage	 **Figure 7b:** Field bindweed flamed with 10 gallons of propane per acre at the 10-leaf (V10) stage
 **Figure 8a:** Kochia at the 10-leaf (V10) stage	 **Figure 8b:** Kochia flamed with 10 gallons of propane per acre at the 10-leaf (V10) stage
 **Figure 9a:** Ivyleaf morningglory at the 10-leaf (V10) stage	 **Figure 9b:** Ivyleaf morningglory flamed with 10 gallons of propane per acre at the 10-leaf (V10) stage

Before Flame Weeding	10 Days After Flame Weeding
 **Figure 10a:** Ivyleaf morningglory at the 14-leaf (V14) stage	 **Figure 10b:** Ivyleaf morningglory flamed with 10 gallons of propane per acre at the 14-leaf (V14) stage
 **Figure 11a:** Velvetleaf at the 7-leaf (V7) stage	 **Figure 11b:** Velvetleaf flamed with 10 gallons of propane per acre at the 7-leaf (V7) stage
 **Figure 12a:** Venice mallow at the 5-leaf (V5) stage	 **Figure 12b:** Venice mallow flamed with 10 gallons of propane per acre at the 5-leaf (V5) stage

Before Flame Weeding	10 Days After Flame Weeding
 **Figure 13a:** Common ragweed at the 14-leaf (V14) stage	 **Figure 13b:** Common ragweed flamed with 10 gallons of propane per acre at the 14-leaf (V14) stage
 **Figure 14a:** Common lambsquarters at the 5-leaf (V5) stage	 **Figure 14b:** Common lambsquarters flamed with 10 gallons of propane per acre at the 5-leaf (V5) stage
 **Figure 15a:** Tansy mustard at the 9-leaf (V9) stage	 **Figure 15b:** Tansy mustard flamed with 10 gallons of propane per acre at the 9-leaf (V9) stage

Before Flame Weeding	10 Days After Flame Weeding
	
Figure 16a: Henbit at the flowering stage	**Figure 16b:** Henbit flamed with 10 gallons of propane per acre at the flowering stage
	
Figure 17a: Green foxtail at the 7-leaf (V7) stage	**Figure 17b:** Green foxtail flamed with 10 gallons of propane per acre at the 7-leaf (V7) stage
	
Figure 18a: Yellow foxtail at the 4-leaf (V4) stage	**Figure 18b:** Yellow foxtail flamed with 10 gallons of propane per acre at the 4-leaf (V4) stage

Before Flame Weeding	10 Days After Flame Weeding
	
Figure 19a: Barnyardgrass at the 7-leaf (V7) stage	**Figure 19b:** Barnyardgrass flamed with 10 gallons of propane per acre at the 7-leaf (V7) stage

6. Crop Tolerance To Post-Emergent Flame Weeding

6.1. Recommended Growth Stages for Flame Weed Control on Common Crops

The growth stage of a crop is critical when deciding whether to use flame weeding to control weeds after crop emergence (Knezevic and Ulloa, 2007). All agronomic crops are sensitive to heat, and flaming crops at the incorrect growth stage could result in severe yield losses. As shown in Table 3, grass-type crops, such as field corn, popcorn, sweet corn, and sorghum, are more tolerant to propane-fueled post-emergence flame weeding than broadleaf crops, such as soybean and sunflower. Post-emergence flame weeding is not recommended in winter wheat due to high injury level and unacceptable yield loss.

During post-emergence flame weeding, torches should be configured for banded flaming (i.e., torches are positioned at least 6 inches from the crop row). This configuration enables flaming beneath the crop canopy, which protects the growing point of the crop during flame weeding and reduces the potential for crop damage. Crop damage can be further minimized by using custom-designed hoods that keep the flame entirely beneath the crop canopy. The use of banded flame weeding allows for treatment at a greater span of crop growth stages than non-selective broadcast flame weeding directly over the crop row.

Table 3: Recommended crop growth stages for post-emergent flame weeding, as influenced by the position of the torches and flames relative to the crop row

Crop	Broadcast flame weeding (leaf stage and height)	Banded flame weeding (below crop canopy)	Source
Field corn	VE–V1(1″–2″)	V1–V10 (2″–36″)	Ulloa et al. (2011a)
Popcorn	VE–V1 (1″–2″)	V1–V10 (2″–36″)	Ulloa et al. (2010d)
Sweet corn	VE–V1 (1″–2″)	V1–V10 (2″–36″)	Ulloa et al. (2010c)
Sorghum	VE–V1 (1″–2″)	V1–V10 (2″–24″)	Ulloa et al. (2011b)
Soybean	VE–VC (1″–2″)	V4–V5 (12″–16″)	Ulloa et al. (2010e)
Sunflower	VE–VC (1″–2″)	V8–V14 (14″–28″)	Neilson et al. (2011)
Winter wheat			Ulloa et al. (2010f)

VE = emergence growth stage; VC = cotyledon growth stage; V# = Number of leaves of growth stage

Based on testing by the University of Nebraska, Lincoln, it is recommended that flame weeding treatments of these crops use a propane dose of 10 gallons of propane per acre for broadcast flaming and 5 gallons of propane per acre for banded flame weeding, with a maximum of two post-emergence flaming operations per season. Flame weeding should be performed around noon to achieve maximum weed control with minimal crop damage (Ulloa et al., 2012).

6.1.1. Recommended Growth Stages for Flame Weeding in Corn

Corn can be safely flamed from its emergence (VE) to 10-leaf (V10) growth stages, with a maximum of two post-emergence flaming operations per season. Based on the University of Nebraska, Lincoln testing, flame weeding conducted three times in field corn at the 2-leaf (V2), 4-leaf (V4), and 6-leaf (V6) growth stages exhibited more than 30 percent injury with as high as a 15 percent yield reduction compared to the weed-free control plots (Nedeljkovic et al., 2011).

The recommended corn growth stages for flame weeding treatment and directions for treatment during these stages are provided in Table 4. Figures 20a–23c demonstrate corn recovery over time when crops are flamed at the recommended crop growth stages for post-emergence flame weeding. The recommended flame weeding treatment of corn crops can also be applied to sorghum.

Table 4: Recommended crop growth stages for flame weeding in various corn types (field corn, popcorn, and sweet corn)

Growth stage	Treatment Recommendations
Pre-emergence	If there are standing weed populations in the field, it is recommended to flame the entire field using broadcast flame weeding before crop planting or crop emergence.
Emergence/spike stage (V1)	When corn crops are treated at the V1 stage with broadcast flame weeding, the young leaves may show temporary injury, but there will be no effects on crop yield.
2–3 leaf stage (V2–V3)	There is potential for high crop injury (greater than 50 percent) after flaming at these growth stages, but it does not cause yield reduction because corn plants are able to recover over time (Figures 20a–20c and 21a–21c).
4–10 leaf stage (V4–V10)	When using flame weeding at these growth stages, keep the flames below the crop canopy to avoid potential reductions in crop yield. The bottom leaves may show some temporary injury following treatment at this growth stage, but there will be no effects on crop yield. (Figures 22a–22c and 23a–23c).

Figures 20a–23c: Corn recovery over time following propane-fueled flame weeding

Before Flame Weeding	1 Day After Flame Weeding	14 Days After Flame Weeding
		
Figure 20a: Corn at the 2-leaf (V2) stage	**Figure 20b:** 1 day after flaming corn at the 2-leaf (V2) stage	**Figure 20c:** 14 days after flaming corn at the 2-leaf (V2) stage
		
Figure 21a: Corn at the 3-leaf (V3) stage	**Figure 21b:** 1 day after flaming corn at the 3-leaf (V3) stage	**Figure 21c:** 14 days after flaming corn at the 3-leaf (V3) stage
		
Figure 22a: Corn at the 4-leaf (V4) stage	**Figure 22b:** 1 day after flaming corn at the 4-leaf (V4) stage	**Figure 22c:** 14 days after flaming corn at the 4-leaf (V4) stage

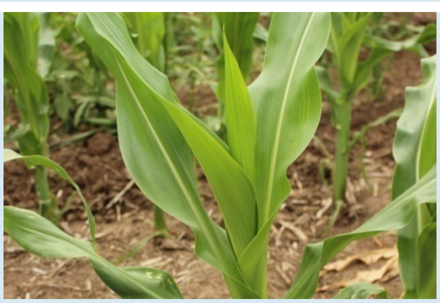
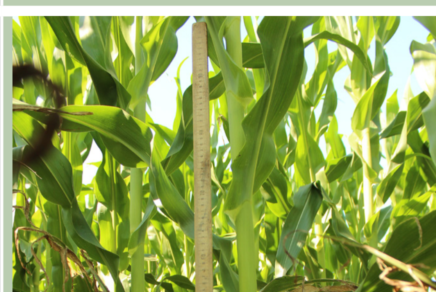

		

Figure 23a: Corn at the 6-leaf (V6) stage	**Figure 23b:** 1 day after flaming corn at the 6-leaf (V6) stage	**Figure 23c:** 14 days after flaming corn at the 6-leaf (V6) stage

6.1.2. Recommended Growth Stages for Flame Weeding in Soybean

Soybean is tolerant to flame weeding only at the emergence-unfolded cotyledon (VE–VC) stages and at the 4–5 trifoliate (V4–V5) growth stages. The recommended soybean growth stages for flame weeding treatment and directions for treatment during these stages are provided in Table 5. Figures 24a–25c demonstrate soybean recovery over time when crops are flamed at the recommended crop growth stages for post-emergence flame weeding.

Soybean can tolerate a maximum of two post-emergence flaming operations per season. Based on the University of Nebraska, Lincoln testing, flame weeding conducted three times in soybean crops at the cotyledon (VC), second-trifoliate (V2), and fifth-trifoliate (V5) growth stages resulted in more than 90 percent crop injury and as high as 90 percent yield reduction (Tursun et al., 2011).

Table 5: Recommended crop growth stages for flame weeding in soybean

Growth stage	Comments
Pre-emergence	If there are standing weed populations in the field, it is recommended to flame the entire field using broadcast flame weeding before crop planting or crop emergence.
Emergence/cotyledon (VE and VC)	Soybean cotyledons are tolerant to heat produced by the recommended dose of propane. While soybean may show temporary injury in the form of browning after broadcast flame weeding, flaming during this growth stage does not cause yield reduction because soybean plants are able to recover over time (Figures 24a–24c). As shown in Figure 24a, soybeans should be flamed when cotyledons are closed or partially open. If cotyledons are fully open and the growing point is exposed to flame, flame weeding treatments could cause major reductions in crop yields (greater than 50 percent). Depending on the heat of the season, the soybean emergence stage may last for a few days, while the cotyledon stage may last only 2–4 days. Treatment during this phase requires prompt action.
4–5 trifoliate (V4–V5)	When using flame weeding at these growth stages, keep the flames below the crop canopy to avoid potential reductions in crop yield. The bottom leaves may show some temporary injury following treatment at this growth stage, but there will be no effects on crop yield (Figures 25a–25c).

Figures 24a–25c: Soybean recovery over time following propane-fueled flame weeding

Before Flame Weeding | **1 Day After Flame Weeding** | **14 Days After Flame Weeding**

Figure 24a: Soybean at the unfolded cotyledon (VC) stage

Figure 24b: 1 day after broadcast flaming soybean at the unfolded cotyledon (VC) stage

Figure 24c: 14 days after broadcast flaming soybean at the unfolded cotyledon (VC) stage

Figure 25a: Soybean at the fifth-trifoliate (V5) stage

Figure 25b: 1 day after flaming soybean at the fifth-trifoliate (V5) stage with a hooded flame weeding system

Figure 25c: 14 days after flaming soybean at the fifth-trifoliate (V5) stage

It is not recommended to flame soybean at the unifoliate (VU), first-trifoliate (V1), second-trifoliate (V2), or third-trifoliate (V3) growth stages because soybean at these stages is not tall enough to safely direct the flame and heat beneath the crop's canopy. Exposure to heat at these growth stages could result in very high crop injury (greater than 50 percent) and reduced crop yields (greater than 50 percent). The soybean growth stages *not recommended* for flame weeding treatment are provided in Table 6. Figures 26a–26b show the soybean growth stages not recommended for post-emergence flame weeding.

Table 6: Growth stages of soybean not recommended for flame weeding

Growth stage	Comments
Unifoliate (VU)	The unifoliate (VU) stage (Figure 26a) is very sensitive to flame weeding. Do not use flame weeding at the unifoliate (VU) stage, as it can cause high crop injury (greater than 50 percent) and can result in major yield reduction (greater than 50 percent).
First-trifoliate (V1)	Flame weeding is not recommended at the first-trifoliate (V1) stage.
Second-trifoliate (V2)	Do not use flame weeding at the second-trifoliate (V2) stage (Figure 26b), as soybean crops at this growth stage are very sensitive to heat. Flame weeding at the second-trifoliate (V2) stage can cause high crop injury (greater than 70 percent) and can result in major yield reduction (greater than 70 percent).
Third-trifoliate (V3)	Flame weeding is not recommended at the third-trifoliate (V3) stage unless the soybean is a taller variety that allows the operator to direct the heat below the canopy and growing point or the operator uses specialty hoods that are designed to protect the crop's growing point.

Figures 26a–26b: Growth stages of soybean not recommended for post-emergence flame weeding

Figure 26a: Unifoliate (VU) soybean

Figure 26b: Second-trifoliate (V2) soybean

6.1.3. Recommended Growth Stages for Flame Weeding in Sunflower

Sunflower is tolerant to flame weeding only at the emergence–cotyledon (VE–VC) stage and at the 8–14 leaf (V8–V14) growth stages. The recommended sunflower growth stages for flame weeding treatment and directions for treatment during these stages are provided in Table 7. Figures 27a–28c demonstrate sunflower recovery over time when crops are flamed at the recommended crop growth stages for post-emergence flame weeding.

The vegetative growth stages of sunflower are determined by counting the number of pairs of leaves at least 1.6 inches (4 cm) in length, beginning as 1- to 2-leaf (V1–V2), 3- to 4-leaf (V3–V4), and 5- to 6-leaf (V5–V6) pairs. If natural drying of the lower leaves has occurred, it is recommended to count leaf scars (excluding those where the cotyledons were attached) to determine the proper growth stage (Schneiter and Miller, 1981).

Table 7: Recommended crop growth stages for flame weeding in sunflower

Growth stage	Comments
Pre-emergence	If there are standing weed populations in the field, it is recommended to flame the entire field before crop planting or crop emergence.
Emergence/cotyledon (VE and VC)	Sunflower cotyledons are tolerant to heat produced by the recommended dose of propane. While sunflower plants may show temporary injury in the form of browning after flame weeding, flaming during these growth stages does not cause yield reduction because sunflower plants are able to recover over time (Figures 27a–27c). As shown in Figure 27a, sunflower should be flamed when cotyledons are closed or partially open. If cotyledons are fully open and the growing point is exposed to flame, flame weeding treatments could cause major reductions in crop yields (greater than 50 percent). The sunflower cotyledon stage lasts only 2–4 days, requiring prompt action for flame weeding treatment during this phase.
8–14 leaf (V8–V14)	When using flame weeding at these growth stages, keep the flames below the crop canopy to avoid potential reductions in crop yield. The bottom leaves may show some temporary injury following treatment at these growth stages, but there will be no effects on crop yield (Figures 28a–28c).

Figures 27a–28c: Sunflower recovery over time following propane-fueled flame weeding

Before Flame Weeding	1 Day After Flame Weeding	14 Days After Flame Weeding
 **Figure 27a:** Sunflower at the cotyledon (VC) stage	 **Figure 27b:** 1 day after flaming sunflower at the cotyledon (VC) stage	 **Figure 27c:** 14 days after flaming sunflower at the cotyledon (VC) stage
 **Figure 28a:** Sunflower at the 10–12 leaf (V10–V12) stage	 **Figure 28b:** 1 day after flaming sunflower at the 10–12 leaf (V10–V12) stage	 **Figure 28c:** 14 days after flaming sunflower at the 10–12 leaf (V10–V12) stage

It is not recommended to flame sunflower between 2-leaf (V2) and 6-leaf (V6) growth stages. Flame weeding at these growth stages could result in very high crop injury and reduced crop yields. The sunflower growth stages *not recommended* for flame weeding treatment are provided in Table 8. Figures 29a–29b show the most heat-sensitive sunflower growth stages not recommended for post-emergence flame weeding.

Table 8: Growth stages of sunflower not recommended for flame weeding

Growth stage	Comments
1–2 true leaf (V1–V2)	The 2-leaf (V2) stage (Figure 29a) is very sensitive to flame weeding. Do not use flame weeding at the V2 stage, as it will cause high crop injury and will result in major yield reduction.
3–4 true leaf (V3–V4)	Flame weeding is not recommended at the 3–4 true leaf (V3–V4) stage. The V4 growth stage (Figure 29b) is very sensitive to heat. Flaming at the V4 stage will cause high crop injury (greater than 50 percent) and will result in severe yield reduction (about 50 percent).
5–6 true leaf (V5–V6)	Do not use flame weeding at the 5–6 true leaf (V5–V6) stage.
7 true leaf (V7)	Flame weeding is not recommended at the 7 true leaf (V7) stage, unless the heat can be directed below the growing point or specialty hoods are designed to protect the growing point of the sunflower.

Figures 29a–29b: Growth stages of sunflower not recommended for post-emergence flame weeding

Figure 29a: 2 true leaf (V2) sunflower

Figure 29b: 4 true leaf (V4) sunflower

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