DEVELOPMENT OF NEW TECHNOLOGIES TO IMPROVE WEED CONTROL IN ONION AND OTHER VEGETABLE CROPS

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ABSTRACT

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Weeds compete directly with crops for light, nutrients, and moisture and can cause significant economic loss. Most modern weed control technologies are developed for use in high-value agronomic crops and do not necessarily lend themselves to adoption in minor crops, such as vegetables. The limited number and low efficacy of weed control tools available to vegetable growers demand creativity and resourcefulness in developing successful weed control programs. This research examines several recently labeled onion herbicides as well as new, safer formulations of existing chemistries. The studies conducted intend to improve our understanding of the effects of these compounds under various application regimes, as they relate to weed control efficacy and onion phytotoxicity and yield. This research also examines the feasibility of using machine-vision guidance for postemergence weed control tool in vegetable crops. By combining a tractor-mounted, shielded weed flamer/sprayer with a camera and computer guidance system, it appears possible to control weeds while reducing the input of residual chemicals.

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INTRODUCTION

Weeds compete directly with crops for light, water, and nutrients. Weed suppression comes at great expense and difficulty to commercial growers, and inadequate weed control is often the most important limiting factor in the production of many vegetable crops (Rifai 1996, Fennimore and Doohan 2008).

Conventional methods of weed control rely heavily on tillage and/or synthetic chemicals. While these practices are relatively efficient and cost-effective, there are several issues associated with each. Tillage can diminish soil structure, cause depletion of soil organic matter, and promote soil erosion (Hatcher and Melander 2003; Boyd et al. 2006). Applying herbicides for weed control may contaminate groundwater, and pesticide residues remaining on produce raise concern for public health (Slaughter et al. 2008). Herbicide drift is a common cause of plant injury in areas adjacent to agricultural fields. Another concern regarding herbicide use is the exponential increase in the number of herbicide-resistant weed biotypes. Many vegetable crops have very few herbicides registered, and overuse of these herbicides, which often have a similar mode of action, increases the likelihood that resistant weed biotypes will develop over time (Wszelaki et al. 2007). Herbicide resistance creates persistent, hard-to-manage weeds which demand more expensive weed management strategies, greater chemical use, or a change in crop or crop genetics (Heiniger 1998).

To exacerbate matters, there are few new vegetable herbicides in development, as chemical companies do not want to assume the liability associated with registering herbicides in crops that are grown on small acreage and which may demonstrate the potential for crop injury. Most herbicides that are registered in vegetable crops often lack effective control of the entire weed spectrum (Fennimore and Doohan 2008). Any weeds that are not controlled by herbicide application usually entail additional weed management costs or yield loss. Labor for hand weeding is often the most costly aspect of vegetable crop production, and the cost of labor continues to rise while the availability of labor is becoming increasingly scarce (Sivesind et al. 2009; Fennimore and Doohan 2008).

An assessment of herbicide use patterns is needed from time to time to determine if current horticultural practices maximize the potential for weed control in specific crops. In recent years, there have been several new herbicide registrations in onion, which may provide enhanced crop safety and more effective weed control. Several of these new herbicides have different modes of action, and their use may reduce potential for the development of herbicide resistant weed biotypes. An in depth evaluation of these herbicides is needed to determine the optimum dosages, application timings, and tank mix compatibility issues as they relate to crop safety and weed control.

Weed control practices that enhance agricultural sustainability also need to be considered. For example, recent innovations in agricultural machine vision guidance have presented potential for new weed control techniques (Slaughter et al. 2008). There is also a renewed interest in thermal weed control, which may provide an additional tool for non-chemical methods of production (Knezevic and Ulloa 2007; Wszelaki 2007). By combining digital vision guidance technology and flame weeding, it may be possible to supplement current weed control methods, which rely heavily on chemical inputs, tillage, and labor for hand weeding. A thorough examination of this technology needs to be performed to assess its potential as an alternative method of weed control.

CHAPTER 1. IMPROVED WEED CONTROL IN ONION

LITERATURE REVIEW

Onion Domestication and Taxonomy

Onion (*Allium cepa*) cultivation began in southwest Asia over 5000 years ago, making it one of the oldest cultivated vegetable crops in the world. Two Middle Eastern species, *A. vavilovii* and the recently-discovered *A. asarense*, are onion's closest wild relatives, but neither species is believed to be the wild progenitor of onion. The direct ancestry of onion remains a mystery (Rabinowitch and Currah 2002). It is suggested that the wild progenitor of onion was a slow-growing perennial which produced a cluster of small bulbs. Selection for a single large bulb and biennial life cycle enhanced the potential for onion propagation and use as a storage vegetable (Brewster 2008). Today, onion is cultivated in most regions of the world, across a wide range of climates and latitudes.

Onion is a biennial crop that grows vegetatively during the first year of its life cycle and produces an overwintering storage organ called a bulb. Onions are dependent on daylength, and the induction of bulb formation is initiated in part by the perception of a critical minimum photoperiod. 'Short-day' onion varieties are grown in southern latitudes and require a photoperiod of 12-14 hours to induce bulbing. 'Long-day' varieties are typically grown in northern latitudes and require a 14-16 hour photoperiod to induce bulb formation (Lancaster et al. 1996).

Production Practices and Challenges

In Michigan, long-day storage onions are typically direct seeded in April and early May. Planting after May 10 results in yield reduction because the growing season in Michigan is too short for late-maturing storage varieties to achieve adequate size and quality. Most Michigan onions are grown on high organic soils due to their excellent water infiltration and retention capacities (Zandstra et al. 1996). Barley (*Hordeum spontaneum)* is often broadcast seeded at the time of onion seeding. Barley germinates and grows rapidly, which prevents soil erosion and protects young onions from wind damage. Before the barley becomes competitive, it is sprayed with a selective grass-killing herbicide so that the young onions may grow unencumbered (Zandstra et al. 1996).

Onion is among the poorest competitors of all vegetable crops. Germination of direct-seeded onion may require two weeks or longer if early-season temperatures are cool, favoring the proliferation of fast growing weeds (Bond and Burston 1996). After onion emergence, the slow rate of growth, shallow root system, and sparse upright foliage require growers to maintain season-long weed control (Dunan et al. 1996). Onions never produce a dense leaf canopy, which is needed to suppress weed growth and germination. If weeds are allowed to persist from sowing until harvest, 96-100% reduction in onion fresh weight may occur (Grundy et al. 2004; Bond and Burston 1996, Wicks et al. 1973). Several studies have demonstrated that season-long weed control is critical, as weed competition for short durations and at low levels of infestation can cause serious onion yield reduction or pose problems with harvesting equipment (Bond and Burston 1996; Dunan et al. 1996; Wicks et al. 1973; Menges and Tamez 1981, Williams et al. 2007).

Because of its poor competitive ability, onion has been used as a model crop to explore the economic viability of applying the preemergence herbicide DCPA (Dunan et al. 1995). It was determined that the high cost and low weed control efficacy of DCPA made its application economically unadvisable in most instances. Concerns regarding groundwater contamination have also been an issue when considering application of DCPA (Dunan et al. 1995). In recent years, several other preemergence herbicides have been labeled for use in onion.

Preemergence Herbicides

Several studies have assessed the effects of preemergence herbicides in onion. Pendimethalin, formulated as an emulsifiable concentrate, has been labeled for preemergence weed control in onion for several decades. Application of the emulsifiable concentrate formulation of pendimethalin has been shown to cause yield reduction in green onion (Norsworthy et al. 2007). A microencapsulated water-dispersible formulation of pendimethalin is now available, and research has demonstrated improved crop tolerance with the new formulation of pendimethalin (Hatzinikolaou et al. 2004). *S*-metolachlor and dimethenamid-p were evaluated for preemergence control of yellow nutsedge (*Cyperus esculentus* L.), a serious weed for which there are no effective postemergence herbicides registered for use in onion (Keeling et al. 1990). *S*-metolachlor and dimethenamid-p are registered for use in onion after the onion 2-leaf stage, but there may be adequate crop safety to apply these on organic soils prior to onion emergence. Ethofumesate is now registered for use in onion and was found to provide suppression of volunteer potato (Boydston and Seymour 2002). Ethofumesate was also compared to pendimethalin, quinclorac, pronamide, *s*-metolachlor, dimethenamid-p, and DCPA for preemergence weed control in green onion (Norsworthy et al. 2007). Other herbicides that provide preemergence weed suppression, such as oxyfluorfen, oxadiazon, metribuzin, have also been assessed (Ghosheh 2004; Qasem 2005, 2006).

Much of the scientific literature pertaining to preemergence weed control in onion assesses the effect of herbicides on onion transplants or sets (Keeling et al. 1990; Ghosheh 2004; Qasem 2005) or on direct-seeded green onion (Norsworthy et al. 2007). There are few recent studies that assess preemergence herbicide application to direct-seeded dry bulb onion (Boydston and Seymour 2002; Qasem 2006), and nearly all of the published preemergence weed control studies in onion have been conducted on mineral soil. Soil-applied herbicides adsorb more readily and are less mobile in organic soils than in mineral soils. As a result, the phytoxicity of soil-applied herbicides is inversely related to the organic matter content of the soil, so higher application rates are needed on muck soils to achieve the same weed control efficacy as application on mineral soils (Sharom and Stephenson 1976; Zandstra 2011). A thorough investigation of preemergence onion herbicides applied to direct-seeded onion grown on organic soils is needed.

Postemergence Herbicides

Although preemergence herbicides may be applied prior to onion emergence, they do not provide adequate control of the entire weed spectrum (Schumacher and Hatterman-Valenti 2007). Therefore, a successful weed control program usually requires the use of both preemergence and postemergence herbicides. Because young onion plants are especially susceptible to herbicide injury which can cause yield reduction, no postemergence broadleaf herbicides are labeled for application in onion until the 2 true-leaf stage (Williams et al. 2007). In Michigan this application timing is usually 6-8 weeks after the planting date, and by this time weeds are able to gain a competitive advantage over the onions (Loken and Hatterman-Valenti 2010). In fact, weeds allowed to compete for 2 weeks after onion emergence can cause up to 20% yield reduction (Wicks et al. 1973). Additionally, as weeds mature they become increasingly difficult to control with the limited number of postemergence herbicides registered for use in onion (Schumacher and Hatterman-Valenti 2007). Several new postemergence herbicides have been labeled for use in onion recently, and these herbicides may provide increased crop safety, earlier application timing, and greater control of the weed spectrum.

For much of the past three decades, oxyfluorfen and bromoxynil, both formulated as emulsifiable concentrates, have been the only postemergence herbicides registered for broadleaf weed control in onion (Cudney and Orloff 1988). Applying reduced rates of oxyfluorfen and bromoxynil in onion prior to the onion 2 leaf stage improved early-season control of several broadleaf weeds including common lambsquarters, which can be difficult to control if allowed to grow too large (Loken and Hatterman-Valenti 2010). Recently, oxyfluorfen was formulated as a suspension concentrate, and improved crop tolerance has been demonstrated in several vegetable crops, including onion (Richardson et al. 2006). Earlier application timing could allow for greater control of ladysthumb, which is one of the most serious weeds in Michigan onion production. Onions also exhibit tolerance to ethofumesate and flumioxazin (Norsworthy et al. 2007; Boydston and Seymour 2002). Both herbicides provide residual and burndown activity on susceptible weeds and are now labeled for application to emerged onions. Mustard weeds such as marsh yellowcress and Virginia pepperweed are becoming increasingly problematic in Michigan onion production, and these new herbicides may offer greater levels of control for these weeds. Fluroxypyr is also labeled for use in onion in Michigan and provides postemergence control of volunteer potato and several other weeds (Boydston and Seymour 2002). Postemergence control of yellow nutsedge, one of the most problematice weeds in onion, may be possible with bentazon. Bentazon is not currently labeled in onion, but there appears to be some level of onion tolerance to the herbicide (Peachey et al. 2008; Keeling et al.1990; Smith 2007). These postemergence onion herbicides must be evaluated to optimize use patterns such as application rate, timing, and tank mix compatibility.

WEED CONTROL IN ONION WITH PRE- AND POSTEMERGENCE HERBICIDES

Abstract

Field experiments were conducted in 2008, 2009, and 2010 to determine crop tolerance and weed control efficacy of several herbicides applied to direct-seeded dry bulb onions grown on organic soil. The preemergence herbicides examined include acetochlor, dimethenamid-p, ethofumesate, flumioxazin, pendimethalin, propachlor, and *s*-metolachlor. The postemergence herbicides examined were bentazon, bromoxynil, ethofumesate, flumioxazin, fluroxypyr, and oxyfluorfen. Preemergence application of pendimethalin at 2.24 or 4.48 kg/ha or propachlor at 4.48 kg/ha resulted in less than 10% injury in all years and provided good to fair preemergence control of most weed species. Acetochlor, dimethenamid-p, propachlor, and s-metolachlor provided adequate suppression of yellow nutsedge, but only propachlor was reliably safe when applied prior to onion emergence. Postemergence application of flumioxazin at 0.072 kg/ha or oxyfluorfen at 0.071 kg/ha resulted in less than 20% onion injury when applied at the 2 or 4 onion leaf stage and provided good control of most small broadleaf weeds. Bentazon, bromoxynil, and fluroxypyr resulted in unacceptable onion injury under the application rates and timings evaluated.

Nomenclature: Acetochlor; bentazon; bromoxynil; dimethenamid-p; ethofumesate; flumioxazin; fluroxypyr; pendimethalin; propachlor; oxyfluorfen; *s*-metolachlor; yellow nutsedge, *Cyperus esculentus* L.; onion, *Allium cepa* L.

Key Words: Onion, preemergence, postemergence, weed control.

Introduction

The United States onion industry is the third largest in the world, accounting for 2.5% of the world onion hectarage and over 7% of world onion production (Anonymous 2008a). Onion production in the United States is an intensively-managed system, and any factor that causes yield reduction may result in a loss of profitability to growers. Weed control is a critical component of successful onion production, as onion is one of the poorest competitors of all vegetable crops. Numerous studies have documented onion's poor competitive ability (Bond and Burston 1996; Dunan et al. 1996; Menges and Tamez 1981; Wicks et al. 1973; Williams et al. 2007). Weeds allowed to compete with onion for a short duration and/or at a low density will result in serious onion yield reduction. If allowed to persist for the entire season, weed interference can reduce onion yield 96-100% (Bond and Burston 1996, Wicks et al. 1973).

Michigan is one of the top 10 states in onion production, with approximately 2000 hectares in production annually. Most Michigan onions are grown on high organic soils, where they are direct-seeded in April through early May and harvested in September (Zandstra et al. 1996). Onions never develop a dense crop canopy necessary for preventing weed growth or germination, so growers must maintain complete weed control throughout the season (Dunan et al. 1996). This usually requires several applications of preemergence and postemergence herbicides. No herbicide labeled for use in onion provides adequate control of the entire weed spectrum, and any weeds that persist after an herbicide application require cultivation or hand weeding (Schumacher and Hatterman-Valenti 2007). Cultivation may be performed early in the growing season before the onion plants become too large, but onions are shallow-rooted and easily injured by cultivation. To exacerbate matters, labor for hand weeding is expensive and may be difficult to acquire (Fennimore and Doohan 2008).

Historically, very few herbicides have been labeled for use in onion. Allidochlor, propachlor, and chlorpropham were once labeled for preemergence weed control in onion, but their registrations have not been renewed for over two decades. For many years, DCPA and pendimethalin have been the only herbicides labeled for preemergence weed control in onion. The high cost and low efficacy of DCPA make its application economically unadvisable in many instances (Dunan et al. 1995). The emulsifiable concentrate formulation of pendimethalin, when applied to green onion, has been shown to cause injury and yield reduction (Norsworthy et al. 2007).

During much of the past several decades, bromoxynil, oxyfluorfen, and nitrofen were the only herbicides labeled for postemergence broadleaf weed control in onion (Cudney and Orloff 1988). The registration for nitrofen was withdrawn about 30 years ago. Bromoxynil and oxyfluorfen are labeled for application only after onion is at the 2 true leaf stage (Williams et al. 2007, Schumacher and Hatterman-Valenti 2007). By the time onion develops its second true leaf, weeds often have gained a competitive advantage over onion (Loken and Hatterman-Valenti 2010). Research has demonstrated that weeds allowed to compete with onion for as few as 2 weeks can cause 20% yield reduction (Wicks et al. 1973). Furthermore, the ability to achieve good postemergence weed control with bromoxynil or oxyfluorfen diminishes as weeds grow larger, and attempting to increase herbicide application rate to control weeds can cause serious injury to onion (Loken and Hatterman-Valenti 2010).

In recent years, several herbicides have been registered for use in onion. These herbicides may provide enhanced crop safety, earlier application timing, and greater control of the weed spectrum. Recently, a microencapsulated water-dispersible formulation of pendimethalin was developed, and research has demonstrated improved crop tolerance with the new formulation of pendimethalin (Hatzinikolaou et al. 2004). *S*-metolachlor and dimethenamid-p were recently labeled in onion and provide preemergence control of yellow nutsedge (*Cyperus esculentus*), a serious weed for which there are no effective postemergence herbicides in onion (Keeling et al. 1990). Postemergence control of yellow nutsedge may be possible with bentazon. Bentazon is not currently labeled in onion, but there appears to be some level of onion tolerance to the herbicide (Ghosheh 2004; Keeling et al.1990). Ethofumesate and flumioxazin provide residual and burndown control of numerous weeds, and both herbicides are now labeled in onion (Zandstra 2011). Recently, oxyfluorfen was formulated as a suspension concentrate, and improved crop tolerance has been demonstrated in several vegetable crops, including onion (Richardson et al. 2006). Fluroxypyr is also labeled for use in onion in several states and provides postemergence control of volunteer potato and several other weeds (Boydston and Seymour 2002).

A thorough investigation of these herbicides is needed to determine the optimum dosages, application timings, and tank mix compatibility issues as they relate to onion crop safety and weed control.

Materials and Methods

Field experiments were conducted in 2008, 2009, and 2010 at the Michigan State University Muck Research Station in Laingsburg, MI to evaluate preemergence and postemergence herbicides in onion. The soil at Laingsburg was a Houghton muck (Euic, mesic Typic Medisaprist) containing 76% organic matter and a pH of 6.7. Due to high weed pressure and flooding in Laingsburg in 2009, another iteration of experiments were conducted in a commercial onion field in 2010 at Bath, MI, where the soil was a Houghton muck (Euic, mesic Typic Medisaprist) containing 77% organic matter and a pH of 6.6.

In Laingsburg, plots consisted of 1.7 by 7.6 m raised beds planted with 3 single rows of direct-seeded onion planted on April 30, 2008, May 13, 2009, and May 4, 2010 to achieve a final population of approximately 620,000 plants/ha. Row spacing was 41cm. Each row within the plot was planted with a different variety of dry bulb onion typical of Michigan production, and the varieties 'Festival'[1], 'Santana'[2], and 'Sherman'[3] were selected. In Bath, plots consisted of 1.7 by 7.6 m beds planted with 4 double rows of direct-seeded onion ('Pulsar'[4]) planted on April 15, 2010 to achieve a final population of approximately 620,000 plants/ha. The experimental design at both locations was a randomized complete block with four replications. Fertilizers, insecticides, and fungicides were applied to all plots according to recommended Michigan crop production practices (Zandstra et al. 1996). Herbicide applications were made with a CO_2-pressurized backpack sprayer calibrated to deliver 187 L/ha at 210 kPa using a boom with four 8002 flat fan nozzles[5].

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[1] Festival hybrid onion. Bejo Seeds, Inc., 1972 Silver Spur Place, Oceano, CA 93445
[2] Santana hybrid onion. Bejo Seeds, Inc., 1972 Silver Spur Place, Oceano, CA 93445
[3] Sherman hybrid onion. Bejo Seeds, Inc., 1972 Silver Spur Place, Oceano, CA 93445
[4] Pulsar hybrid onion. Stokes Seeds, Inc., P.O. Box 548, Buffalo, NY 14240
[5] Teejet 8002 flat fan spray nozzles. Spraying Systems Co., P.O. Box 7900 Wheaton, Illinois 60189

Preemergence Herbicide Experiment. In the preemergence experiment, herbicide treatments were applied sequentially at three timings during the season, coinciding with commercial application timings which are separated by approximately 30 days to maximize longevity of herbicide activity in the soil (Table 1). The first preemergence application (PRE1) was made within 10 days after seeding, before onion emergence. Among the herbicides applied at the PRE1 timing, only pendimethalin is labeled for application prior to onion emergence on organic soils. Other herbicides applied at the PRE1 timing included ethofumesate, flumioxazin, and the chloroacetamide herbicides *s*-metolachlor, dimethenamid-p, propachlor, and acetochlor. The second application (PRE2) was made when the onions had 2 true leaves, and the third application (PRE3) was made when the onions had 4 to 5 true leaves. Oxyfluorfen SC at 0.07 kg/ha and sethoxydim at 0.2 kg/ha plus crop oil concentrate (COC) at 1% (v/v) were applied as needed for postemergence weed control. All postemergence herbicide applications were separated from preemergence herbicide treatments by at least 5 days to avoid any possible interaction. Regular hand weeding was performed to minimize the effect of weed interference.

Postemergence Herbicide Experiment. Within 10 days of seeding and prior to onion emergence, all postemergence plots received a broadcast application of pendimethalin ACS at 2.2 kg/ha for preemergence weed control plus bromoxynil at 0.3 kg/ha for control of any small emerged weeds. This preemergence application is a standard practice for Michigan onion production on high organic soils (Zandstra et al. 1996). The herbicide treatments in the postemergence experiment were applied at two timings based on the developmental stage of the onions (Table 2). The first postemergence herbicide application (POST1) was made when onions had 2 true leaves, the earliest labeled application timing for most postemergence onion herbicides. The second postemergence application (POST2) was made when onions had 4 to 5 true leaves, or about 30 days after the POST1 application. Herbicide treatments included flumioxazin, ethofumesate, fluroxypyr, bentazon, bromoxynil, and two formulations of oxyfluorfen. Various application rates were evaluated, as well as several herbicide combinations. Sethoxydim at 0.2 kg/ha plus COC at 1% (v/v) were applied as needed for postemergence grass control. Regular hand weeding was performed to minimize the effects of weed interference.

Data Collection and Statistical Analysis. Visual estimates of crop injury and weed control by species were recorded approximately 30 days after treatment (DAT) for all PRE application timings and at 7 DAT for each POST treatment. Visual estimates were based on a scale of 0 to 100%, where 0 = no injury or control and 100 = complete plant death. Onion growth and development were assessed by recording onion height and leaf number for a subsample of 10 randomly selected onion plants in each plot. To quantify weed control by species, the number of living weeds was counted from within 0.3 by 0.3 m quadrants, and two subsamples were recorded in each plot. Prior to harvest, onion stand was evaluated by counting the total number of onion plants within a 3 m section of each plot. Yields were measured separately for each variety at crop maturity by hand harvesting the entire plot in Laingsburg and the middle 5 m of each plot in Bath.

All data were subjected to analysis of variance using the Mixed procedure of SAS[6]. Means were separated using Fisher's protected LSD at $P \leq 0.05$. Data for crop injury and weed control evaluations were transformed prior to analysis using the arcsine square root transformation to stabilize variances. Transformation did not affect mean rank, so nontransformed means are presented for clarity.

[6] SAS version 9.1, SAS Institute Inc., 100 SAS Campus Dr., Cary, NC 27513.

Results and Discussion

Because of significant location by treatment interactions, data for Laingsburg and Bath are presented separately. Heavy rainfall and flooding in Laingsburg in 2009 resulted in extremely high weed pressure, onion stunting, and as the season progressed, caused confounding environmental effects and serious yield reduction. Therefore, 2009 yield data from Laingsburg were not included in the analysis. There were no significant variety by treatment or year by treatment interactions in the preemergence or postemergence experiment in Laingsburg for the 2008 and 2010 seasons. Therefore, data for both years and all onion varieties in Laingsburg were combined for analysis.

Preemergence Experiment. In Laingsburg and Bath, PRE1 application of pendimethalin ACS, pendimethalin EC, propachlor, or ethofumesate resulted in less than 10% injury at the application rates evaluated (Table 3). PRE1 application of pendimethalin at 4.48 kg/ha is double the labeled rate, but no onion injury was observed at this application rate. In both Laingsburg and Bath, early-season injury was greatest with dimethenamid-p or acetochlor (14 to 25% or 14 to 42%, respectively). In Laingsburg, PRE1 application of *s*-metolachlor or flumioxazin resulted in minimal injury but in Bath caused 25 and 31% injury, respectively. Treatments that included an application of acetochlor resulted in stunting and stand thinning (Table 4). After 3 sequential applications of acetochlor onion height was reduced 15% and onion leaf number was reduced 11%, when compared to the hand weeded control. In Bath, treatments that included acetochlor resulted in approximately 25% yield reduction, when compared to the highest yielding treatments. The hand weeded treatment yielded poorly in both locations because weed pressure was high, and without chemical weed suppression it was difficult to maintain complete control of the weeds without uprooting the onions or causing them physical injury.

Doubling the labeled rate of pendimethalin from 2.24 to 4.48 kg/ha improved early-season control of ladysthumb (*Polygonum persicaria*) from 44 to 67% and redroot pigweed (*Amaranthus retroflexus* L.) from 50 to 79% (Table 3). The four chloroacetamide herbicides, *s*-metolachlor, dimethenamid-p, propachlor, and acetochlor, were the only herbicides that provided moderate to good preemergence suppression of yellow nutsedge, with weed control ratings ranging from 61-72%. *S*-metolachlor and dimethenamid-p are labeled for use in onion at the 2 leaf stage, but yellow nutsedge emergence occurs prior to this application timing. Since there are no postemergence herbicides that effectively control yellow nutsedge, application of *s*-metolachlor or dimethenamid-p prior to onion emergence may enhance control of this weed, but consideration must be given to soil organic matter and soil moisture if crop stunting and stand thinning is to be prevented. Applying these herbicides prior to crop emergence has been shown to cause stand thinning in direct-seeded crops if soil moisture is excessive (Smith 2007). Propachlor provided good weed control of several weed species, including yellow nutsedge, but propachlor is not currently labeled in onion or manufactured for sale in the United States (Anonymous 2008b). Flumioxazin provided good suppression of redroot pigweed and common purslane (*Portulace oleracea* L.) when applied prior to onion emergence, but it is currently labeled for application to onions with 3 to 6 true leaves. Ethofumesate did not provide adequate preemergence control of any of the weeds evaluated on organic soils.

Postemergence Experiment.

Onion Injury. Onion injury caused by oxyfluorfen EC at 0.071 kg/ha did not exceed 20% at either application timing (Table 6). Oxyfluorfen SC applied at the equivalent rate did not cause more than 10% foliar injury. Postemergence application of oxyfluorfen SC at 0.071 kg/ha was 9 to 13% less injurious than postemergence application of oxyfluorfen EC at 0.071 kg/ha, with the exception of the POST1 application in Bath, where neither formulation caused significant onion injury.

Flumioxazin applied at 0.036 or 0.072 kg/ha caused slight foliar injury of 7 to 18%, but injury was similar at both application rates. Flumioxazin and oxyfluorfen, both PPO inhibitors, caused injury that consisted of small necrotic lesions and kinking of the onion foliage. Combining flumioxazin at 0.036 kg/ha and oxyfluorfen SC at 0.071 kg/ha resulted in 10 to 19% greater injury than the injury caused by application of these herbicides alone, with the exception of the POST1 timing in Bath, where injury was equivalent among the flumioxazin, oxyfluorfen, and flumioxazin plus oxyfluorfen SC tank mix treatments.

Ethofumesate was very safe for postemergence application in onion, and neither the 0.56 or 1.12 kg/ha application rate resulted in significant onion injury when applied at the 2 leaf stage or 4 to 5 leaf stage. Fluroxypyr caused serious onion injury at both application rates and timings. Within a day or two of fluroxypyr application, onion foliage appeared to lay flat on the soil. Chlorosis was noted within a week after fluroxypyr application. Fluroxypyr at 0.28 kg/ha caused 7 to 16% more injury than fluroxypyr at 0.14 kg/ha. The POST2 application of fluroxypyr resulted in severe onion injury of 44 to 56%, as the onions did not have sufficient time to recover from the POST1 application of fluroxypyr before receiving a second application.

Bentazon at 1.12 kg/ha caused 42% injury in Laingsburg and 28% onion injury in Bath at the POST1 application timing. POST2 application of bentazon resulted in less foliar injury than POST1 application, with 37% injury in Laingsburg and 19% injury in Bath.

Bromoxynil at 0.28 kg/ha caused slightly more injury than bromoxynil at 0.14 kg/ha, with the exception of the POST1 application in Bath, where minimal injury occurred at either rate. For several days prior to and after the POST1 application in Bath, unseasonably high air temperature and solar radiation were recorded (data not shown). In response, the onions likely developed a thicker leaf cuticle. This may have prevented the higher level of injury noted in the POST2 timing in Bath and both application timings in Laingsburg, as low temperature and radiation have been shown to result in increased bromoxynil phytotoxicity in onion (Menges and Tamez 1981).

Onion Yield. Fluroxypyr at 0.14 or 0.28 kg/ha resulted in 25 to 26% yield reduction in Laingsburg, when compared to the handweeded control (Table 6). Fluroxypyr did not provide good control of most of the weeds present in Bath and Laingsburg, and yield reduction with this herbicide was probably due to a combination of herbicide injury and weed interference.

Bentazon at 1.12 kg/ha caused 38% yield reduction in Laingsburg and 22% yield reduction in Bath, when compared to the highest yielding treatment. Bromoxynil at 0.28 kg/ha caused slight yield reduction in Laingsburg, when compared to the highest yielding treatment. Ethofumesate at 1.12 kg/ha also caused slight yield reduction in Laingsburg, but this reduction in yield was more likely a consequence of excessive weed interference than herbicide injury, as ethofumesate resulted in poor control of most weeds present.

Onion Height, Leaf Number, and Stand Density. Treatments that included fluroxypyr or bentazon consistently resulted in onion stunting and delay in development, evident in the reduction in onion plant height and leaf number, when compared to less injurious treatments (Table 7). Oxyfluorfen EC at 0.071 kg/ha caused slight but measurable stunting 7 days after POST1 application, but onions recovered rapidly and no adverse effects were noted later in the season.

Ethofumesate at 1.12 kg/ha, fluroxypyr at 0.14 or 0.28 kg/ha, and bromoxynil at 0.14 kg/ha resulted in stand count reduction in Laingsburg, when compared to treatments with the highest stands. However, the stand count in the hand weeded control was similar to the aforementioned treatments, indicating that stand thinning was probably due to excessive hand weeding rather than thinning caused by herbicide treatment, as these treatments were the poorest performing in terms of weed control. In Bath, where weed pressure was lower, these treatments had stands that were equivalent to treatments with the highest stands. Bentazon was the only herbicide to cause a reduction in stand at both locations, causing 21 and 48% stand reduction in Bath and Laingsburg, respectively.

Weed Control after POST2 Application. There were no significant year by treatment or location by treatment interactions for any of the weed control evaluations, with the exception of ladysthumb control. Therefore, ladysthumb control is presented separately for Laingsburg and Bath. Weed control evaluations for other weed species are combined over all trials whenever weeds were present in a particular year.

Seven days after the POST2 application, oxyfluorfen EC provided 92% control of common lambsquarters (*Chenopodium album* L.) and 64 to 72% control of ladysthumb (Table 9). Oxyfluorfen SC was less effective against these problematic early-season weeds than oxyfluorfen EC, providing 75% control of common lambsquarters and 39 to 51% control of ladysthumb. Combining flumioxazin and oxyfluorfen SC provided much better control of ladysthumb than applying either herbicide alone. The combination of flumioxazin and oxyfluorfen was one of the most effective treatments for control of all weeds present, with the exception of yellow nutsedge. Flumioxazin performed similarly to oxyfluorfen EC in regard to most weed species with the exception of spotted spurge (*Chamaesyce maculata* L.), which was not controlled by oxyfluorfen. Flumioxazin at 0.036 or 0.072 kg/ha provided equivalent levels of control for nearly all weed species. The higher flumioxazin rate provided 23% greater control of ladysthumb in Laingsburg, when compared to the 0.036 kg/ha rate.

Bromoxynil at 1.12 kg/ha provided 30 to 34% greater control of ladysthumb, redroot pigweed, and spotted spurge than did bromoxynil at 0.56 kg/ha. Both application rates provided excellent control of common lambsquarters and essentially no control of common purslane. Bromoxynil at 1.12 kg/ha was among the most effective treatments for early-season control of ladysthumb.

Ethofumesate did not provide adequate control of most weeds present, but ethofumesate at 1.12 kg/ha did provide greater than 70% control of common lambsquarters and common purslane. Fluroxypyr gave excellent control of common purslane and spotted spurge but was generally ineffective against most of the weeds commonly present in onion.

Bentazon was the only herbicide under evaluation that provided good postemergence control of yellow nutsedge (92%). Bentazon did not provide good control of redroot pigweed or spotted spurge but was the only herbicide that provided complete control of ladysthumb in both Laingsburg and Bath.

Weed Counts After POST2 Application. Information gathered from weed counts supported the qualitative visual estimations of weed control discussed above (Table 10). For example, bentazon reduced yellow nutsedge population by 94% when compared to the hand weeded control and was the only treatment to significantly reduce yellow nutsedge population. Bromoxynil was the only herbicide that did not reduce the population of common purslane. Ladysthumb population was significantly reduced after treatment with bentazon, bromoxynil, or the combination of flumioxazin plus oxyfluorfen SC, the most efficacious treatments for ladysthumb control.

Conclusions. Pendimethalin and propachlor were the only preemergence herbicides that provided consistent crop safety and effective weed suppression when applied prior to onion emergence. Pendimethalin ACS at 4.48 kg/ha is double the labeled rate for a single application. However, pendimethalin ACS at 4.48 kg/ha resulted in minimal onion injury, and control of many weed species was improved when compared to pendimethalin at 2.24 kg/ha. Although ethofumesate was very safe in onion, it did not provide sufficient preemergence weed control on organic soils. S-metolachlor and dimethenamid-p provided good suppression of yellow nutsedge when applied prior to onion emergence. These materials are not labeled for use in onion until the 2-leaf stage, and applying prior to this timing resulted in inconsistent and marginal crop safety. However, yellow nutsedge often emerges prior to the onion 2-leaf stage, and since there are no effective postemergence herbicides for control of yellow nutsedge in onion, severe infestations of this weed can reduce onion yield significantly. Acetochlor is not currently labeled for use in onion, and significant crop injury was observed in most experiments. Flumioxazin is not labeled for application prior to onion emergence, and crop safety was highly inconsistent at this timing. Furthermore, flumioxazin was no more efficacious than pendimethalin for most weed species present.

Oxyfluorfen EC and flumioxazin applied at the onion 2-leaf stage resulted in slight crop injury consisting of small necrotic lesions, but onions recovered quickly and these herbicides offered good to fair postemergence control of many small broadleaf weeds. Flumioxazin provided better control of spotted spurge than did oxyfluorfen EC. Oxyfluorfen SC was less injurious than oxyfluorfen EC but also less effective on many weeds when applied at the onion 2-leaf or 4-leaf stage. Bromoxynil caused serious onion injury in all cases except when application was preceded by several days of warm, dry, and sunny conditions. Bromoxynil at 0.28 kg/ha provided excellent control of common lambsquarters, redroot pigweed, and ladysthumb but was ineffective against common purslane. Fluroxypyr caused serious onion injury and provided inadequate control of most weeds. Bentazon is not labeled for use in onion, and severe crop injury was observed.

POSTEMERGENCE WEED CONTROL IN ONION WITH FLUMIOXAZIN, OXYFLUORFEN, AND BENTAZON

Abstract

Field experiments were conducted in 2008, 2009, and 2010 to evaluate crop tolerance and postemergence weed control in onion with oxyfluorfen, flumioxazin, and bentazon. Oxyfluorfen SC applied at the onion 1 leaf stage resulted in 12-15% less injury than equivalent rates of oxyfluorfen EC. Applying oxyfluorfen at the onion 1 leaf stage greatly improved control of 1 to 2 inch ladysthumb when compared with application of oxyfluorfen at the onion 2 leaf stage. Application of flumioxazin alone or in combination with pendimethalin ACS resulted in minimal onion injury and no yield reduction. Combining flumioxazin in a tank mix with pendimethalin EC, dimethenamid-p, or *s*-metolachlor resulted in 70 to 75% onion injury and 45 to 53% yield reduction. Bentazon applied at 0.56 kg/ha produced 20-27% onion injury and did not adequately control infestations of yellow nutsedge. Applying bentazon at 1.12 kg/ha provided good control of yellow nutsedge but caused severe onion injury and yield loss.

Nomenclature: Bentazon; dimethenamid-p; flumioxazin; pendimethalin; oxyfluorfen; *s*-metolachlor; yellow nutsedge, *Cyperus esculentus* L.; ladysthumb, *Polygonum persicaria* L.; onion, *Allium cepa* L.

Key Words: Onion, postemergence, weed control.

Introduction

Onion is one of the poorest competitors of all vegetable crops (Dunan et al. 1996; Menges and Tamez 1981). Direct-seeded onion requires several weeks to germinate under cool early-season conditions, and after emergence onion exhibits a slow rate of growth and development. Onion's poor competitive ability is also attributed to its shallow root system and sparse, upright foliage, which never achieves complete canopy closure (Dunan et al. 1996; Shumacher and Hatterman-Valenti 2006). To attain full yield potential, onion growers must suppress and remove weeds for the duration of the growing season, as minimal levels of weed infestation have been shown to result in serious yield reduction in onion. Early season weeds allowed to interfere with onions for as few as two weeks have been shown to reduce onion yield by 20% (Wicks et al. 1973).

The majority of onion production in Michigan occurs on organic soils because of their high capacity for water retention and infiltration (Zandstra et al. 1996). Numerous weed species also thrive under the optimal growing conditions provided by well-drained organic soils. Preemergence and postemergence herbicides are labeled for use in onion but often lack adequate control of the entire weed spectrum. Any weeds that are not controlled with herbicides must be hand weeded, which is expensive and has the potential to cause crop injury (Fennimore and Doohan 2008). Onions are also very sensitive to herbicide injury, especially during the early stages of development. Moderate stunting or foliar injury caused by herbicide application may result in yield reduction (Loken and Hatterman-Valenti 2010). In recent years, several herbicides have been labeled for use in onion, providing enhanced crop safety and/or expanding the spectrum of weed control.

For many years oxyfluorfen, formulated as an emulsifiable concentrate, has been one of the only herbicides labeled for postemergence broadleaf weed control in onion. Oxyfluorfen is a protoporphyrinogen oxidase (PPO) inhibitor that provides good burndown control of numerous broadleaf weeds and is labeled for application to direct-seeded onions with 2 or more true leaves (Boydston and Seymour 2003). A new water soluble suspension concentrate (SC) formulation of oxyfluorfen has been demonstrated to improve crop safety in several vegetable crops, including onion (Richardson et al. 2006). The new oxyfluorfen SC formulation may allow for earlier application, at the onion 1 leaf stage. This application timing is approved in several western states and may improve early-season weed control while maintaining crop safety.

Flumioxazin is a PPO inhibitor that was labeled in 2007 for over-the-top application to onions at the 3 to 6 leaf stage for residual control of numerous weed species. Flumioxazin also exhibits good postemergence burndown activity on many small broadleaf weeds (Zandstra 2011). Despite the potential for enhanced weed control, onion growers have been reluctant to add flumioxazin as a component of their weed control program for several reasons. Flumioxazin has been noted to cause severe onion injury if tank mixed with other pesticides or surfactants, and applying flumioxazin alone increases the number of pesticide applications to be made during the growing season (Norsworthy et al. 2007). Furthermore, the labeled application timing of flumioxazin, from the 3 to 6 leaf stage, is a relatively short span of time, considering that many onion varieties require 100 days or more to reach maturity. Application prior to the onion 3 leaf stage is critical for achieving good burndown control of weeds before they grow too large (Qasem 2005). To enhance the potential of applying flumioxazin as part of a weed control program in onion, a thorough assessment is needed to determine optimal usage patterns for flumioxazin, such as application timing and tank mix compatibility with other pesticides.

Bentazon has been studied for postemergence weed control in onion for a number of years but was never labeled for use in onion (Keeling et al.1990; Ghosheh 2004). There are no herbicides labeled for use in onion that provide postemergence control of yellow nutsedge, a serious weed that emerges over several months and can cause severe infestations in fields for many years. Bentazon controls yellow nutsedge and may be safe for use in onion. Keeling (1990) conducted experiments in 1987 and 1988 and applied bentazon at 0.8 kg/ha to transplanted onion 5 to 6 weeks after transplanting, when onions had 10 true leaves and yellow nutsedge was approximately 7.5 cm tall. No significant onion injury or yield loss was noted in either year. However, control of yellow nutsedge varied by year, with 80% control in 1987 and 35% control in 1988. Ghosheh (2004) found that set-grown onions treated with bentazon at 0.75 kg/ha at the 3 to 4 leaf stage were measurably stunted 5 weeks after treatment, and yields were significantly reduced when compared to the hand weeded control. Other reports also reveal the variable success of bentazon application, in regard to both onion injury and yellow nutsedge control (Peachey et al. 2008; Smith 2007). It appears possible to achieve bentazon selectivity in onion, but additional research is needed to optimize application parameters such as application timing and rate.

The objective of this research was to evaluate the impact of application rate, timing, and tank mix compatibility of oxyfluorfen, flumioxazin, and bentazon on weed control efficacy, crop injury, and yield of direct-seeded dry bulb onion grown on high organic soil.

Materials and Methods

Field experiments were conducted at the Michigan State University Muck Research Station in Laingsburg, MI in 2008, 2009, and 2010. The soil at Laingsburg was a Houghton muck (Euic, mesic Typic Medisaprist) containing 76% organic matter and a pH of 6.7. A second iteration of the experiments were conducted in 2010 at a commercial onion field in Bath, MI where the soil was a Houghton muck (Euic, mesic Typic Medisaprist) containing 77% organic matter and a pH of 6.6.

In Laingsburg, plots consisted of 1.7- by 7.6-m raised beds planted with 3 single rows of direct-seeded onion planted to achieve a final population of 620,000 plants/ha. Row spacing was 41cm, and each row was planted with a different variety of dry bulb onion typical of Michigan production. In the oxyfluorfen and flumioxazin experiments, varieties 'Festival'[7], 'Santana'[8], and 'Sherman'[9] were planted. In the bentazon experiment, varieties 'Highlander'[10], 'Nebula'[11], and 'T-439'[12] were planted. The planting dates in Laingsburg were April 30, 2008, May 13, 2009, and May 4, 2010. In Bath, plots consisted of 1.7- by 7.6-m beds planted with 4 double rows of direct-seeded onion ('Pulsar'[13]) planted on April 15, 2010 to achieve a final population of 620,000 plants/ha. No bentazon experiment was conducted in Bath. Fertilizers, insecticides, fungicides, and sprinkler irrigation were applied to all plots according to recommended Michigan crop production practices (Zandstra et al. 1996).

[7] Festival hybrid onion. Bejo Seeds, Inc., 1972 Silver Spur Place, Oceano, CA 93445
[8] Santana hybrid onion. Bejo Seeds, Inc., 1972 Silver Spur Place, Oceano, CA 93445
[9] Sherman hybrid onion. Bejo Seeds, Inc., 1972 Silver Spur Place, Oceano, CA 93445
[10] Highlander hybrid onion. Stokes Seeds, Inc., P.O. Box 548, Buffalo, NY 14240
[11] Nebula hybrid onion. Stokes Seeds, Inc., P.O. Box 548, Buffalo, NY 14240
[12] T-439 hybrid onion. American Takii, Inc., 301 Natividad Road, Salinas, CA 93906
[13] Pulsar hybrid onion. Stokes Seeds, Inc., P.O. Box 548, Buffalo, NY 14240

Herbicide applications were made with a CO_2-pressurized backpack sprayer calibrated to deliver 187 L/ha at 210 kPa using a boom with four 8002 flat-fan nozzles[14]. Within 10 days of seeding and prior to onion emergence, all trials received a broadcast application of pendimethalin ACS at 2.24 kg/ha for preemergence weed control plus bromoxynil at 0.28 kg/ha for burndown of any weeds that emerged after bed preparation and planting. Sethoxydim at 0.2 kg/ha plus crop oil concentrate (COC) at 1% (v/v) was applied as needed for postemergence grass control, and regular hand weeding was performed to minimize the effects of weed interference.

Oxyfluorfen Experiment. Treatments in the oxyfluorfen experiment were arranged as a four by two by two factorial, and the experimental design was a randomized complete block with four replications. Two levels of herbicide formulation, oxyfluorfen EC and oxyfluorfen SC, were compared and evaluated at four levels of application rate (0.035, 0.07, 0.14, and 0.21 kg/ha). Each combination of formulation and application rate was evaluated at two different levels of sequential application timing beginning at either the 1 leaf or 2 leaf stage of onion. A hand weeded control was used for comparison (Table 11).

Flumioxazin Experiment. Treatments in the flumioxazin experiment were arranged as a three by five factorial with three levels of flumioxazin rate (0, 0.036, and 0.072 kg/ha) and five levels of tank mix partner at their labeled rates (pendimethalin ACS, pendimethalin EC, *s*-metolachlor, dimethenamid-p, and none). The experimental design was a randomized complete block with four replications. Treatments were applied sequentially when the onions had 2 true leaves and again when they reached the 4 to 5 leaf stage (Table 12).

Bentazon Experiment. Treatments in the bentazon experiment were arranged in a randomized complete block design with four replications. Bentazon was applied at two rates, 0.56 or 1.12 kg/ha, and several treatments included a surfactant or herbicide added to the tank mix.

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[14] Teejet 8002 flat fan spray nozzles. Spraying Systems Co., P.O. Box 7900 Wheaton, Illinois 60189

Sequential applications of each treatment were applied at the onion 2 and 4 leaf stages. The onion 2 leaf stage coincided with yellow nutsedge emergence. Due to excessive onion injury, stand thinning, and yield reduction after application at the 2 leaf stage in 2008, additional treatments were added to the experiment in 2009 and 2010 to compare sequential application of bentazon beginning at the 2 leaf stage and application beginning at the 3 leaf stage. A hand weeded control was used for comparison (Table 13).

Data Collection and Statistical Analysis. Visual estimates of crop injury and weed control by species were recorded approximately 7 days after each treatment. Visual estimates were based on a scale of 0 to 100%, where 0 = no injury or control and 100 = complete plant death. Onion growth and development were assessed by recording onion height and leaf number for a subsample of 10 randomly selected onion plants in each plot. To quantify weed control by species, the number of living weeds was counted within 0.3 by 0.3 m quadrants, and two subsamples were collected in each plot. Prior to harvest, onion stand density was evaluated by counting the total number of onion plants within a 3 m section of each plot. Yields were measured at crop maturity by hand harvesting the entire plot in Laingsburg and the middle 5 m of each plot in Bath.

All data were subjected to analysis of variance using the MIXED procedure of SAS[15]. Means were compared using Fisher's protected LSD (P = 0.05).

[15] SAS version 9.1, SAS Institute Inc., 100 SAS Campus Dr., Cary, NC 27513.

Results and Discussion

Oxyfluorfen Experiment. There were no significant onion variety, year, or location interactions. Therefore, data were pooled over varieties and experimental iterations. There were significant formulation, timing, and rate interactions, so these data are presented separately. At the onion 1 leaf stage, application of oxyfluorfen SC at 0.070, 0.140, or 0.210 was 12 to 15% safer than the equivalent rate of oxyfluorfen EC (Table 14). Control of common lambsquarters and redroot pigweed was comparable for equivalent rates of the two formulations, but oxyfluorfen EC provided slightly better control of 1 to 2 inch ladysthumb than did oxyfluorfen SC when applied at the onion 1 leaf stage. Delaying the first application until the 2 leaf stage resulted in less disparity between the two formulations in terms of onion injury (Table 15). Ladysthumb was much more difficult to control at the onion 2 leaf stage than at the onion 1 leaf stage, especially with the SC formulation. Ladysthumb control surpassed 80% only when the first oxyfluorfen application was made prior to the 2 leaf stage (Table 16). Delaying the first application until the 2 leaf stage resulted in inadequate control of ladysthumb, which was 2 to 4 inches tall at application.

Oxyfluorfen SC did not cause yield reduction in onion under any of the parameters evaluated. Oxyfluorfen EC at 0.210 kg/ha caused significant yield reduction when the first application was made at either the 1 or 2 leaf stages. It appears that oxyfluorfen SC offers improved crop safety in onion when compared to equivalent rates of oxyfluorfen EC and may be applied safely at the onion 1 leaf stage for improved early-season weed control.

Flumioxazin Experiment. Because there were no significant onion variety, year, or location interactions, data were pooled over varieties and experimental iterations. There was a highly significant interaction of flumioxazin rate by tank mix partner for all variables assessed ($P \leq 0.001$ for all variables except yield, where $P = 0.017$). Flumioxazin at 0.036 kg/ha was equivalent to flumioxazin at 0.072 kg/ha in terms of onion injury and weed control, so data were pooled in a manner such that these rates of flumioxazin were combined at each level of tank mix partner and compared to treatments with no flumioxazin (Table 17).

Combining flumioxazin in a tank mix with pendimethalin EC, dimethenamid-p, or *s*-metolachlor resulted in severe onion injury (70 to 75%) and 45 to 53% yield reduction. However, applying flumioxazin alone or tank mixing flumioxazin with pendimethalin ACS caused minimal visual injury and resulted in no yield reduction. When dimethenamid-p or *s*-metolachlor was applied without the addition of flumioxazin, injury was 17 to 34% depending on application timing, but no significant yield loss was detected. *S*-metolachlor applied alone at the 2 leaf stage resulted in 25% onion height reduction and caused a delay in onion development at 14 DAT, evident in the 15% reduction in onion leaf number (Table 18). Pendimethalin ACS applied alone resulted in a reduction in leaf number when compared to the combination of pendimethalin ACS and flumioxazin, but there was no difference between the untreated and pendimethalin ACS treatments. Weed interference was probably the cause of this phenomenon, as pendimethalin ACS was very safe on onion but the least effective herbicide in terms of weed control.

Bentazon Experiment. Because of significant treatment by year interactions, all injury and yield data are presented separately for each year. There were no significant treatment by onion variety interactions in any year, so data were combined over all onion varieties. Weed control efficacy was similar among years, so data were combined over years for each weed species.

Bentazon applied at 1.12 kg/ha to onions with 2 leaves resulted in more injury than bentazon at 0.56 kg/ha (Table 19). In 2008, injury was 68% at the higher rate and only 18% at the lower rate. In 2009 and 2010, there was less disparity between application rates, with only 8 to 10% more injury at the higher rate. The addition of crop oil concentrate (COC) increased onion injury 13 to 42% when compared to equivalent rates of bentazon without COC. Adding COC did not improve early-season control of ladysthumb, redroot pigweed, or yellow nutsedge. Control of yellow nutsedge was less than 50% when bentazon was applied at 0.56 kg/ha, but bentazon at 1.12 kg/ha provided up to 90% yellow nutsedge control.

Onion injury and weed control after two sequential applications of bentazon are presented in Table 20. Two applications of bentazon at 0.56 kg/ha caused 20 to 24% injury in 2009 and 2010, and there was no difference in injury when the first application was made at the 2 leaf stage or 3 leaf stage. Application of bentazon at 1.12 kg/ha at the 3 and 4 leaf stage resulted in 13 to 19% less injury than application at the 2 and 4 leaf stage. Bentazon applied twice at 0.56 kg/ha provided only partial control of yellow nutsedge. However, when bentazon was applied twice at 1.12 kg/ha, yellow nutsedge control was over 94%. Ladysthumb control was excellent after two applications of bentazon at either 0.56 or 1.12 kg/ha. The only treatments to provide adequate control of redroot pigweed were the treatments that included oxyfluorfen or flumioxazin.

In 2008 all treatments resulted in stand reduction when compared to the hand weeded control (Table 21). In 2010, weed pressure was high and any stand reduction was most likely due to excessive hand weeding rather than herbicide injury, as some of the most injurious treatments had the densest stands of onion. In 2009 stand thinning occurred when bentazon was applied at 1.12 kg/ha with or without COC to onions at the 2 leaf stage. Bentazon at 0.56 kg/ha also caused stand thinning in 2009, but this may have been a consequence of high weed pressure and excessive hand weeding. Flooding caused excessive yield reduction in 2009, so those data were excluded in the analysis (Table 21). In 2008 and 2010, bentazon at 0.56 kg/ha applied alone or tank mixed with oxyfluorfen did not result in significant yield reduction when applied at the 2 leaf stage. Delaying the first bentazon application until the 3 leaf stage did not improve onion yield.

While there may be potential for bentazon selectivity in onion, it appears difficult to determine an adequate set of parameters for safe, effective weed control. It has been suggested that environmental conditions may affect bentazon phytotoxicity in onion (Peachey et al. 2008). Additional research is needed to assess the validity and implication of this observation.

APPENDIX

Table 1. List of herbicides, formulations, rates, and application timings for preemergence experiment.

Herbicide	Formulation	Rate[a]	Application timing[b]
		---kg/ha---	
Pendimethalin ACS	3.8 ACS	2.24	PRE1, PRE2, PRE3
Pendimethalin ACS	3.8 ACS	4.48	PRE1, PRE2, PRE3
Pendimethalin EC	3.3 EC	2.24	PRE1, PRE2, PRE3
S-metolachlor	7.62 EC	1.48	PRE1[d], PRE2, PRE3
Dimethenamid-p	6.0 EC	1.10	PRE1[d], PRE2, PRE3
Propachlor	4.0 F	4.48	PRE1[d], PRE2[d], PRE3[d]
Acetochlor[c]	6.4 EC	1.12	PRE1[d], PRE2[d], PRE3[d]
Ethofumesate	4.0 SC	1.12	PRE1, PRE2, PRE3
Flumioxazin	51 WDG	0.036	PRE1[d], PRE2[d], PRE3
Pendimethalin ACS fb. Pendimethalin EC	3.8 ACS 3.3 EC	2.24 2.24	PRE1, PRE2, PRE3
Pendimethalin ACS fb. Dimethenamid-p fb. S-metolachlor	3.8 ACS 6.0 EC 7.62 EC	2.24 1.10 1.48	PRE1, PRE2, PRE3
Pendimethalin ACS fb. S-metolachlor fb. Dimethenamid-p	3.8 ACS 7.62 EC 6.0 EC	2.24 1.48 1.10	PRE1, PRE2, PRE3
Pendimethalin ACS fb. Flumioxazin	3.8 ACS 51 WDG	2.24 0.032	PRE1, PRE2[d], PRE3
Pendimethalin ACS fb. Dimethenamid-p fb. Flumioxazin	3.8 ACS 6.0 EC 51 WDG	2.24 1.10 0.032	PRE1, PRE2, PRE3
Pendimethalin ACS fb. Acetochlor[c]	3.8 ACS 6.4 EC	2.24 1.12	PRE1, PRE2[d], PRE3[d]
Hand weeded	---	---	---

[a]Application rate at each application timing.

Table 1. (cont'd).

[b]Abbreviations: PRE1, application made 7 days after sowing but prior to onion emergence; PRE2, application at the onion 2-leaf stage; PRE3, application at the onion 4 to 5-leaf stage.

[c]Herbicide not currently labeled for use in onion.

[d]Herbicide not currently labeled for use in onion at this application timing.

Table 2. List of herbicides, formulations, rates, and application timings for postemergence experiment.

Herbicide	Formulation	Rate[a]	Application timing[b]
		kg/ha	
Oxyfluorfen EC	2.0 EC	0.071	POST1, POST2
Oxyfluorfen SC	4.0 SC	0.071	POST1, POST2
Flumioxazin	51 WDG	0.036	POST1[d], POST2
Flumioxazin	51 WDG	0.072	POST1[d], POST2
Ethofumesate	4.0 SC	0.56	POST1, POST2
Ethofumesate	4.0 SC	1.12	POST1, POST2
Fluroxypyr	2.8 L	0.14	POST1, POST2
Fluroxypyr	2.8 L	0.28	POST1, POST2
Bentazon[c]	4.0 L	1.12	POST1[d], POST2[d]
Bromoxynil	2.0 EC	0.14	POST1, POST2
Bromoxynil	2.0 EC	0.28	POST1, POST2
Oxyfluorfen SC + Flumioxazin	4.0 SC + 51 WDG	0.071 + 0.036	POST1[d], POST2
Oxyfluorfen SC + Ethofumesate	4.0 SC + 4.0 SC	0.071 + 0.56	POST1, POST2
Oxyfluorfen SC + Fluroxypyr	4.0 SC + 2.8 L	0.071 + 0.14	POST1, POST2
Oxyfluorfen SC + Bromoxynil	4.0 SC + 2.0 EC	0.071 + 0.14	POST1, POST2
Hand weeded	---	---	---

[a]Application rate at each application timing.

[b]Abbreviations: POST1, application at the onion 2-leaf stage; POST2, application made at the onion 4 to 5-leaf stage.

[c]Herbicide not currently labeled for use in onion.

[d]Herbicide not currently labeled for use in onion at this application timing.

Table 3. Onion injury and weed control 30 d after PRE1 application.

			Onion Injury[b]		Weed control[c]				
Herbicide	Rate	Application timing[a]	Laingsburg	Bath	Yellow nutsedge	Redroot pigweed	Ladys-thumb	Common lambs-quarters	Common purslane
	kg/ha		---%---						
Pendimethalin ACS	2.24	PRE1	1	3	14	50	44	94	86
Pendimethalin ACS	4.48	PRE1	2	3	14	79	67	98	92
Pendimethalin EC	2.24	PRE1	4	6	14	63	45	95	86
S-metolachlor	1.48	PRE1	6	25	64	89	44	36	81
Dimethenamid-p	1.10	PRE1	14	25	72	97	64	65	92
Propachlor	4.48	PRE1	2	3	61	93	56	73	89
Acetochlor	1.12	PRE1	16	42	64	99	54	81	94
Ethofumesate	1.12	PRE1	5	6	22	54	32	36	42
Flumioxazin	0.036	PRE1	1	31	17	90	52	62	92
Hand weeded	---	---	0	0	0	0	0	0	0
LSD			3.4	8.5	6.6	8.9	7.7	6.1	10.5
CV			37.1	28.1	27.6	15.5	15.3	11.8	9.4

[a]Abbreviations: PRE1, application made 7 days after sowing but prior to onion emergence.

[b]Data were pooled over experiments in 2008, 2009, and 2010 in Laingsburg and presented separately for 2010 in Bath due to significant treatment by location interactions.

Table 3. (cont'd).

[c]Data were pooled over experiments in 2008, 2009, and 2010 in Laingsburg and in 2010 in Bath.

Table 4. Effect of sequential preemergence herbicide application on onion height, leaf count, stand count, and yield.

Herbicide	Rate	Application timing[a]	Height[b] 10 d after PRE3	Leaf count[b] 10 d after PRE3	Stand count[b] 10 d after PRE3	Yield[c] Laingsburg	Yield[c] Bath
	kg/ha		cm	Leaves/plant	Plants/3 m	kg/plot	kg/plot
Pendimethalin ACS	2.24	PRE1, PRE2, PRE3	36.0	4.63	79.9	75.7	51.6
Pendimethalin ACS	4.48	PRE1, PRE2, PRE3	33.8	4.53	75.9	85.0	52.8
Pendimethalin EC	2.24	PRE1, PRE2, PRE3	35.3	4.58	77.4	76.8	56.5
S-metolachlor	1.48	PRE1, PRE2, PRE3	34.7	4.48	76.0	74.6	55.4
Dimethenamid-p	1.10	PRE1, PRE2, PRE3	34.8	4.72	72.4	76.9	53.3
Propachlor	4.48	PRE1, PRE2, PRE3	36.9	4.80	76.7	78.5	60.4
Acetochlor	1.12	PRE1, PRE2, PRE3	32.2	4.33	66.9	75.7	44.2
Ethofumesate	1.12	PRE1, PRE2, PRE3	35.8	4.74	79.4	74.9	54.1
Flumioxazin	0.036	PRE1, PRE2, PRE3	34.9	4.75	80.3	82.4	53.1
Pendimethalin ACS fb. Pendimethalin EC	2.24 2.24	PRE1, PRE2, PRE3	35.6	4.81	76.6	74.2	51.4
Pendimethalin ACS fb. Dimethenamid-p fb. S-metolachlor	2.24 1.10 1.48	PRE1, PRE2, PRE3	35.5	4.67	79.4	82.2	51.2
Pendimethalin ACS fb. S-metolachlor fb. Dimethenamid-p	2.24 1.48 1.10	PRE1, PRE2, PRE3	35.8	4.63	78.1	79.7	54.7

Table 4. (cont'd).

Pendimethalin ACS fb. Flumioxazin	2.24 0.032	PRE1, PRE2, PRE3	35.3	4.72	76.5	74.9	53.7
Pendimethalin ACS fb. Dimethenamid-p fb. Flumioxazin	2.24 1.10 0.032	PRE1, PRE2, PRE3	36.4	4.73	80.5	78.5	54.0
Pendimethalin ACS fb. Acetochlor	2.24 1.12	PRE1, PRE2, PRE3	32.9	4.52	69.2	77.0	44.7
Hand weeded	---	---	37.7	4.86	72.7	53.6	46.9
LSD			3.8	0.25	10.3	10.8	11.9
CV			13.1	17.5	11.3	13.6	11.9

[a]Abbreviations: PRE1, application made 7 days after sowing but prior to onion emergence; PRE2, application at the onion 2-leaf stage; PRE3, application at the onion 4 to 5-leaf stage.

[b]Data were pooled over experiments in 2008, 2009, and 2010 in Laingsburg and in 2010 in Bath.

[c]Data were pooled over experiments in 2008 and 2010 in Laingsburg and presented separately for 2010 in Bath due to significant treatment by location interactions.

Table 5. Effect of sequential preemergence herbicide application on weed counts for common weed species 10 d after PRE3.

Herbicide	Rate	Application timing[a]	Large crabgrass[b]	Yellow nutsedge[b]	Common lambs-quarters[b]	Common purslane[b]	Ladys-thumb[b]	Redroot pigweed[b]
	kg/ha		------------------------------Plants/0.1 m^2----------------------------					
Pendimethalin ACS	2.24	PRE1, PRE2, PRE3	0.25	3.25	0.00	0.56	0.88	0.63
Pendimethalin ACS	4.48	PRE1, PRE2, PRE3	0.00	3.50	0.13	0.25	0.25	0.38
Pendimethalin EC	2.24	PRE1, PRE2, PRE3	1.00	1.00	0.25	0.38	0.88	0.13
S-metolachlor	1.48	PRE1, PRE2, PRE3	0.00	1.25	0.69	1.06	1.25	0.00
Dimethenamid-p	1.10	PRE1, PRE2, PRE3	0.00	0.25	0.69	0.13	1.63	0.00
Propachlor	4.48	PRE1, PRE2, PRE3	0.75	1.50	0.75	2.44	0.63	0.38
Acetochlor	1.12	PRE1, PRE2, PRE3	0.00	0.25	0.81	0.25	1.19	0.06
Ethofumesate	1.12	PRE1, PRE2, PRE3	0.00	1.50	0.75	0.63	0.88	0.19
Flumioxazin	0.036	PRE1, PRE2, PRE3	2.25	2.00	0.38	0.44	0.13	0.13
Pendimethalin ACS fb. Pendimethalin EC	2.24 2.24	PRE1, PRE2, PRE3	0.25	1.75	0.50	0.94	0.38	0.50
Pendimethalin ACS fb. Dimethenamid-p fb. S-metolachlor	2.24 1.10 1.48	PRE1, PRE2, PRE3	0.00	1.00	0.94	0.81	1.63	0.06
Pendimethalin ACS fb. S-metolachlor fb. Dimethenamid-p	2.24 1.48 1.10	PRE1, PRE2, PRE3	0.00	1.00	1.19	1.63	1.44	0.00

Table 5. (cont'd).

Pendimethalin ACS fb. Flumioxazin	2.24 0.032	PRE1, PRE2, PRE3	0.75	2.50	0.19	1.38	0.50	0.06
Pendimethalin ACS fb. Dimethenamid-p fb. Flumioxazin	2.24 1.10 0.032	PRE1, PRE2, PRE3	0.00	1.25	0.25	0.19	0.44	0.06
Pendimethalin ACS fb. Acetochlor	2.24 1.12	PRE1, PRE2, PRE3	0.25	0.75	0.50	0.13	1.44	0.13
Hand weeded	---	---	1.50	1.00	1.75	4.50	1.00	0.44
LSD			0.91	NS	0.82	1.45	0.71	NS
CV			26.7	37.9	12.4	20.7	20.9	10.9

[a]Abbreviations: PRE1, application made 7 days after sowing but prior to onion emergence; PRE2, application at the onion 2-leaf stage; PRE3, application at the onion 4 to 5-leaf stage.

[b]Data were pooled over experiments in 2008, 2009, and 2010 in Laingsburg and in 2010 in Bath.

Table 6. Effect of postemergence herbicides on onion injury and yield.

Herbicide	Rate	Application timing[a]	Injury 7 d after POST1[b]		Injury 7 d after POST2[b]		Yield[c]	
			Laingsburg	Bath	Laingsburg	Bath	Laingsburg	Bath
	kg/ha		---------------------------%-----------------------				kg/plot	kg/plot
Oxyfluorfen EC	0.071	POST1, POST2	20	6	19	17	77.5	53.7
Oxyfluorfen SC	0.071	POST1, POST2	7	6	10	6	73.0	50.4
Flumioxazin	0.036	POST1, POST2	7	14	16	14	74.6	53.9
Flumioxazin	0.072	POST1, POST2	11	8	18	14	71.4	51.4
Ethofumesate	0.56	POST1, POST2	2	0	3	0	67.4	55.9
Ethofumesate	1.12	POST1, POST2	5	8	3	3	60.7	57.2
Fluroxypyr	0.14	POST1, POST2	30	28	45	44	51.8	46.7
Fluroxypyr	0.28	POST1, POST2	37	44	53	56	52.7	39.5
Bentazon	1.12	POST1, POST2	42	28	37	19	49.7	46.5
Bromoxynil	0.14	POST1, POST2	16	6	25	11	67.0	51.7
Bromoxynil	0.28	POST1, POST2	21	11	35	19	64.8	58.7
Oxyfluorfen SC + Flumioxazin	0.071 + 0.036	POST1, POST2	23	14	26	25	80.1	58.9

Table 6. (cont'd).

Oxyfluorfen SC + Ethofumesate	0.071 + 0.56	POST1, POST2	16	11	11	11	78.3	57.5
Oxyfluorfen SC + Fluroxypyr	0.071 + 0.14	POST1, POST2	39	33	36	44	73.7	47.6
Oxyfluorfen SC + Bromoxynil	0.071 + 0.14	POST1, POST2	25	8	22	17	75.9	59.4
Hand weeded	---	---	0	0	0	0	69.4	44.8
LSD			4.5	9.9	5.3	7.0	15.0	9.9
CV			20.5	26.3	19.9	17.0	12.1	12.2

[a]Abbreviations: POST1, application at the onion 2-leaf stage; POST2, application at the onion 4 to 5-leaf stage.

[b]Data were pooled over experiments in 2008, 2009, and 2010 in Laingsburg and presented separately for 2010 in Bath due to significant treatment by location interactions.

[c]Data were pooled over experiments in 2008 and 2010 in Laingsburg and presented separately for 2010 in Bath due to significant treatment by location interactions.

Table 7. Effect of postemergence herbicides on onion height, leaf count, and stand count.

Herbicide	Rate	Application timing[a]	Height 1[b] 10 d after POST1	Height 2[b] 10 d after POST2	Leaf count[b] 10 d after POST2	Stand count 10 d after POST2[c] Laingsburg	Bath
	kg/ha		------------cm----------		Leaves/plant	---------Plants/3 m----------	
Oxyfluorfen EC	0.071	POST1, POST2	18.0	38.9	4.56	68.6	73.8
Oxyfluorfen SC	0.071	POST1, POST2	20.3	41.4	4.73	68.7	73.5
Flumioxazin	0.036	POST1, POST2	19.9	40.3	4.79	70.0	70.5
Flumioxazin	0.072	POST1, POST2	19.9	40.9	4.83	71.5	70.8
Ethofumesate	0.56	POST1, POST2	20.1	41.3	4.83	72.5	75.8
Ethofumesate	1.12	POST1, POST2	20.0	38.0	4.68	62.8	73.5
Fluroxypyr	0.14	POST1, POST2	19.7	36.1	4.53	64.1	77.0
Fluroxypyr	0.28	POST1, POST2	18.7	33.4	4.33	61.5	73.8
Bentazon	1.12	POST1, POST2	17.4	32.0	4.31	38.5	66.0
Bromoxynil	0.14	POST1, POST2	18.0	37.9	4.79	61.3	80.5
Bromoxynil	0.28	POST1, POST2	18.9	39.7	4.75	67.3	83.3
Oxyfluorfen SC + Flumioxazin	0.071 + 0.036	POST1, POST2	19.2	39.6	4.64	73.8	81.0

Table 7. (cont'd).

Oxyfluorfen SC + Ethofumesate	0.071 + 0.56	POST1, POST2	19.6	40.7	4.61	73.2	75.3
Oxyfluorfen SC + Fluroxypyr	0.071 + 0.14	POST1, POST2	18.4	35.7	4.44	72.3	77.5
Oxyfluorfen SC + Bromoxynil	0.071 + 0.14	POST1, POST2	19.2	38.7	4.64	72.8	76.8
Hand weeded	---	---	20.8	39.9	4.78	61.5	69.5
LSD			2.0	3.2	0.22	9.1	10.2
CV			21.3	16.4	16.6	11.5	9.8

[a]Abbreviations: POST1, application at the onion 2-leaf stage; POST2, application at the onion 4 to 5-leaf stage.

[b]Data were pooled over experiments in 2008 and 2010 in Laingsburg.

[c]Data were pooled over experiments in 2008 and 2010 in Laingsburg and presented separately for 2010 in Bath due to significant treatment by location interactions

Table 8. Effect of postemergence herbicides on control of common weed species 7 d after POST1.

Herbicide	Rate	Application timing[a]	Yellow nutsedge[b]	Common lambs-quarters[b]	Common purslane[b]	Ladysthumb[c] Laings-burg	Ladysthumb[c] Bath	Redroot pigweed[b]	Spotted spurge[b]
	kg/ha		--------	--------	--------	%	--------	--------	--------
Oxyfluorfen EC	0.071	POST1, POST2	14	92	100	67	25	94	53
Oxyfluorfen SC	0.071	POST1, POST2	8	47	97	40	22	90	86
Flumioxazin	0.036	POST1, POST2	8	81	94	45	42	99	86
Flumioxazin	0.072	POST1, POST2	11	94	100	59	33	100	89
Ethofumesate	0.56	POST1, POST2	11	94	56	33	17	53	47
Ethofumesate	1.12	POST1, POST2	8	67	44	30	42	54	47
Fluroxypyr	0.14	POST1, POST2	6	56	78	40	53	65	69
Fluroxypyr	0.28	POST1, POST2	8	47	92	53	75	68	89
Bentazon	1.12	POST1, POST2	89	97	100	100	100	65	89
Bromoxynil	0.14	POST1, POST2	3	100	28	71	56	88	50
Bromoxynil	0.28	POST1, POST2	6	100	31	92	100	89	69
Oxyfluorfen SC + Flumioxazin	0.071 + 0.036	POST1, POST2	11	94	100	65	61	100	75

Table 8. (cont'd).

Oxyfluorfen SC + Ethofumesate	0.071 + 0.56	POST1, POST2	31	86	100	68	50	96	92
Oxyfluorfen SC + Fluroxypyr	0.071 + 0.14	POST1, POST2	28	89	97	76	69	97	94
Oxyfluorfen SC + Bromoxynil	0.071 + 0.14	POST1, POST2	8	100	100	88	67	99	81
Hand weeded	---	---	0	0	0	0	0	0	0
LSD			8.0	14.9	11.8	7.5	14.2	9.2	21.5
CV			14.8	21.9	9.9	16.0	20.5	17.0	30.1

[a]Abbreviations: POST1, application at the onion 2-leaf stage; POST2, application at the onion 4 to 5-leaf stage.

[b]Data were pooled over experiments in 2008, 2009, and 2010 in Laingsburg and 2010 in Bath.

[c]Data were pooled over experiments in 2008, 2009, and 2010 in Laingsburg and presented separately for 2010 in Bath due to significant treatment by location interactions.

Table 9. Effect of sequential application of postemergence herbicides on control of common weed species 7 d after POST2.

Herbicide	Rate	Application timing[a]	Yellow nutsedge[b]	Common lambs-quarters[b]	Common purslane[b]	Ladysthumb[c] Laings-burg	Ladysthumb[c] Bath	Redroot pigweed[b]	Spotted spurge[b]
	kg/ha		%						
Oxyfluorfen EC	0.071	POST1, POST2	13	92	100	72	64	98	17
Oxyfluorfen SC	0.071	POST1, POST2	21	75	100	51	39	94	22
Flumioxazin	0.036	POST1, POST2	15	84	100	65	64	99	86
Flumioxazin	0.072	POST1, POST2	22	92	100	88	56	98	94
Ethofumesate	0.56	POST1, POST2	8	66	63	28	25	44	72
Ethofumesate	1.12	POST1, POST2	7	73	74	17	42	42	56
Fluroxypyr	0.14	POST1, POST2	7	42	100	35	56	21	81
Fluroxypyr	0.28	POST1, POST2	7	44	99	44	72	43	92
Bentazon	1.12	POST1, POST2	92	81	97	100	100	38	14
Bromoxynil	0.14	POST1, POST2	7	95	1	61	58	43	42
Bromoxynil	0.28	POST1, POST2	3	100	13	94	92	76	72
Oxyfluorfen SC + Flumioxazin	0.071 + 0.036	POST1, POST2	25	97	100	92	81	100	94

Table 9. (cont'd).

Oxyfluorfen SC + Ethofumesate	0.071 + 0.56	POST1, POST2	26	94	100	85	56	87	67
Oxyfluorfen SC + Fluroxypyr	0.071 + 0.14	POST1, POST2	24	78	100	81	69	98	89
Oxyfluorfen SC + Bromoxynil	0.071 + 0.14	POST1, POST2	13	92	88	86	67	92	44
Hand weeded	---	---	0	0	0	0	0	0	0
LSD			8.1	13.2	11.3	11.7	14.3	11.2	26.9
CV			14.6	22.2	11.8	16.1	18.3	17.0	21.4

[a]Abbreviations: POST1, application at the onion 2-leaf stage; POST2, application at the onion 4 to 5-leaf stage.

[b]Data were pooled over experiments in 2008, 2009, and 2010 in Laingsburg and 2010 in Bath.

[c]Data were pooled over experiments in 2008, 2009, and 2010 in Laingsburg and presented separately for 2010 in Bath due to significant treatment by location interactions

Table 10. Effect of sequential postemergence herbicide application on weed counts for common weed species 10 d after POST2.

Herbicide	Rate	Application timing[a]	Large crabgrass[b]	Yellow nutsedge[b]	Common purslane[b]	Ladys-thumb[b]	Redroot pigweed[b]	Spotted spurge[b]
	kg/ha		---------------------------------Plants/0.1 m^2					-------------------------------
Oxyfluorfen EC	0.071	POST1, POST2	0.38	10.25	0.00	0.88	0.69	1.63
Oxyfluorfen SC	0.071	POST1, POST2	0.69	10.63	0.00	0.63	0.75	0.56
Flumioxazin	0.036	POST1, POST2	0.25	10.25	0.06	0.88	0.13	0.19
Flumioxazin	0.072	POST1, POST2	0.13	13.44	0.00	1.13	0.00	0.13
Ethofumesate	0.56	POST1, POST2	0.38	9.69	0.38	1.69	1.19	0.56
Ethofumesate	1.12	POST1, POST2	0.06	8.63	0.19	1.63	0.38	0.31
Fluroxypyr	0.14	POST1, POST2	0.13	9.50	0.06	1.81	0.94	0.38
Fluroxypyr	0.28	POST1, POST2	0.38	9.88	0.00	1.81	0.19	0.19
Bentazon	1.12	POST1, POST2	0.50	0.69	0.25	0.25	0.81	1.13
Bromoxynil	0.14	POST1, POST2	0.19	9.81	8.38	0.19	1.00	1.00
Bromoxynil	0.28	POST1, POST2	0.06	14.19	7.38	0.00	0.06	0.38
Oxyfluorfen SC + Flumioxazin	0.071 + 0.036	POST1, POST2	0.19	12.00	0.13	0.25	0.25	0.25
Oxyfluorfen SC + Ethofumesate	0.071 + 0.56	POST1, POST2	0.31	12.81	0.13	1.19	0.06	0.75

Table 10. (cont'd).

Oxyfluorfen SC + Fluroxypyr	0.071 + 0.14	POST1, POST2	0.00	10.44	0.13	1.13	0.25	0.31
Oxyfluorfen SC + Bromoxynil	0.071 + 0.14	POST1, POST2	0.25	17.50	0.13	0.00	0.00	1.06
Hand weeded	---	---	0.13	11.13	8.69	1.69	2.19	1.13
LSD			NS	6.96	3.15	1.28	1.11	NS
CV			45.7	25.4	16.5	23.1	15.2	36.2

[a]Abbreviations: POST1, application at the onion 2-leaf stage; POST2, application at the onion 4 to 5-leaf stage.

[b]Data were pooled over experiments in 2008, 2009, and 2010 in Laingsburg and in 2010 in Bath.

Table 11. List of herbicides, formulations, rates, and application timings for the oxyfluorfen experiment.

Herbicide[a]	Formulation	Rate[b]	Application timing[c]
		kg/ha	
Oxyfluorfen SC	4 SC	0.035	1 LS, 2 LS, 3 LS
Oxyfluorfen SC	4 SC	0.070	1 LS, 2 LS, 3 LS
Oxyfluorfen SC	4 SC	0.140	1 LS, 2 LS, 3 LS
Oxyfluorfen SC	4 SC	0.210	1 LS, 2 LS, 3 LS
Oxyfluorfen EC	2 EC	0.035	1 LS, 2 LS, 3 LS
Oxyfluorfen EC	2 EC	0.070	1 LS, 2 LS, 3 LS
Oxyfluorfen EC	2 EC	0.140	1 LS, 2 LS, 3 LS
Oxyfluorfen EC	2 EC	0.210	1 LS, 2 LS, 3 LS
Oxyfluorfen SC	4 SC	0.035	2 LS, 4 LS
Oxyfluorfen SC	4 SC	0.070	2 LS, 4 LS
Oxyfluorfen SC	4 SC	0.140	2 LS, 4 LS
Oxyfluorfen SC	4 SC	0.210	2 LS, 4 LS
Oxyfluorfen EC	2 EC	0.035	2 LS, 4 LS
Oxyfluorfen EC	2 EC	0.070	2 LS, 4 LS
Oxyfluorfen EC	2 EC	0.140	2 LS, 4 LS
Oxyfluorfen EC	2 EC	0.210	2 LS, 4 LS
Hand weeded	---	---	---

[a]Oxyfluorfen is formulated as 1) a water soluble suspension concentrate (SC) and sold under the trade name Goaltender® and 2) as an emulsifiable concentrate (EC) sold under the trade name Goal 2XL®.

[b]Application rate at each application timing

[c]Abbreviations: LS, onion leaf stage or number of true leaves at application.

Table 12. List of herbicides, formulations, rates, and application timings for the flumioxazin experiment.

Flumioxazin	Formulation	Rate[a]	Application timing[b]
		kg/ha	
Flumioxazin + Pendimethalin ACS	51 WDG + 3.8 ACS	0.072 + 2.24	2 LS, 4 LS
Flumioxazin + Pendimethalin EC	51 WDG + 3.3 ACS	0.072 + 2.24	2 LS, 4 LS
Flumioxazin + Dimethenamid-p	51 WDG + 6.0 EC	0.072 + 1.10	2 LS, 4 LS
Flumioxazin + *S*-metolachlor	51 WDG + 7.62 EC	0.072 + 1.48	2 LS, 4 LS
Flumioxazin	51 WDG	0.072	2 LS, 4 LS
Flumioxazin + Pendimethalin ACS	51 WDG + 3.8 ACS	0.036 + 2.24	2 LS, 4 LS
Flumioxazin + Pendimethalin EC	51 WDG + 3.3 ACS	0.036 + 2.24	2 LS, 4 LS
Flumioxazin + Dimethenamid-p	51 WDG + 6.0 EC	0.036 + 1.10	2 LS, 4 LS
Flumioxazin + *S*-metolachlor	51 WDG + 7.62 EC	0.036 + 1.48	2 LS, 4 LS
Flumioxazin	51 WDG	0.036	2 LS, 4 LS
Pendimethalin ACS	3.8 ACS	2.24	2 LS, 4 LS
Pendimethalin EC	3.3 ACS	2.24	2 LS, 4 LS
Dimethenamid-p	6.0 EC	1.10	2 LS, 4 LS
S-metolachlor	7.62 EC	1.48	2 LS, 4 LS
Hand weeded	---	---	---

[a]Application rate at each application timing

[b]Abbreviations: LS, onion leaf stage or number of true leaves at application.

Table 13. List of herbicides, formulations, rates, and application timings for the bentazon experiment.

Herbicide[a]	Formulation	Rate[b]	Application timing[a]
		kg/ha	
Bentazon	4.0 L	0.56	2 LS, 4 LS
Bentazon	4.0 L	1.12	2 LS, 4 LS
Bentazon + COC	4.0 L	0.56	2 LS, 4 LS
Bentazon + COC	4.0 L	1.12	2 LS, 4 LS
Bentazon + Oxyfluorfen	4.0 L 4.0 SC	0.56 + 0.071	2 LS, 4 LS
Bentazon + Flumioxazin	4.0 L 51 WDG	0.56 + 0.072	2 LS, 4 LS
Bentazon	4.0 L	0.56	3 LS, 4 LS
Bentazon	4.0 L	1.12	3 LS, 4 LS
Bentazon + COC	4.0 L	0.56	3 LS, 4 LS
Bentazon + COC	4.0 L	1.12	3 LS, 4 LS
Bentazon + NIS	4.0 L	0.56	3 LS, 4 LS
Bentazon + NIS	4.0 L	1.12	3 LS, 4 LS
Hand weeded	---	---	---

[a]Abbreviations: COC, crop oil concentrate at 1 % v/v; NIS, non-ionic surfactant at 0.25% v/v; LS, onion leaf stage or number of true leaves at application.

[b]Application rate at each application timing

Table 14. Effect of oxyfluorfen formulation and rate on onion injury and weed control 7 d after treatment at 1-leaf stage.

			Weed Control[a]		
Formulation	Rate	Onion injury[a]	Common lambsquarters	Ladysthumb	Redroot Pigweed
	kg/ha	--------	--------	%--------	--------
---	0.0	0	0	0	0
SC	0.035	2	81	42	97
SC	0.070	5	69	56	94
SC	0.140	15	94	67	100
SC	0.210	23	92	79	100
EC	0.035	4	77	52	97
EC	0.070	17	94	70	100
EC	0.140	29	100	83	100
EC	0.210	38	97	92	100
LSD		4.9	15.1	13.4	4.7
CV		28.0	29.0	16.4	4.3

[a]Data were pooled over experiments in 2008 and 2010 in Laingsburg and in 2010 in Bath.

Table 15. Effect of oxyfluorfen formulation and rate on onion injury and weed control 7 d after treatment at 2-leaf stage.

			Weed Control[b]		
Formulation	Rate[a]	Onion injury[b]	Common lambsquarters	Ladysthumb	Redroot Pigweed
	kg/ha	%			
---	0.0	0	0	0	0
SC	0.035	4	78	30	94
SC	0.070	8	90	48	100
SC	0.140	15	83	48	100
SC	0.210	17	94	63	100
EC	0.035	8	94	44	100
EC	0.070	13	100	50	100
EC	0.140	21	100	61	100
EC	0.210	30	100	70	100
LSD		5.6	13.3	6.8	5.8
CV		25.1	18.1	18.5	8.1

[a]Application rate at each application timing.

[b]Data were pooled over experiments in 2008 and 2010 in Laingsburg and in 2010 in Bath.

Table 16. Effect of sequential application of oxyfluorfen on onion injury and weed control (7 d after final application) and onion yield.

Timing	Formulation	Rate[a]	Injury[b]	Weed Control[b] Common lambsquarters	Weed Control[b] Ladysthumb	Weed Control[b] Redroot Pigweed	Yield[b]
		kg/ha	----------------%		----------------%		----kg/plot----
---	---	0.0	0	0	0	0	27.7
1, 2, 3 LS	SC	0.035	8	80	44	85	28.2
1, 2, 3 LS	SC	0.070	6	81	62	96	28.1
1, 2, 3 LS	SC	0.140	8	98	72	94	27.2
1, 2, 3 LS	SC	0.210	14	100	90	100	28.7
1, 2, 3 LS	EC	0.035	9	94	69	91	28.5
1, 2, 3 LS	EC	0.070	17	100	90	98	27.5
1, 2, 3 LS	EC	0.140	14	98	84	100	26.8
1, 2, 3 LS	EC	0.210	25	100	100	98	24.2
2, 4 LS	SC	0.035	10	87	38	93	27.7
2, 4 LS	SC	0.070	20	93	48	94	27.4
2, 4 LS	SC	0.140	13	87	47	89	27.4
2, 4 LS	SC	0.210	22	96	60	100	26.7

Table 16. (cont'd).

2, 4 LS	EC	0.035	16	94	37	100	25.6
2, 4 LS	EC	0.070	24	100	54	100	26.8
2, 4 LS	EC	0.140	28	100	67	100	24.5
2, 4 LS	EC	0.210	30	100	74	100	20.8
LSD			5.8	13.3	6.8	5.8	4.3
CV			30.9	18.2	19.8	12.6	21.9

[a]Application rate at each application timing.

[b]Data were pooled over experiments in 2008 and 2010 in Laingsburg and in 2010 in Bath

Table 17. Effect of flumioxazin tank mixed with preemergence onion herbicides on onion injury and yield.

		Injury 7 d after treatment at onion 2-leaf stage[b]		Injury 7 d after treatment at onion 4-leaf stage[b]		Yield[c]	
Tank mix partner	Rate[a]	Flumioxazin	No flumioxazin	Flumioxazin	No flumioxazin	Flumioxazin	No flumioxazin
	kg/ha	--%	--			------------kg/plot-------------	
Pendimethalin ACS	2.24	10	7	13	9	72.4	65.0
Pendimethalin EC	2.24	70	19	74	14	37.2	68.9
Dimethenamid-p	1.10	72	29	72	17	39.7	69.9
S-Metolachlor	1.48	74	37	75	31	34.1	55.6
No herbicide	---	9	0	15	0	70.3	61.6
LSD		5.8		6.9		23.2	
CV		22.0		24.1		24.6	

[a]Application rate at each application timing.

[b]Data were pooled over experiments in 2008, 2009, and 2010 in Laingsburg and in 2010 in Bath.

[c]Data were pooled over experiments in 2008 and 2010 in Laingsburg and in 2010 in Bath.

Table 18. Effect of sequential application of flumioxazin tank mixed with preemergence onion herbicides on onion height, leaf number, and stand density 10 d after application at 4-leaf stage.

Tank mix partner	Rate[a]	Height[b]		Leaf number[b]		Stand density[b]	
		Flumioxazin	No flumioxazin	Flumioxazin	No flumioxazin	Flumioxazin	No flumioxazin
	kg/ha	----------------cm----------------		-----------Leaves/plant-----------		-------------Plants/3 m--------------	
Pendimethalin ACS	2.24	19.9	20.2	4.18	3.83	75.2	71.5
Pendimethalin EC	2.24	13.2	19.8	3.47	4.02	49.1	74.6
Dimethenamid-p	1.10	13.7	18.9	3.72	4.15	52.6	70.7
S-Metolachlor	1.48	13.4	15.0	3.46	3.53	48.2	61.9
No herbicide	---	21.4	20.9	4.14	3.80	72.1	70.3
LSD		2.8		0.26		14.0	
CV		21.4		17.5		26.2	

[a]Application rate at each application timing (onion 2 leaf stage and onion 4 leaf stage).

[b]Data were pooled over experiments in 2008 and 2010 in Laingsburg and in 2010 in Bath.

Table 19. Effect of bentazon on onion injury and weed control 7 d after application at the onion 2-leaf stage.

Herbicide	Rate	Application timing[a]	Injury[b] 2008	Injury[b] 2009	Injury[b] 2010	Weed Control[c] Yellow nutsedge	Weed Control[c] Ladys-thumb	Weed Control[c] Redroot pigweed
	kg/ha		--------------------	--------------------	--------------------	%	--------------------	--------------------
Bentazon	0.56	2 LS	18	36	34	38	69	19
Bentazon	1.12	2 LS	68	44	44	90	85	17
Bentazon + COC	0.56	2 LS	55	66	49	43	76	17
Bentazon + COC	1.12	2 LS	96	86	57	85	85	19
Bentazon + oxyfluorfen	0.56 + 0.071	2 LS	33	42	39	47	78	64
Bentazon + flumioxazin	0.56 + 0.072	2 LS	---	30	37	46	75	72
Hand weeded	---	---	0	0	0	0	0	0
LSD			13.1	6.4	5.2	6.0	8.9	10.6
CV			26.7	21.9	20.1	16.9	18.3	27.2

[a]Abbreviations: LS, onion leaf stage or number of true leaves at application.

[b]Data were presented separately in 2008, 2009, and 2010 due to significant treatment by year interactions..

[c]Data were pooled over experiments in 2008, 2009, and 2010.

Table 20. Effect of sequential application of bentazon on onion injury and weed control 7 d after application at the onion 4-leaf stage.

Herbicide	Rate[a]	Application timing[b]	Injury[c] 2008	Injury[c] 2009	Injury[c] 2010	Weed Control[d] Yellow nutsedge	Weed Control[d] Ladys-thumb	Weed Control[d] Redroot pigweed
	kg/ha		----------%	----------%	----------%	----------%	----------%	----------%
Bentazon	0.56	2 LS, 4 LS	27	22	20	53	97	19
Bentazon	1.12	2 LS, 4 LS	67	31	34	94	100	25
Bentazon + COC	0.56	2 LS, 4 LS	69	53	41	61	100	28
Bentazon + COC	1.12	2 LS, 4 LS	93	72	54	97	100	25
Bentazon + oxyfluorfen	0.56 + 0.071	2 LS, 4 LS	46	21	19	49	99	81
Bentazon + flumioxazin	0.56 + 0.072	2 LS, 4 LS	---	16	12	53	96	89
Bentazon	0.56	3 LS, 4 LS	---	21	24	47	99	25
Bentazon	1.12	3 LS, 4 LS	---	12	21	94	100	25
Bentazon + COC	0.56	3 LS, 4 LS	---	25	30	69	99	19
Bentazon + COC	1.12	3 LS, 4 LS	---	24	41	99	100	28
Bentazon + NIS	0.56	3 LS, 4 LS	---	16	34	63	99	22
Bentazon + NIS	1.12	3 LS, 4 LS	---	23	52	99	100	28
Hand weeded	---	---	0	0	0	0	0	0
LSD			7.4	8.8	8.5	8.2	2.5	8.6
CV			26.0	22.8	25.4	11.5	3.82	23.9

[a]Application rate at each application timing.

Table 20. (cont'd).

[b]Abbreviations: LS, onion leaf stage or number of true leaves at application.

[c]Data were presented separately in 2008, 2009, and 2010 due to significant treatment by year interactions.

[d]Data were pooled over experiments in 2008, 2009, and 2010.

Table 21. Effect of bentazon on onion stand density and yield.

Herbicide	Rate[a]	Application timing[b]	Stand density[c]			Yield[d]	
			2008	2009	2010	2008	2010
	kg/ha		-------------Plants/3 m------------			-------------kg/plot-------------	
Bentazon	0.56	2 LS, 4 LS	51.5	52.0	57.5	49.5	43.6
Bentazon	1.12	2 LS, 4 LS	21.9	40.3	53.4	23.9	39.6
Bentazon + COC	0.56	2 LS, 4 LS	29.3	31.5	61.8	27.4	32.1
Bentazon + COC	1.12	2 LS, 4 LS	5.6	13.9	65.2	4.5	26.2
Bentazon + oxyfluorfen	0.56 + 0.071	2 LS, 4 LS	39.4	54.6	63.1	44.2	42.6
Bentazon + flumioxazin	0.56 + 0.072	2 LS, 4 LS	---	57.9	53.9	---	47.9
Bentazon	0.56	3 LS, 4 LS	---	40.4	49.5	---	28.4
Bentazon	1.12	3 LS, 4 LS	---	55.5	49.5	---	34.7
Bentazon + COC	0.56	3 LS, 4 LS	---	46.4	57.5	---	36.0
Bentazon + COC	1.12	3 LS, 4 LS	---	48.6	59.5	---	28.5
Bentazon + NIS	0.56	3 LS, 4 LS	---	66.1	55.7	---	29.6
Bentazon + NIS	1.12	3 LS, 4 LS	---	59.2	60.5	---	21.9
Hand weeded	---	---	66.9	60.0	46.4	50.1	41.4
LSD			8.4	13.9	14.7	13.4	11.7
CV			16.3	22.8	30.4	31.2	34.4

[a]Application rate at each application timing.

[b]Abbreviations: LS, onion leaf stage or number of true leaves at application.

Table 21. (cont'd).

[c]Data were presented separately in 2008, 2009, and 2010 due to significant treatment by year interactions.

[d]Data were presented separately in 2008 and 2010 due to significant treatment by year interactions..

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CHAPTER 2. POSTEMERGENCE WEED CONTROL WITH A PRECISION GUIDED, SHIELDED WEED FLAMER/SPRAYER

LITERATURE REVIEW

History of Flame Weed Control

Flame weeding is the most widely used method of thermal weed control in practice today (Cisneros and Zandstra 2008). In the United States, flame weeding was first attempted in cotton in the 1940's. By the 1960's flame weeding with liquefied propane gas had spread to a variety of crops, including corn, bean, potato, onion, and several fruit crops (Sniauka and Pocius 2008). At the end of the 1960's, synthetic herbicides became the primary method of weed control in agriculture. With the rise in propane prices in the 1970's, the practice of flame cultivation began to fade in the United States. However, as flaming declined in the Unites States, it became popular in Europe where it was used for weed control in organic farming (Kang 2001).

Over the past several years, renewed interest in propane flaming has been sparked by increasing demand for organic produce, as well as elevated concern for environmentally-sound growing practices (Wszelaki 2007). Organic product sales in the United States have increased over 20% annually for the past decade. Although organic farmland accounts for only 0.5% of the national total, it is the fastest growing segment of US agriculture and has increased over 300% in the past 20 years (Ulloa et al. 2010a).

Benefits and Properties of Flame Weed Control

Flame weeding has several advantages compared to other methods of weed control. Hand weeding is very expensive on a commercial scale, and labor is often difficult to find (Rifai 1996; Fennimore et al. 2010). Organically-approved herbicides are cost prohibitive and have the potential to cause serious crop injury (Ulloa et al. 2010b). Other methods of thermal weed control, such as steaming or microwaving, are more costly and less effective than flame weeding

(Sartorato et al. 2006; Rifai et al. 2002; Melander et al. 2005). Since flaming does not disturb the soil surface, this eliminates the risk of crop root injury and reduces additional weed seed germination (Hatcher and Melander 2003; Boyd et al. 2006; Rasmussen 2003). Other advantages of flame weeding include its compatibility with no-tillage systems of production and the lack of carryover issues associated with the preceding year's crop (Cisneros and Zandstra 2008). Flaming releases no chemical residues into the soil, water, or crop tissue, and may even provide insect and disease control (Hatcher and Melander 2003; Wszelaki et al. 2007). Additionally, herbicide-resistant weed biotypes can be controlled easily with the use of flame weeding, since no plant is immune to temperatures above the boiling point of water (Heiniger 1998).

Propane flaming results in thermal injury to plants by causing intracellular water expansion and denaturation of the cell membrane, which leads to subsequent cellular leakage, dehydration, and cell death (Rifai et al 2002; Ascard 1995). Denaturation of membrane proteins begins to occur at about 40 °C. Leaf mortality occurs at cellular temperatures ranging from 55-94 °C. An exposure time of 65-130 milliseconds has been shown to be sufficient to kill leaf tissue, but it has also been reported that obtaining good weed control requires a flame temperature of 800-1000°C and an exposure time of about 1 second (Ascard 1995, 1997). It is important to note that increasing the temperature of the flame decreases the exposure time needed to achieve a lethal effect (Ascard 1997). Propane burners generate temperatures of up to 1900 °C, and temperature may be regulated to some extent by adjusting the propane pressure. (Cisneros and Zandstra 2008, Hatcher and Melander 2003). Achieving a lethal effect, however, is usually controlled by regulating driving speed (Ascard 1995). After an effective flame treatment, weed leaves appear darkened, dull, and water soaked, and it is possible to leave an imprint of a fingerprint by pressing on the leaf (Mutch et al 2008).

Plants survive flaming by heat tolerance or heat avoidance, which may be attributed to protective hairs or a thick waxy cuticle on the leaf surface, protected growing points, increased water content of the leaf tissue, and favorable environmental conditions at the time of flaming. Plants with an upright habit and thin leaves are more susceptible to thermal injury than prostrate plants with protected growing points, such as grasses (Ascard 1995). Additionally, some weeds have the ability to regrow from their root systems within several days of flaming (Mojzis 2002).

Flame Weeding Techniques and Practices

Flaming weed seedlings prior to crop emergence is called the stale seedbed technique (Ascard 1994, 1995; Melander et al. 2005; Kang 2001). It is the predominant method of thermal weed control in vegetable crops (Hatcher and Melander 2003). With the stale seedbed technique, the soil surface is treated with a flame application just prior to crop emergence, killing the small emerged weed seedlings with minimal disturbance of the soil surface. This depletes the weed seed bank in the top layer of soil, thereby reducing subsequent weed pressure in the crop.

Preemergence flaming may reduce weed density by 64-92% (Rifai 1996). Boyd et al. (2006) demonstrated that propane flaming resulted in fewer weeds emerging with the crop than other seedbed preparation techniques, even though initial broadleaf weed control (72-89%) was lowest with the flamer. This relatively low level of initial weed kill with the flamer may be attributed to an insufficient propane dose of 24 kg/ha, which was too low to provide a lethal effect on all broadleaf weed species (Boyd et al. 2006). Rasmussen (2003) modified the stale seedbed technique slightly for use in fodder beet, coupling the use of a punch planter with seedbed flaming. The combination of punch planting and preemergence flame weeding reduced weed density in the crop by 50%, when compared to conventional seedbed preparation and planting equipment. Flaming alone reduced weed density in the crop by 30%.

Preemergence flaming usually does not control weeds sufficiently to prevent yield loss, because it only controls a fraction of the weeds that emerge during a season (Cisneros and Zandstra 2008). Many vegetable crops are poor competitors, and low levels of weed competition can cause significant yield reduction. Weeds that emerge with the crop are difficult to control without injuring the crop (Heiniger 1998). Although preemergence broadcast flaming is an effective method to control small emerged weeds, additional weed control efforts must be made, as many weeds continue to germinate throughout the season, and some are capable of regrowing after being flamed (Hatcher and Melander 2003, Cisneros and Zandstra 2008).

Ascard (1994) examined how weed size and density affect flame weed control efficacy. White mustard (*Sinapis alba*) was used as an artificial weed, sown at various rates and treated at various developmental stages. For 0- to 2-true leaf white mustard, 95% reduction in plant number was possible when plots were treated at a propane dose of 40 kg/ha. To achieve 95% reduction in plant number for weeds with 2- to 4-true leaves, a propane dose of 70 kg/ha was required. Ascard hypothesized that larger, more developed weeds require a higher propane dose to obtain an equivalent level of weed control because they have several adventitious buds, and the flame must penetrate stems and petioles to reach buds at lower nodes. The doses required to achieve 95% reduction in weed biomass were 40% lower than the doses required to achieve 95% reduction in weed number. Plant density had no significant influence on weed control efficacy (Ascard 1994).

Ascard (1995) also developed dose response curves to describe the relationship between propane dose, in kg/ha, and the level of weed control achieved for several weed species at different developmental stages. Ascard divided weeds into four categories, based on their susceptibility or tolerance to flaming and their ability to regrow after flaming. The most sensitive weeds were thin-leaved dicots, while the most tolerant species were grasses with protected growing points. Smaller dicot weeds are more susceptible to flaming than larger, more developed weeds of the same species. Ascard demonstrated that propane doses of 10-40 kg/ha were required to achieve 95% control of sensitive weed species with 0- to 4-true leaves. Sensitive weeds with 4- to 12-true leaves required a propane dose of 40-150 kg/ha. Tolerant weeds, such as annual bluegrass (*Poa annua*), could not be controlled with a single flame treatment at any growth stage. Split applications at lower rates were not as effective as a single full dose (Ascard 1995).

Sivesind et al. (2009) generated dose response curves for a cross-flaming system, assessing several weed species treated at various developmental stages. Fuel usage rates ranged from 27-148 kg/ha. Over 95% control of common lambsquarters with 6 or fewer leaves and redroot pigweed (*Amaranthus retroflexus*) with 4 or fewer leaves was possible at propane doses under 100 kg/ha. Shepherd's purse (*Capsella bursa-pastoris*) was more difficult to control than common lambsquarters or redroot pigweed, probably due to its rosette growth habit. Barnyardgrass (*Echinochloa crus-galli*) control was no greater than 25% at any dose, and yellow foxtail (*Setaria glauca*) control was no greater than 50% (Sivesind et al. 2009).

Cisneros and Zandstra (2008) evaluated weed control efficacy using a shielded conveyor bench burner in a laboratory setting. Propane pressure was held constant at 0.20 MPa and dose was adjusted by regulating the conveyor speed from 2 to 8 km/hr. Redroot pigweed, common lambsquarters, and common ragweed (*Ambrosia artimisiifolia*) were relatively easy to kill at all propane doses evaluated, with stand reductions of 80-99% and biomass reductions of 93% or higher. It appeared possible to reduce green foxtail (*Setaria veridis*) number with sufficient heat exposure, and flaming was especially effective when the weed was at the 0- to 2- leaf stage. Barnyardgrass control was more difficult, as no significant weed number reduction was observed at any propane dosage or application timing (Cisneros and Zandstra 2008).

Flaming may be used for postemergence weed control in heat-tolerant agronomic crops such as corn, cotton, and sugarcane. For these heat-tolerant crops, flame can be directed at the base of the crop row to control intrarow weeds (Cisneros and Zandstra 2008). This method of postemergence flaming is known as broadcast or cross flaming. Knezevic and Ulloa (2007) performed field experiments to develop dose-response curves for several major weeds and field crops. Propane was broadcast applied at rates ranging from 0-87.22 kg/ha. Field corn and sorghum were found to be tolerant to flaming at these rates, while sunflower and soybean were seriously injured at most rates. No yield data was recorded for the crops (Knezevic and Ulloa 2007). Another study (Ulloa et al. 2010a) assessed the tolerance of sweet corn to broadcast flaming as influenced by timing and dose. The V7 stage of sweet corn was the most tolerant growth stage to flaming, while the V2 and V5 stages were most sensitive. There was a 6% yield reduction for sweet corn treated at the V7 stage and greater yield reductions for sweet corn treated at other application timings (Ulloa et al. 2010a).

Although propane flaming has been an effective method of postemergence weed control in several field crops, little information is available on quality and yield of vegetable crops. Wszelaki et al. (2009) assessed the effects of postemergence broadcast flaming on horticultural quality of cabbage and tomato. Propane pressure was held constant at 0.20 MPa and dose was adjusted by regulating tractor speed from 4 to 12 km/h. Flame weeding in the morning was more injurious to both cabbage and tomato than flaming in the afternoon. Wszelaki et al. (2009)

explain the discrepancy between morning and afternoon flaming by citing increased moisture levels in the morning, when the greater moisture on the surface of the leaves and higher humidity levels in the air increased the heat transmission from the flame to the crop leaves. In 2003, cabbage yield in the hand weeded control treatment was over 100% higher than yields in highest-yielding flame weeded treatments. Cabbage head size was also over 20% larger in the hand weeded control. Tomato yields were similar for the hand weeded control and the 4 km/h treatment in 2003. In tomato, the 4 and 8 km/h treatments had greater yield than the weedy check in both years, due to diminished weed competition (Wszelaki et al. 2009).

Several of the most effective flame treatments resulted in weed control levels comparable to those obtained with herbicides or cultivation. Common purslane (*Portulaca oleracea*), a succulent broadleaf weed commonly associated with vegetable crops, was found to be more tolerant to propane flaming than other broadleaf weeds (Wszelaki et al. 2009).

Rifai (1996) reported that applying one postemergence broadcast flame application in onion at the 2 leaf stage caused 25% yield reduction. He concluded that postemergence flaming requires great precision to avoid injury to the crop (Rifai 1996).

Shields and Covers

Heat shields improve the precision of propane flame weeding. Shields may be used to confine the heat generated by a propane torch, to protect the crop, or to increase the temperature in the target region (Rifai et al. 2002). By implementing a shield, the amount of fuel necessary to achieve a desired temperature is reduced, as flamers with covered burners are more energy efficient than open burners (Ascard 1995). The heat beneath the shield is also more uniform and constant (Ascard 1995, Robinson 2002).

Robinson conducted a series of experiments with a covered flamer and found that one treatment under evaluation (0.28 MPa and 2 mi/hr) controlled 90% of the weeds present. This level of weed control was comparable to a single paraquat application, which gave 95% weed control (Robinson 2002). For sensitive crop plants such as many vegetables, shields can be used to direct heat away from the crop row and onto interrow weeds, a technique referred to as parallel flaming (Cisneros and Zandstra 2008).

Precision Guidance Systems

One of the problems associated with operating tractor-mounted cultivation equipment in close proximity to crop rows is the risk of crop injury associated with steering inaccuracy or operator error. Over the past two decades, machine vision guidance technology has been developed for agricultural equipment (Slaughter et al. 2008). Some electronic guidance systems, such as the Eco-Dan® cultivator, claim to have the capability of lowering the steering precision to 1.5 cm on either side of a crop row at speeds up to 10 km/hr. The Eco-Dan cultivator employs a digital camera that takes 25 pictures/s and uses these images to differentiate between the pattern of the crop row and the random pattern of weeds. The digital images are relayed to a computer, and a computer algorithm allows for detection of the crop row's center line (Fennimore et al. 2010, Sogaard and Olsen 2003). As the centerline of the crop row shifts, lateral position of the cultivation implement is controlled by regulating oil flow into a hydraulic cylinder, which shifts the whole implement in relation to the crop row to maintain the centerline directly beneath the camera. The goal of this steering system is to guide the implement and not the tractor (Sogaard and Olsen 2003).

Accuracy in detection of the crop row increases with the number of cameras used to detect multiple rows. For example, a weed growing next to a crop row may displace the true centerline of the crop row, so additional cameras detecting more crop rows improve the likelihood that the algorithm will be correct and that the implement will be steered accurately. However, high weed density between the crop rows will disturb the row detection algorithm, regardless of the number of cameras used (Sogaard and Olsen 2003, Tillett et al. 2002). Other problems associated with electronic guidance systems include crop leaf architecture, sloping fields, and poor crop stand (Melander et al. 2005). In early stages of crop growth, crop plant leaf area accounts for only a small portion of the image area, which may pose a problem for row detection, especially if there are numerous interrow weeds present. In an experimental situation, a crop of small sugar beet plants with only 2 true leaves was growing on a bed with a dense flush of small newly germinated weeds. Due to the relatively small crop image area and confounding weed patterns, it was concluded that the electronic guidance system was operating too close to its limit of detection. Therefore, the minimum crop growth stage for sugar beets was considered to be 2 true leaves, and high weed densities were to be avoided if the precision guidance system was to be effective (Tillett et al. 2002).

POSTEMERGENCE WEED CONTROL WITH A PRECISION GUIDED WEED FLAMER

Abstract

A tractor-mounted, shielded weed flamer with a camera and computer guidance system was developed for between-row flaming in vegetable crops. Experiments were conducted in snap bean, carrot, and lettuce. A propane torch was installed under each shield to flame weeds growing between crop rows. Due to the requirements of vision-guidance systems in detecting the crop row, the crops were 5 to 8 cm tall with 2 to 4 leaves at the time of treatment, and most weeds had 4 to 8 true leaves. Common lambsquarters and redroot pigweed were controlled with a propane dose of approximately 100 kg/ha, whereas large crabgrass and common purslane were more difficult to control and often regrew within 2 weeks of treatment. Snap bean was the most heat tolerant crop, and Romaine and head lettuce recovered from thermal injury. Carrot and leaf lettuce were more sensitive to thermal injury.

Nomenclature: Redroot pigweed, *Amaranthus retroflexus* L.; common lambsquarters, *Chenopodium album* L., yellow nutsedge, *Cyperus esculentus* L.; large crabgrass, *Digitaria sanguinalis* L.; common puslane, *Portulaca oleracea* L.; carrot, *Daucus carota* L.; lettuce, *Lactuca sativa* L.; snap bean, *Phaseolus vulgaris* L.

Key Words: postemergence weed control, machine vision guidance, flame weed control, carrot, lettuce, snap bean.

Introduction

Flame weeding is an effective, non-selective, and organically-certified method of weed control. First developed in cotton in the 1930's and 1940's, flame weed control has been adapted for use in numerous crops (Sniauka and Pocius 2008). The increase in fuel prices in the 1970's all but eliminated flame weed control in the United States (Kang 2001). Recently, however, there is renewed interest in the technology, which may be attributed to its compatibility with no-tillage systems, the increased emphasis on sustainable and organic crop production, and the decreased availability and high cost of labor for hand weeding.

Flaming weed seedlings prior to crop emergence in slow-germinating crops such as carrot and onion is well documented in the literature (Ascard 1994, 1995; Melander et al. 2005; Kang 2001). This method of preemergence flaming is known as the stale seedbed technique, and it is the predominant method of thermal weed control in vegetable crops (Hatcher and Melander 2003). Several days after seeding and prior to crop emergence, the soil surface is treated with an herbicide or flame application, killing the emerged weed seedlings with minimal disturbance of the soil surface. This depletes the weed seed bank in the top layer of soil, thereby reducing subsequent weed pressure in the crop. The efficacy of the stale seedbed technique is somewhat variable, as 30 to 92% reduction in weeds emerging with the crop has been reported (Rifai 1996, Rassmussen 2003).

Preemergence flaming does not control all weeds sufficiently to prevent yield loss in most situations (Cisneros and Zandstra 2008). Most vegetable crops are poor competitors, and moderate levels of weed competition can cause significant yield reduction. Weeds that emerge with the crop in the rows are difficult to remove without injuring the crop (Heiniger 1998). Preemergence broadcast flaming kills early germinating weeds, but additional weed control efforts are needed to control weeds that germinate throughout the season (Hatcher and Melander 2003, Cisneros and Zandstra 2008).

Ascard (1994) examined how weed size and density affect flame weed control efficacy. For white mustard weeds with 0 to 2 leaves, 95% reduction in plant number was possible when plots were treated at a propane dose of 40 kg/ha. To achieve 95% reduction in white mustard plant number for weeds with 2 to 4 leaves, a propane dose of 70 kg/ha was required (Ascard 1994). Weeds with 4 to 12 leaves required a propane dose of 40-150 kg/ha (Ascard 1995). Ascard hypothesized that larger, more developed weeds require a higher propane dose to obtain an equivalent level of weed control because they have several adventitious buds, and the flame must penetrate stems and petioles to reach buds at lower nodes.

Many studies support Ascard's findings. Sivesind et al. (2009) generated dose response curves for a cross-flaming system, assessing several weed species treated at various developmental stages. Liquified propane usage rates ranged from 27-148 kg/ha. Over 95% control of common lambsquarters with 6 or fewer true leaves and redroot pigweed (*Amaranthus retroflexus*) with 4 or fewer true leaves was possible at propane doses under 100 kg/ha. Shepherd's purse (*Capsella bursa-pastoris*) was more difficult to control, due to its growth habit as a basal rosette. Barnyardgrass (*Echinochloa crus-galli*) control was no better than 25% at any dose, and yellow foxtail (*Setaria glauca*) control was no greater than 50% (Sivesind et al. 2009).

Cisneros and Zandstra (2008) evaluated weed control efficacy using a shielded conveyor bench burner in a laboratory setting. Propane pressure was held constant at 0.20 MPa and dose was adjusted by regulating the conveyor speed from 2 to 8 km/hr. Broadleaf weeds such as redroot pigweed, common lambsquarters, and common ragweed (*Ambrosia artimisiifolia*) were relatively easy to kill at all propane doses evaluated, with stand reductions of 80-99% and biomass reductions of 93% or higher. It appeared possible to reduce green foxtail (*Setaria veridis*) number with sufficient heat exposure, and flaming was especially effective when the weed was at the 0- to 2- leaf stage. Barnyardgrass control was more difficult, as no significant weed number reduction was observed at any propane dosage or application timing (Cisneros and Zandstra 2008).

Flaming may be used for postemergence weed control in heat-tolerant agronomic crops such as corn, cotton, and sugarcane. For these heat-tolerant crops, flame can be directed at the base of the crop row to control intra-row weeds (Cisneros and Zandstra 2008). This method of postemergence flaming is known as broadcast or cross flaming. Although propane flaming has been an effective method of postemergence weed control in a number of crops, little information is available on the effects of flaming on quality and yield of vegetable crops. Wszelaki et al. (2009) assessed the effects of postemergence broadcast flaming on horticultural quality of cabbage and tomato. Propane pressure was held constant at 0.20 MPa and dose was adjusted by regulating tractor speed from 4 to 12 km/h. Cabbage and tomato exhibited a reduction in yield after flaming, when compared to the handweeded check. Several of the most effective flame treatments resulted in weed control levels that were comparable to those obtained with herbicides or cultivation. Common purslane (*Portulaca oleracea*) was found to be more tolerant to propane flaming than other broadleaf weeds (Wszelaki et al. 2009).

Rifai (1996) reported that applying one postemergence broadcast flame application in onion at the 2 leaf stage caused 25% yield reduction. He concluded that postemergence flaming requires great precision to avoid injury to the crop (Rifai 1996).

Machine vision guidance technology has been developed for automated steering of tractors and implements, which greatly improves the speed and precision of field operations such as cultivation. Eco-Dan® manufactured a camera/computer precision guidance system that employs digital vision guidance to differentiate between the distinguishable pattern of a crop row and the random pattern of weeds. A camera mounted to cultivation equipment captures images and relays them to an on-board computer, and a computer algorithm allows for detection of the crop row's center line (Fennimore et al. 2010, Sogaard and Olsen 2003). Once the center line is detected, a hydraulic cylinder shifts the cultivation equipment from left to right in real time to maintain proper orientation of the cultivation equipment in relation to the crop row.

These experiments were conducted to determine the feasibility of using a camera and computer vision guidance system for improved postemergence flaming in vegetable crops.

Materials and Methods

Machine Design. The precision guided, shielded weeder is a tractor-driven apparatus comprised of four stainless steel shields mounted to a toolbar. Each shield is 1.5 m in length and may be adjusted from 36 to 61 cm wide to accommodate various row spacings. Under each shield a 528 megajoule Red Dragon®[16] liquefied propane torch is mounted backward at a 45 degree angle to the soil surface. Between the torches and propane tank, a solenoid is installed to allow the operator to switch between a low, or pilot, setting that is used when entering or exiting the field, and a high pressure setting for which the pressure can be adjusted with a pressure regulator. An Eco-Dan® precision guidance system is installed to provide real time lateral steering adjustment via a hydraulic cylinder, which shifts the toolbar to maintain proper orientation of the torches and shields in relation to the crop rows. An LCD display is mounted next to the tractor's steering column and informs the tractor operator in the event that additional steering corrections must be performed to prevent the hydraulic cylinder from reaching the end of its range. The machine was mounted to a John Deere 5225 tractor with wheels set at 150 cm apart to straddle a 3-row bed.

Field Experiments. Field experiments were conducted at the Michigan State University Horticulture Farm in Holt in 2008, 2009, and 2010 and at the Michigan State University Muck Research Station in Laingsburg, MI in 2009 and 2010. The soil at Holt was a Marlette fine sandy loam (Mixed, mesic Haplic Glossudalfs) containing 3.2% organic matter and a pH of 6.5. The soil at Laingsburg was a Houghton muck (Euic, mesic Typic Medisaprist) containing 76% organic matter and a pH of 6.7.

The experimental design for the flame weeder experiment was a two-factor factorial arranged in a randomized complete block with four replications. Factors included three tractor

[16] Red Dragon LT 1.5 X 8D L.P. Torch. Flame Engineering, Inc., P.O. Box 577, Lacrosse, Kansas 67584

ground speeds (1.61, 3.22, and 6.44 km/h) and three propane pressures (0.07, 0.14, and 0.28 MPa) which resulted in propane doses of 16, 26, 33, 48, 51, 66, 95, 123, and 191 kg/ha. Treatments were applied once the crop rows were sufficiently established for detection by the precision guidance system, at which time most weeds had 4 to 8 true leaves. The machine was evaluated for use in snap bean ('Hercules') at Holt in 2008, 2009, and 2010. Snap bean was 7 to 12 cm tall with one expanded trifoliate leaf at the time of treatment. Carrot ('Carson') experiments were conducted at Holt in 2009 and 2010 and at Laingsburg in 2010. Carrot was 5 to 7 cm tall with one true leaf at the time of treatment. Experiments with leaf, Romaine, and head lettuce ('Black Seeded Simpson', 'Paris Island Cos', and 'Great Lakes', respectively) were conducted in Laingsburg in 2009 and 2010. Each row of the 3-bed plot was planted with a different variety, and lettuce was 5-7 cm tall with 4-6 leaves at the time of treatment. For all crops, plots were 15 m long and consisted of beds with 3 rows spaced 36 cm apart. A 5 cm band centered on each crop row remained untreated, so 90% of the plot area was effectively treated.

Data Collection and Statistical Analysis. Visual estimates of crop injury and weed control by species were recorded 7 days after treatment. Visual estimates were based on a scale of 0 to 100%, where 0 = no injury or control and 100 = complete plant death. To quantify weed control by species, the number of living weeds was counted in two 0.3 by 0.3 m quadrants per plot. Weed biomass data by species was collected by harvesting weeds from within 1.0 by 1.0 m quadrants in each plot. Snap bean and carrot yields were measured at crop maturity by hand harvesting 3 m within each plot. Lettuce yields were measured by hand harvesting 8 m within each plot.

All data were subjected to analysis of variance using the Mixed procedure of SAS[17]. Means were separated using Fisher's protected LSD at P = 0.05. Data for crop injury and weed control ratings were transformed prior to analysis using the arcsine square root transformation to stabilize variances. Transformation did not affect mean rank, so nontransformed means are presented for clarity.

[17] SAS version 9.1, SAS Institute Inc., 100 SAS Campus Dr., Cary, NC 27513.

Results and Discussion

Machine Performance in the Field. In order to operate the machine effectively, several hours of experience were required to coordinate the driving speed, steering, and propane pressure, and to achieve the proper settings for the Eco-Dan precision guidance system. The Eco-Dan guidance system performed well at speeds under 6 km/h and accurately guided the shields in proper orientation to the crop rows. At speeds greater than 6 km/h, the hydraulic system had difficulty keeping up with the row's center line and occasionally caused the machine to lose proper orientation. Large gaps in the crop stand also made it difficult for detection of the crop row, and the machine would momentarily lose its orientation. In one case, an extremely dense flush of weeds made detection of the crop row nearly impossible because the Eco-Dan could not differentiate between the patterns of the crop row and dense weeds. When the machine was trialed in direct-seeded onion, the sparse foliage of the small onions was not sufficient for the Eco-Dan to be able to detect the pattern of the crop row. One other important fact to note is that the operator needs to make only small driving corrections when the hydraulic cylinder nears the end of its range, as large, jerky steering corrections confound the detection of the center row.

Crop Response to Shielded Flame Weeding. There was no interaction between tractor speed and propane fuel pressure, so all observations were considered to be an effect of the propane dose. Snap bean was the most tolerant crop, with less than 25% injury for all doses under 100 kg/ha (Table 22). The only detectable reduction in snap bean yield occurred at the highest propane dose of 191 kg/ha (Table 23). Carrot was much slower to germinate and develop than snap bean, and injury occurred more readily in carrot than in snap bean. Doses as low as 51 kg/ha resulted in carrot injury greater than 30% (Table 22). There was a significant reduction in carrot yield at doses over 95 kg/ha (Table 23). Leaf lettuce was more susceptible to thermal injury than Romaine or head lettuce, and significant yield reduction occurred at most doses over 50 kg/ha. It appears that Romaine and head lettuce, two later maturing varieties of lettuce, grew out of any injury attributed to thermal injury, as there was no significant yield loss at any dose (Table 23).

Weed Response to Shielded Flame Weeding. Large crabgrass was the predominant grass weed in all experiments. Propane doses greater than 66 kg/ha resulted in greater than 50% control of large crabgrass 7 days after treatment (Table 24). However, visual assessment of large crabgrass control did not correlate to a significant reduction in weed biomass or weed density, as there was no significant reduction in either of these measures, except in 2008 when the highest propane dose reduced biomass compared to the untreated check (Table 25 and Tabel 26). The growing point of most grasses is below the soil surface, and this may explain why there was not a complete kill of grasses following flame treatment (Ascard 1995, Mojzis 2002). Large crabgrass often regrew within 2 weeks of flaming.

The predominant broadleaf weeds were common lambsquarters, common purslane, and redroot pigweed. Greater than 60% control of common lambsquarters and redroot pigweed was possible with propane doses of 48 kg/ha or more (Table 24). Increasing the dose to 95 kg/ha resulted in 90% control of common lambsquarters and 76% control of redroot pigweed. There was a significant reduction in weed biomass and weed density for both common lambsquarters and redroot pigweed at most doses of 48 kg/ha or higher in 2008 and 2009. Common purslane was the most difficult broadleaf weed to control, and even the highest dose of 191 kg/ha did not achieve 80% control of common purslane. The thick, succulent leaves and location of the growing point deep in the leaf axil may have contributed to the ability of common purslane to withstand the brief high temperature associated with flame weeding (Wszelaki et al. 2009).

Measurements of common purslane biomass and density supported this, as there was no difference between the untreated check and any treatment dosage, with the exception of a reduction in weed biomass in 2009 when purslane was treated at 191 kg/ha (Table 25 and Table 26).

POSTEMERGENCE WEED CONTROL WITH A PRECISION GUIDED WEED SPRAYER

Abstract

A shielded weed sprayer with a camera and computer guidance system was developed for between-row herbicide application in vegetable crops. Experiments were conducted at Holt and Laingsburg, MI in 2009 and 2010 to evaluate postemergence weed control efficacy and crop injury and yield in snap bean, carrot, and lettuce. Glyphosate at 0.24 kg/ha resulted in less than 20% injury and no yield reduction in all crops, and provided greater than 70% control of redroot pigweed, common lambsquarters, and large crabgrass and 56% control of yellow nutsedge. Paraquat at 0.84 kg/ha provided greater than 70% control of all weeds present, including yellow nutsedge. Paraquat caused 26 to 54% injury in lettuce and reduced leaf lettuce yield 69% in 2009. Carfentrazone at 0.07 kg/ha resulted in 29 to 63% injury in all crops and is not recommended for application in this manner.

Nomenclature: Carfentrazone; glyphosate; paraquat; redroot pigweed, *Amaranthus retroflexus* L.; common lambsquarters, *Chenopodium album* L., yellow nutsedge, *Cyperus esculentus* L.; large crabgrass, *Digitaria sanguinalis* L.; common puslane, *Portulaca oleracea* L.; carrot, *Daucus carota* L.; lettuce, *Lactuca sativa* L.; snap bean, *Phaseolus vulgaris* L.

Key Words: postemergence weed control, machine vision guidance, carrot, lettuce, snap bean.

Introduction

Computer-vision technology has been developed to guide cultivation and tillage equipment. The vision system uses a digital camera and computer to determine location of crop plants and rows, and to maintain the tillage tool safely between the rows (Moeller 2010). This principle may be used to control a sprayer which applies herbicides either directly over the rows, or between the rows. Non-selective herbicides may be applied under shields in very close proximity to the crop rows.

Previous research on vision guidance for postemergence weed control has centered on robotic weed removal systems and sensor-based herbicide application to specific weed plants or weedy areas (Slaughter et al. 2008; Tian 2002; Van Zuydam et al. 1995). Another approach is to apply preemergence herbicides directly over crop rows (Fennimore et al. 2010). A more traditional approach is to use protective shields to protect the crop and spray non-selective herbicides on the inter-row area (Wolf et al. 1993).

These experiments were conducted to determine whether the Eco-Dan vision and guidance system and the shielded applicator that we developed for inter-row flaming could be adapted for use as a postemergence non-selective weed control mechanism in vegetable crops.

Materials and Methods

Machine Design. The precision guided, shielded weeder is a tractor-driven apparatus comprised of four stainless steel shields mounted to a toolbar. Each shield is 1.5 m in length and may be adjusted from 36 to 61 cm wide to accommodate various row spacings. Under each shield a 9502 flat-fan nozzle[18] is mounted backward at a 45 degree angle to the soil surface. All herbicide applications were made with a CO_2-pressurized delivery system calibrated to deliver 187 L/ha at 170 kPa. An Eco-Dan® precision guidance system is installed to provide real time lateral steering adjustment via a hydraulic cylinder, which shifts the toolbar to maintain proper orientation of the shields in relation to the crop rows. An LCD display is mounted next to the tractor's steering column and informs the tractor operator in the event that additional steering corrections must be performed to prevent the hydraulic cylinder from reaching the end of its range. The machine was mounted to a John Deere 5225 tractor with wheels set at 150 cm apart to straddle a 3-row bed.

Field Experiments. Field experiments were conducted in 2009 and 2010 at the Michigan State University Horticulture Farm in Holt, MI and Michigan State University Muck Research Station in Laingsburg, MI. The soil at Holt was a Marlette fine sandy loam (Mixed, mesic Haplic Glossudalfs) containing 3.2% organic matter and a pH of 6.5. The soil at Laingsburg was a Houghton muck (Euic, mesic Typic Medisaprist) containing 76% organic matter and a pH of 6.7.

The shielded herbicide applicator experiment was arranged as a randomized complete block with four replications. A ground speed of 3.2 km/hr was used for all treatments. Treatments included carfentrazone, glyphosate, and paraquat applied at 0.07, 0.24, and 0.84 kg/ha, respectively. An untreated control was included for comparison. Treatments were applied once the crop rows were sufficiently established for detection by the precision guidance

[18] Teejet 9502 flat fan spray nozzles. Spraying Systems Co., P.O. Box 7900 Wheaton, Illinois 60189

system, at which time most weeds had 4 to 8 true leaves. The machine was evaluated for use in snap bean ('Hercules') at Holt. Snap bean was 7 to 12 cm tall with one expanded trifoliate leaf at the time of treatment. Carrot ('Carson') experiments were conducted at Holt. Carrot was 5 to 7 cm tall with one true leaf at the time of treatment. Experiments with leaf, Romaine, and head lettuce ('Black Seeded Simpson', 'Paris Island Cos', and 'Great Lakes', respectively) were conducted in Laingsburg. Each row of the 3-bed plot was planted with a different variety, and lettuce was 5-7 cm tall with 4-6 leaves at the time of treatment. For all crops, plots were 15 m long and consisted of beds with 3 rows spaced 36 cm apart. A 5 cm band centered on each crop row remained untreated, so 90% of the plot area was effectively treated.

Data Collection and Statistical Analysis. Visual estimates of crop injury and weed control by species were recorded 10 days after treatment. Visual estimates were based on a scale of 0 to 100%, where 0 = no injury or control and 100 = complete plant death. To quantify weed control by species, the number of living weeds was counted in two 0.3 by 0.3 m quadrants per plot. Weed biomass data by species was collected by harvesting weeds from within 1.0 by 1.0 m quadrants in each plot. Snap bean and carrot yields were measured at crop maturity by hand harvesting 3 m within each plot. Lettuce yields were measured by hand harvesting 8 m within each plot.

All data were subjected to analysis of variance using the Mixed procedure of SAS[19]. Means were separated using Fisher's protected LSD at P = 0.05. Data for crop injury and weed control ratings were transformed prior to analysis using the arcsine square root transformation to stabilize variances. Transformation did not affect mean rank, so nontransformed means are presented for clarity.

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[19] SAS version 9.1, SAS Institute Inc., 100 SAS Campus Dr., Cary, NC 27513.

Results and Discussion

Crop Response to Shielded Herbicide Application. Glyphosate at 0.24 kg/ha applied under the shields was safe for use in all crops except snap bean, where it resulted in 19% injury (Table 27). Crop injury was not statistically different from the untreated check for carrot and all varieties of lettuce treated with glyphosate. Paraquat at 0.84 kg/ha resulted in 15% injury in snap bean and 10% injury in carrot. There may be sufficient safety for paraquat application in these crops when applied under shields. However, paraquat applied under the shields in lettuce resulted in serious injury (26 to 54%) to all varieties of lettuce. Carfentrazone at 0.07 resulted in serious injury in all crops, which may be attributed to its vapor pressure of 1.2×10^{-7} Pa at 25°C, which is higher than the negligible vapor pressures of paraquat and glyphosate.

Snap bean and carrot yield were comparable to the untreated control for all shielded herbicide treatments (Table 28). Glyphosate did not reduce lettuce yield in any year or in any variety. In 2009 paraquat reduced the yield of leaf lettuce by 69%. Carfentrazone reduced the yield of leaf lettuce 36% in 2009 and caused 39% yield reduction to head lettuce, pooled across years. In 2010 early season weed pressure was severe, and despite hand weeding efforts, the untreated check was the poorest yielding treatment for both leaf and Romaine lettuce.

Weed Response to Shielded Herbicide Application. Weed response to shielded herbicide treatments was similar across all experiments, and data was pooled for qualitative and quantitative assessments of weed control. Yellow nutsedge, large crabgrass, common purslane, and redroot pigweed where the most prevalent weeds. Carfentrazone did not provide adequate control of yellow nutsedge or large crabgrass but was the best treatment for control of common purslane and redroot pigweed (Table 29). Glyphosate gave 72 to 77% of all weeds except yellow nutsedge, for which control was only 56%. Paraquat provided 75 to 79% control of all weed species.

Weed density observations were similar to visual assessments of weed control. Carfentrazone did not significantly reduce yellow nutsedge or large crabgrass density, but provided the greatest reduction in common purslane and redroot pigweed density (Table 30). Paraquat was the only treatment to significantly reduce yellow nutsedge density.

APPENDIX

Table 22. Effect of liquefied propane dose on crop injury for snap bean, carrot, leaf lettuce, Romaine lettuce, and head lettuce 7 days after application. Snap bean experiments are means of 3 experiments over 3 years. Carrot and lettuce figures are means of 2 experiments over 2 years.

		Injury				
	LP Dose	Snap bean	Carrot	Leaf lettuce	Romaine lettuce	Head lettuce
	kg/ha	-----------------	-----------------	%	-----------------	-----------------
1	0	0	0	0	0	0
2	16	3	5	13	13	6
3	26	6	4	20	17	17
4	33	9	19	24	17	15
5	48	17	28	26	28	24
6	51	20	32	28	31	22
7	66	24	41	52	26	24
8	95	24	56	28	22	13
9	123	40	63	52	24	37
16	191	59	74	61	41	37
	LSD	10.3	14.7	26.7	19.4	24.9
	CV	15.6	21.6	35.3	27.2	32.4

Table 23. Effect of liquefied propane dose on crop yield for snap bean, carrot, leaf lettuce, Romaine lettuce, and head lettuce. Snap bean experiments are means of 3 experiments over 3 years. Carrot and lettuce figures are means of 2 experiments over 2 years.

		Yield				
	LP Dose	Snap bean	Carrot	Leaf lettuce	Romaine lettuce	Head lettuce
	kg/ha	-----------------------------------kg/plot-----------------------------------				
1	0	3.28	12.78	9.91	7.60	10.52
2	16	4.03	13.69	8.26	12.55	19.44
3	26	3.77	12.67	8.23	8.05	11.98
4	33	4.06	10.31	8.36	13.31	18.16
5	48	3.25	9.94	11.18	9.24	11.16
6	51	3.78	9.56	6.31	16.05	22.50
7	66	4.32	8.50	7.09	8.07	19.47
8	95	3.92	5.67	3.89	20.89	19.59
9	123	3.95	7.74	5.65	8.29	9.27
16	191	2.21	8.19	5.85	16.40	22.46
	LSD	1.66	5.92	3.31	NS	NS
	CV	29.6	24.8	36.0	39.9	45.2

Table 24. Effect of liquefied propane dose on weed control 7 days after application. All figures are means of 7 experiments over 3 years.

		Weed Control			
	LP Dose	Large crabgrass	Common lambsquarters	Common purslane	Redroot pigweed
	kg/ha	--------------------	--------------------%	--------------------	--------------------
1	0	0	0	0	0
2	16	14	22	10	22
3	26	19	46	15	33
4	33	33	63	30	56
5	48	48	78	34	63
6	51	42	74	33	65
7	66	58	85	38	69
8	95	65	90	68	76
9	123	77	91	77	89
16	191	85	95	79	88
	LSD	9.3	4.6	16.1	6.4
	CV	16.8	9.5	27.9	13.5

Table 25. Effect of liquified propane dose on weed biomass 7 days after application. Figures are means of 2 experiments in 2008 and 3 experiments in 2009.

	LP Dose	Large crabgrass		Common lambsquarters		Common purslane		Redroot pigweed	
		2008	2009	2008	2009	2008	2009	2008	2009
	kg/ha	---g/plot--							
1	0	7.62	64.64	18.35	246.10	373.60	387.74	22.28	104.57
2	16	4.17	38.68	20.02	155.13	272.53	257.27	32.72	83.82
3	26	5.18	71.68	17.18	105.24	524.97	258.33	13.63	71.65
4	33	3.32	15.62	4.93	120.02	367.23	225.47	22.57	37.12
5	48	2.42	26.40	3.83	19.41	383.07	192.13	2.77	17.55
6	51	2.63	27.80	1.40	27.62	221.07	219.19	7.83	51.07
7	66	5.77	70.53	7.13	78.73	157.77	159.38	12.67	30.33
8	95	3.23	13.79	2.33	35.10	256.63	243.77	4.70	8.44
9	123	2.78	10.70	1.65	47.84	113.13	126.78	4.47	10.88
16	191	1.20	5.10	3.90	32.95	124.07	120.06	2.12	39.85
	LSD	5.57	NS	13.15	184.50	397.43	261.75	14.80	75.52
	CV	33.7	41.0	29.0	33.4	35.2	25.4	22.8	30.8

Table 26. Effect of liquefied propane dose on weed density 7 days after application. Figures are means of 3 experiments in 2009 and 3 experiments in 2010.

	LP Dose	Large crabgrass		Common lambsquarters		Common purslane		Redroot pigweed	
		2009	2010	2009	2010	2009	2010	2009	2010
	kg/ha	Plants/0.1 m^2							
1	0	0.50	0.83	10.31	4.50	2.54	8.81	6.92	8.76
2	16	0.32	0.33	6.78	4.56	2.71	12.00	3.25	4.04
3	26	0.68	0.17	1.29	2.38	3.64	11.52	3.62	6.25
4	33	0.58	0.47	2.89	2.34	2.29	8.33	3.03	4.31
5	48	0.17	0.76	1.47	0.69	4.36	11.57	2.17	4.26
6	51	0.33	0.19	1.36	2.75	1.86	14.58	3.58	1.77
7	66	0.66	0.17	1.07	3.63	2.43	8.33	3.33	2.05
8	95	0.16	0.07	0.50	0.44	2.14	11.17	2.43	0.08
9	123	0.50	0.08	0.78	1.56	2.07	11.24	2.10	0.72
16	191	0.58	0.00	0.33	0.13	1.57	7.08	2.07	0.21
	LSD	NS	NS	4.56	2.11	2.60	NS	3.44	6.04
	CV	37.8	39.4	17.8	24.9	31.8	33.9	17.3	28.6

Table 27. Effect of shielded herbicide application on crop injury 10 d after treatment.

	Herbicide	Rate	Injury				
			Snap bean	Carrot	Leaf lettuce	Romaine lettuce	Head lettuce
		kg/ha	----------------------------------%				-------------------------------------
1	Carfentrazone	0.07	44	32	29	33	63
2	Glyphosate	0.24	19	5	8	11	6
3	Paraquat	0.84	15	10	26	33	54
4	Untreated	---	0	0	0	0	0
	LSD		14.8	5.5	10.1	28.2	12.4
	CV		19.2	16.1	20.0	30.8	23.0

Table 28. Effect of shielded herbicide application on crop yield.

	Herbicide	Rate	Yield						
			Snap bean	Carrot	Leaf lettuce		Romaine lettuce		Head lettuce
					2009	2010	2009	2010	
		kg/ha	----------------------------------kg--						
1	Carfentrazone	0.07	1.15	13.26	7.18	12.30	6.90	23.16	9.64
2	Glyphosate	0.24	0.81	16.23	9.23	12.11	10.04	22.62	19.87
3	Paraquat	0.84	1.15	13.60	3.52	14.03	3.91	28.55	10.28
4	Untreated	---	1.21	15.19	11.19	5.32	8.55	14.74	15.91
	LSD		NS	NS	2.37	5.73	NS	6.15	6.01
	CV		44.7	39.6	17.4	26.0	36.8	31.4	25.1

Table 29. Effect of shielded herbicide application on weed control 10 d after treatment.

	Herbicide	Rate	Weed Control			
			Yellow nutsedge	Large crabgrass	Common purslane	Redroot pigweed
		kg/ha	-----------------------------%-----------------------------			
1	Carfentrazone	0.07	37	39	88	84
2	Glyphosate	0.24	56	77	72	72
3	Paraquat	0.84	76	79	75	79
4	Untreated	---	0	0	0	0
	LSD		5.1	7.7	2.9	2.3
	CV		8.4	16.2	12.0	14.1

Table 30. Effect of shielded herbicide application on weed density 10 d after treatment.

	Herbicide	Rate	Weed Control			
			Yellow nutsedge	Large crabgrass	Common purslane	Redroot pigweed
	kg/ha	kg/ha	---Plants/0.1 m^2---			
1	Carfentrazone	0.07	1.31	0.71	0.29	0.00
2	Glyphosate	0.24	2.37	0.33	0.88	0.21
3	Paraquat	0.84	1.02	0.43	0.71	0.33
4	Untreated	---	6.42	0.48	1.96	0.50
	LSD		5.20	NS	0.64	0.45
	CV		25.6	38.1	17.6	35.4

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