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Pregledni rad – Review paper

Flame weeding as an alternative tool for weed management in agronomic crops: revisiting the old concept

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SUMMARY

Flaming as a vegetation control method is dating back to mid-1800s. This type of weeding is based on the concept of utilizing heat as a source for vegetation control. Various levels of heat can either damage plant tissue or kill a plant. The critical temperature for leaf mortality ranges from 55°C to 70°C. The mechanism by which heat injury affects the plant varies from species to species and is complex. In general, plants die from the loss of membrane semi-permeability and cuticle breakdown (resulting in plant desiccation), denaturation of proteins, water boiling, and other chemical decomposition. The general principle behind flaming is to cause plant death by raising temperatures high enough to boil water inside the plant tissue, which further expends helping disintegrate the plants' cellular membranes. Flaming has a potential to be used effectively in organic crop production systems in at least 6 agronomic crops (field maize, sweet maize, popcorn, sorghum, soybean, sunflower) when conducted properly at the most tolerant growth stage. It is important to mention that propane flaming should not be the only method for non-chemical weed control; however, it could be part of an integrated weed management program. Other measures are still needed to control weeds that emerge throughout the growing season.

Keywords: flame, heat, propane, weed, crop, environment

INTRODUCTION

Weeds are one of the major pests in agronomic crops (both conventional and organic) and are responsible for significant reductions in crop yields (Stopes and Millington, 1991). Lack of effective weed management practices is widely reported to be a major production-related problem in organic crops, where synthetic herbicides are not allowed (Gianessi and Reigner, 2007; Hiltbrunner et al., 2007; Wszelaki et al., 2007). Therefore, organic producers rely extensively on mechanical cultivation and hand weeding for their weed control (Hiltbrunner et al., 2007). However, repeated cultivation causes loss of soil organic matter, destroys soil aggregate, increases the chance for soil erosion and promotes emergence of new weed flushes (Cloutier et al., 2007; Hiltbrunner et al., 2007; Wszelaki et al., 2007). The labour required for hand weeding is expensive in USA (ranging from \$300 to \$800 ha⁻¹), time consuming and difficult to organize (Kruidhof et al., 2008). Hence, systems-oriented approaches to weed management that make better use of alternative weed management tactics need to be developed (Kruidhof et al., 2008). Propane flaming is one of the most promising alternatives for weed control in organic cropping systems, and with the potential for use in the conventional crops as well (Ulloa et al., 2010a, b,c,d,e,f; 2011a,b; 2012; Knezevic, 2009).

Therefore, the objective of this manuscript was to provide a brief overview of the latest information on weed and crop tolerance to flaming. Majority of the flame weeding research in agronomic crops over an eight year period (2006-2014) was conducted at the Haskell Agricultural Laboratory of the University of Nebraska, Concord, Nebraska, USA.

PROPANE FLAMING (FLAME WEEDING)

Propane flaming, also known as flame weeding, is a process of exposing plant tissues to flames coming from a propane burner. Flame weeding is an acceptable weed control option in organic production and has received renewed interest for its potential in both organic and conventional systems (Bond and Grundy, 2001). Propane burners can generate combustion temperatures of up to 1,900 oC, which raises the temperature of the exposed plant tissues rapidly (Ascard, 1998). Direct heat injury results in denaturation of membrane proteins, which results in loss of cell function (Parish, 1990; Pelletier et al., 1995; Rifai et al., 1996; Lague et al., 2001) and eventually the plants die or their competitive ability is drastically reduced.

The use of flaming as a weed control method started in the early 1940s. Liquid fuels such as diesel, kerosene and oils were rapidly replaced by liquefied petroleum gas-LPG (mixture of propane and butane) at that time. During the 1960s, flaming was widely used in the US for controlling weeds in cotton (*Gossypium hirsutum* L.),

maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), soybean (*Glycine max* (L.) Merr.), potato (*Solanum tuberosum* L.), and other crops (Lague et al. 2001). During the 1960s and 70s, flaming was replaced by the use of chemical herbicides due to escalated LPG prices and availability of less expensive and residual herbicides. In recent years, increasing concerns about leaching of pesticide into surface and ground water and pesticide residues in drinking water and food have sparked public awareness and restrictions on herbicide use. For these reasons, flaming has received a renewed interest for its cheaper and effective weed control in organic crop production systems. There is also potential for its use in conventional crops, especially in those fields that experience weed resistance.

PLANT RESPONSE TO HEAT

In general, heat can damage plant tissue, while obviously excess heat can kill plants. It is a function of a “time-temperature” relationship. As temperature increases linearly, tissue damage by heat increases exponentially and the ‘time to kill’ between sensitive and insensitive plants will decline exponentially. The critical temperature reported for effective leaf mortality ranges from 55°C to 70°C, with an exposure time ranging of 65-130 milliseconds (Ascard 1998). The mechanisms in the plant of how heat injury affects the plant are varied from species to species and is complex. In general, plants die from loss of membrane semi-permeability and cuticle breakdown (resulting in plant desiccation), denaturation of proteins, and other chemical decomposition. Morphological differences of plant species are important in determining kill efficiency, including factors such as: leaf, leaf thickness, leaf cuticle type, location of growing point, nature of storage organs. Leaf orientation and shape, cuticle characteristics, presence of hair, growth stage, and degree of stress (both moisture and nutrient) will affect sensitivity or interfere with a passing of the heat. Environmental factors can also impact flaming. Any kind of moisture, including heavy dew and rain droplets on the leaves, will reduce efficacy of flaming. The presence of moisture on the plant tissue can reduce the amount of heat that can reach inside the plant tissue, as the portion of the heat is wasted on evaporating the surface water present on the leaf. However, the presence of moisture can be useful for: (i) reducing the crop injury level and (ii) wetting the crop residue present on the field, thus reducing the chance for fire hazards. Slight irrigation or sprinkle of the crop residue an hour before flaming can also help reduce potential for fire hazards. Irrigation is also useful to promote early emergence of weed species, which can be controlled with the non-selective broadcast flaming operation. Organic vegetable producers often irrigate prepared seedbeds to stimulate weed germination, and then utilize flaming to kill weed seedlings before crop planting, or after planting but before crop emergence

FLAMING WEEDING EQUIPMENT

All propane-fueled flaming equipment must have several equipment components to carry out a successful flaming treatment. The following are basic equipment components (Figure 1, Knezevic et al. 2014b):

Supply Tank: A propane supply tank (Part 1, Figure 1) provides the propane for combustion. The capacity of propane tanks in flame weed control systems can range from 5kg to greater than 2500kg capacity, depending on system size and customer need. Depending on the type of flame weeding system, the tank will need either a liquid or vapor source safety valve (Part 2, Figure 2).

Supply Network: The supply network is a combination of parts that control propane flow and distribution (Parts 3–10, Figure 1). Manual 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 7 to 11bar depending on tank temperature) to the operating pressure (ranging from 0.3-5.5 bar depending on the system's calibration). Additional valves then control the amount of propane that flows to the torches. Tubing or hose compatible with propane pressures carries the propane from the supply tank to the torch throughout this process.

Figure 1: Diagram of basic flame weeding system components (Knezevic et al., 2014b)

Torch or Burner: The torch (also known as the burner) is the point of propane combustion (Parts 11-14, Figure 1). 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 orientation. The frame is commonly a large metal structure that can be attached to a tractor; in the case of handheld flaming equipment, the human body is considered the frame.

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

In addition to these basic equipment components, propane-fueled flaming systems can contain several other features that improve efficiency or protect crops or the operator, including the following:

Flame Shields: Hoods over the torch flames or 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 would be activated in the event of a malfunctioning burner.

Remote Monitoring and Ignition: It is also helpful for a system to immediately inform operators of extinguished torches. This notification system and a remote re-ignition option will increase system efficiency and protect the system operator from the heat generated by the torches.

Several 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 (Knezevic et al., 2007). 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.

WEED RESPONSE TO PROPANE FLAMING

Ascard (1994) reported that plant size had greater influence upon sensitivity than did plant density, with small weeds being more sensitive to flaming than large weeds. The stage of growth of weed species establishes the kind and degree of protec-

tive layers, the lignification level, and the location of growth points. Flaming is the most effective method for controlling most weeds at an early growth stage (Ascard 1995, 1998). Ascard (1995) classified weed species in four groups according to their susceptibility to propane flaming. The first group consisted of species with unprotected growing points and thin leaves (e.g., *Chenopodium album* L.): these species were easily controlled using propane doses of 20 to 50 kg ha⁻¹. The second group consisted of species with relatively protected growing points and leaves that were moderately heat-tolerant (e.g., *Polygonum aviculare* L.): these species can be completely controlled, but required propane doses higher than 50 kg ha⁻¹. The third group contained species with more protected growing points (e.g., *Capsella bursa-pastoris* (L.) Medik.): these species can be completely controlled at early stages (up to 4-leaf stage), but complete control is difficult to achieve at later growth stages. The fourth group consisted of plants with creeping growth habit and well protected growing points (e.g., perennial broadleaf and grasses): these plants regrow from their below ground meristems. To control species belonging from the third and the fourth group, flaming treatments should be conducted more than once. Knezevic et al., (2009c; 2014a,b) determined that the propane doses of 60-80 kg ha⁻¹ were highly effective in controlling many broadleaf weeds at early growth stages (up to 25 cm tall). Such doses provided over 90% control of major broadleaf species (*Abutilon theophrasti* Medik., *Ipomoea hederacea* Jacq., *Amaranthus retroflexus* L., *Amaranthus rudis* L., *C. album*, *Convolvulus arvensis* L., *Kochia scoparia* (L.) Schrad. and *Hibiscus trionum* L.) and 80% control of several grass species (*Echinochloa crus-galli* (L.) Beauv., *Setaria viridis* (L.) Beauv. and *Setaria glauca* (L.) Beauv.). The annual broadleaf and grass weed species responded differently to the flame and heat (Ulloa et al., 2010a,b). Leaves of annual broadleaf species were completely desiccated within a few days after flaming, and there was no plant regrowth especially when flamed with doses above 60 kg propane ha⁻¹. Leaves of grass species turned white shortly after flaming, leaving an appearance of a dead plant; however, within a week or two plants begin to recover with the growth of new leaves. Control of grass species can be improved by second flaming operation within 7 to 10 days after the first flaming. If an additional flaming is not feasible, an aggressive cultivation to push soil onto the top of the flamed grass is very helpful in preventing the regrowth of grass (Stepanovic et al., 2016a,b). This differential tolerance of grass and broadleaf species to broadcast flaming is consistent with previous report by Ascard (1995) who reported that grass species flamed at early growth stages showed initial plant stunting followed by plant recovery after a few weeks. Similar responses were also reported for field crops belonging to grass versus broadleaf families. Teixeira et al. (2008) demonstrated that soybean flamed at the third trifoliate stage had higher injuries than maize flamed at the 5-leaf stage, which re-grew a week later.

Flaming has no residual soil activity and the heat cannot penetrate deeper into the soil profile; therefore, flaming does not provide control of root structures of perennial weeds. However, some biannual and perennial weeds, such as *Cirsium arvense* (L.) Scop., *Carduus crispus* L. and *Carduus acanthoides* L. are extremely sensitive to heat, and their above-ground tissue and biomass can be easily desiccated. A propane dose of 15 kg ha⁻¹ turned leaves of *C. arvense* (L.) Scop. completely black within 24 hours after flaming; however, the plants regrew from their below-ground meristems within a few weeks. Flaming must be repeated several times during the season to control these weeds (Ascard, 1995, Knezevic et al., 2009a,b; Knezevic et al., 2014a,b). It is important to mention that the most important factor affecting the success of thermal weeding is the life cycle of the weeds, and overall perennial species are more tolerant to flaming than annual species (Rifai et al., 2002). In another study, Rifai et al. (1999) also reported less than 60% reduction in perennial weed numbers after one, two or three treatments at a propane dose of 35, 23 or 17 kg ha⁻¹ and only 75% after total gas doses of 320 and 216 kg ha⁻¹ over four flaming treatments. Repeated flaming over several years can deplete the nutrient reserves from the root and result in a complete kill of the plant. For example, experiments conducted by Hakansson (2003) and Rask and Andreasen (2007) showed that, to affect perennial plants sufficiently, the second and subsequent treatment should be carried out after an initial regrowth, but before regrowing shoots become too large.

PROPANE FLAMING IN AGRONOMIC CROPS

Crop susceptibility to propane flaming varies with species and growth stages (Knezevic and Ulloa, 2007; Domingues et al., 2008; Teixeira et al., 2008; Knezevic et al., 2009a,b,c, 2013). Knezevic and Ulloa (2007) observed that maize and sorghum flamed at earlier stages were less susceptible than soybean. In addition, Leroux et al. (2001) reported that maize flamed at coleoptile stage exhibited a 50% decrease in growth at 14 days after treatment.

Several studies assessed the tolerance in other maize types to propane flaming. Ulloa et al. (2010c) reported that sweet maize (*Zea mays* L. var. *rugosa*) was the most tolerant and had the lowest yield reduction (6%) when flamed with 85 kg ha⁻¹ of propane at the 7-leaf collar stage. Ulloa et al. (2010a) reported that popcorn (*Zea mays* L. var. *everta*) was the most tolerant when flamed at the 5-leaf collar stage with a 9% yield reduction when flamed with a propane dose of 85 kg ha⁻¹. Heiniger (1998) compared flaming to mechanical cultivation with respect to overall weed control and grain yield in popcorn and reported better weed control with flaming than cultivation, but there was no difference in popcorn yield. In another study, researchers concluded that the use of propane flaming in winter wheat is not recommended due to

unacceptable yield losses (Ulloa et al., 2010b). Hatfield and Vanderlip (1972) also observed that flaming wheat caused considerable delay in heading and resulted in severe grain yield reduction.

To optimize the use of flaming as a weed control tool, the response of many other crops to flaming and heat needs to be determined.

ECONOMIC OF FLAME WEEDING

From an economic stand point, the costs of a single flaming operation applied broadcast below crop canopy could be \$30-40 per hectare, without taking into account the costs of the equipment and labor [current price of propane (\$0.5/kg x 60-80 kg). Banded application (over the crop row) of flaming can cost \$12-20/ha due to lower propane use rates (30-40 kg ha⁻¹) (Knezevic et al., 2014b).

ADVANTAGES AND DISADVANTAGES OF FLAMING

Flaming is an attractive weed control option because it leaves no chemical residues in plants, soil, air or water, produces no drift hazards or herbicide carry-over to the next season and can control herbicide-tolerant or resistant weeds (Nemming, 1994; Wszelaki et al., 2007). Flame weeding has some major advantages over any herbicide and repeated tillage. Unlike herbicide, flame weeding has no negative impact on the quality of surface or underground water. Flame weeding does not disturb soil structure as repeated mechanical weeding does. It has been reported that repeated cultivation promotes loss of organic matter through the dust particles, and soil erosion induced by wind and heavy rains (Wszelaki et al., 2007; Stepanovic et al., 2016a,b). Flame weeding is also significantly less expensive than hand weeding and organic herbicides (Nemming, 1994) and there is likely no chance for weeds to develop resistance to high level of instant heat produced by flaming torches. In comparison with cultivation, flame weeding can be carried out on wet or stony soils, does not disrupt the soil surface and does not bring buried weed seeds to the soil surface (Ascard et al., 2007; Wszelaki et al., 2007). Flame weeding can significantly reduce the need for hand-weeding in organic systems.

The disadvantages of flame weeding when compared to conventional herbicides include higher cost of equipment compared to herbicide applicators, lack of selectivity for crop safety, low speed of application due to smaller coverage (e.g., most flamer can treat only 4 to 12 rows) and lack of residual weed control (Ascard, 1995; Ascard et al., 2007). Flame weeders have about the same field coverage capacity as

mechanical cultivators, but are much smaller than the chemical sprayers (Ascard et al., 2007). From a resource and environment point of view, the high energy requirement, the ineffective use of fossil fuels and the release of carbon emissions in relation to climate change could be seen as disadvantages; however, propane combustion is relatively clean compared to other fossil fuels, for example, diesel (Ascard et al., 2007).

PRACTICAL IMPLICATIONS OF FLAME WEEDING

A 60 kg propane ha⁻¹ was the most effective field application dose to control many annual broadleaf weeds and grasses. Grass type crops (e.g., field maize, popcorn, sweet maize and sorghum) are more tolerant to propane flaming than the broadleaf crop (e.g., soybean). Post-emergent flaming is not recommended in winter wheat due to high injury level and unacceptable yield reduction. Maize and sorghum can be safely flamed at their growth stages between emergence to 10-leaf collar stage. Soybean is tolerant to flaming only at the stages for emergence to unfolded cotyledon, and at the fourth to fifth trifoliate. It is not recommended to flame soybean at the unifoliate, first, second and third trifoliate, as these stages are very sensitive to heat and will result in very high crop injury and yield reduction (Knezevic et al., 2014b).

Maize and soybean can tolerate a maximum of two post-emergence flaming operations per season. Flaming conducted three times in field maize at the 2, 4 and 6-leaf collar growth stages exhibited more than 30% injury with as high as 15% yield reduction compared to the weed-free control plots (Nedeljkovic et al., 2011). Flaming soybean three times at the cotyledon, 2 trifoliate and 5 trifoliate growth stages resulted in more than 90% crop injury and as high as 90% yield reduction (Tursun et al., 2011). With respect to the time of a day, flame weeding is more effective if conducted during the afternoon, but crop injury will be higher, regardless of the propane dose. Thus, flaming could be done around the noon time in order to obtain the maximum weed control with the minimum crop damage (Ulloa et al., 2012). Flaming has a potential to be used effectively in organic crop production systems of three maize types, sorghum, soybean and sunflower when conducted properly at the most tolerant growth stage. Moreover, some modern precision agriculture techniques such as row detection and weed detection systems could also help in lowering crop injury risks and propane consumption (Van der Weide et al., 2008). It is important to mention that propane flaming should not be the only method for non-chemical weed control; however, it could be part of an integrated weed management program. Other measures are still needed to control weeds that emerge later during the growing season. More research is needed to perhaps develop new flaming equipment and methods, or to examine different positioning of the burners to avoid any significant crop damage and yield

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