EARLY-SEASON WEED CONTROL IN DIRECT-SEEDED ONION (*ALLIUM CEPA* L.)

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Early-Season Weed Control in Direct-Seeded Onion (*Allium cepa L.*)

By

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ABSTRACT

Onion is a poor competitor with early-season broadleaf weeds. In addition, there are no current herbicide labels that allow POST application prior to the onion two-leaf stage in ND and PRE herbicide options provide inconsistent results. Bromoxynil and oxyfluorfen at reduced rates plus adjuvants were evaluated in the greenhouse for common lambsquarters and redroot pigweed control and crop safety when applied to onion prior to the two-leaf stage. Bromoxynil and oxyfluorfen plus methylated seed oil (MSO) or petroleum oil concentrate (POC) had the greatest onion safety compared to other tested adjuvants and provided acceptable weed control 12 d after three sequential applications. ^{14}C-oxyfluorfen absorption was evaluated in the laboratory 24 h after treatment and oxyfluorfen absorption was greatest at 35 C compared to 15 and 25 C. Multiple applications of bromoxynil and oxyfluorfen at reduced rates were further evaluated with MSO or POC in field experiments. Bromoxynil provided 12% better common lambsquarters control and 9 t/ha greater large-grade onion yield than oxyfluorfen. Greater reduced rates resulted in greater common lambsquarters control and reduced common lambsquarters stand density. Common lambsquarters control was 24 to 32% greater when POC or MSO were used, respectively, compared to no adjuvant. Bromoxynil did not reduce onion stand/m as rates increased, but oxyfluorfen reduced onion stand as rates increased. Four or five sequential bromoxynil or oxyfluorfen applications every 7 d resulted in 14 to 19% greater weed control than three sequential applications. Onion stand was severely reduced by PRE herbicide and multiple reduced-rate application combinations.

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LIST OF ABBREVIATIONS

PRE..Preemergence

POST......................................Postemergence

ae..Acid equivalent

ai...Active ingredient

t ....Metric ton

Table A1.................................Appendix table 1

d..Day

wk...Week

h..Hour

microrate ....Multiple applications of reduced-rate herbicides

^{14}C ....Carbon 14 radio-labeled

v/v ....Volume per volume

ANOVA ....Analysis of variance

LSD..Least significant difference

UAN.......................................Urea ammonium nitrate

SOV..Source of variation

df ....Degrees of freedom

MS..Mean square

F ....F-value

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CHAPTER 1. INTRODUCTION

Onion is a crop with potential for high economic return in ND. However, due to slow onion growth, poor competitive morphology, low tolerance to registered herbicides, and the short ND growing season, the maximum onion yield is rarely obtained. Morphological traits that contribute to the poor competitiveness of onion include a shallow root system; long, narrow, erect leaves; and a long establishment period (Ashton and Monaco 1991; Bell and Boutwell 2001). Onion seedlings are slow to emerge from the soil and have a slow growth rate which is exacerbated by cooler temperatures (Brewster 1994), giving onion a competitive disadvantage compared to weeds.

Weed competition has decreased onion yield by up to 90% in high weed populations (Hewson and Roberts 1971), or by 43% if weeds were left uncontrolled only during the establishment stage (Palczynski et al. 2001). If left uncontrolled, weed competition remains a potential problem throughout the growing season (Swaider et al. 1992). The combination of onion slow growth rate, inability of onion to produce a sufficient morphological canopy, and poor broadleaf weed control options, allows early-season broadleaf weeds, such as common lambsquarters and redroot pigweed, to cause substantial yield losses (Boydston and Seymour 2002). The onion establishment period is thus the most critical period for weed control.

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CHAPTER 2. LITERATURE REVIEW

Species Background

Onion is classified as a biennial monocot, and is one of few monocot vegetables (Swaider et al. 1992). A member of the Alliaceae family, relatives of onion within the same genus (*Allium)* include garlic (*Allium sativum* L.), leek (*Allium porrum* L.), and chives (*Allium schoenoprasum* L.). The distinguishing feature of *Allium* is production of a bulb, which is a concentric swollen leaf base below the vegetative leaves. Onion is among the first recorded crops grown for food. Cultivated onion is even mentioned in the Bible, as shown in Numbers 11:4-6:

"The rabble with them began to crave other food, and again the Israelites started wailing and said, "If only we had meat to eat! We remember the fish we ate in Egypt at no cost—also the cucumbers, melons, leeks, onion and garlic. But now we have lost our appetite; we never see anything but this manna!"

Varieties

Onion was introduced to North America by Spanish explorers in 1629 (Sell 1993). Onion grows in a wide range of climates because of its unique response to day length. In most agronomic crops, changes in day length initiate flowering and seed production. In onion, bulbing is initiated by day length changes (Boyhan et al. 2001). This unique response works well with onion's biennial nature, bulbing the first year, and in more temperate climates, initiating seed development the second year.

To maximize yields, onion varieties have been developed based on response to day length (Boyhan et al. 2001; Decoteau 2000; Nonnecke 1989). Varieties are placed into three groups; short-day, intermediate-day, and long-day. In the southern United States, short-day varieties such as 'Vidalia' initiate bulbing with day lengths of 10 to 11 h. Intermediate-day varieties such as

‘Yellow globe’ initiate bulbing with day lengths of 12 to 13 h and are grown in south to central California, Georgia, and the Mid-Atlantic States. Long-day varieties such as ‘Teton’ initiate bulbing with day lengths greater than 14 h and are grown as far north as possible. The longer day length compensates for the shorter growing season by providing more light time for photosynthesis (Nonnecke 1989). Hybrid varieties are more homogenous and higher yielding than traditional varieties (Sell 1993).

Planting Methods

Onion can be grown from transplants, from sets, or from seed. The transplant method is most common in southern production areas to achieve an earlier harvest, thus ensuring earlier marketability (Sell 1993). Transplants can be started from seed in the greenhouse or protective beds and then moved to field production at a height of 15 cm (Decoteau 2000). Growing onion from transplants may provide a head start in cooler production regions, thus lengthening the growing season (Brewster 1994).

Sets are small bulbs which are produced in the late winter of the previous year or early spring to be planted the next spring (Decoteau 2000). The set method of production can be used anywhere, but is most common in the central to southern production regions. Typical set lengths are less than 25 mm in diameter and are grown with a similar purpose as transplants, to lengthen the growing season (Brewster 1994). As a rule of thumb, the larger the set, the shorter the production time to reach marketable bulb size (Decoteau 2000).

In northern climates, direct seeding is the most common form of onion production. Seeds are planted by mid-April to mid-May to achieve maximum yields. Precision vegetable planters are used to plant seed at a depth of 2.5 cm. Accurate planting depth is essential to ensure the desirable round shape of the bulb. If seeded too deep, the resulting bulbs will be longer, or “torpedo” shaped (Sell 1993). In contrast, shallow seeded onion will appear flatter. The recommended seeding rate for long-day cultivars is 685,000 seeds/ha, resulting in a target population of 617,000 plants/ha with 90% seed germination (Swaider et al. 1992).

Direct seeding onion is the most economical form of onion production. Human resources required to grow direct-seeded onion is far less than that of transplants or sets. However, direct-seeded onion requires more intense field management than the other methods of production due to the week competitive nature of onion (Brewster 1994). In ND, field preparation begins the previous year with crop selection, weed control, fall tillage, and often a fall planting of winter wheat or winter rye in strips as a wind break (Hatterman-Valenti 2005, personal communication). The use of strip tillage has also been evaluated for onion production systems with some success (Gegner 2009). All these steps may be taken together to aid establishment and weed control during the onion crop year.

Growth Requirements

Once planted, direct seeded onion experiences best germination conditions at soil temperatures above 2 C. The germination rate increases with increasing soil temperature. Air temperatures from 13 C to 24 C are considered optimum for onion establishment. Establishment depends on optimum air temperatures (Swaider et al. 1992). Onion seedlings can take anywhere from 4 to 6 wk to emerge and reach the two-leaf stage depending on temperature. Warm soil and air temperatures shorten the time of establishment.

Onion grows well in a variety of soil types and soil pH’s. Muck soils (high in organic matter (OM)) provide ideal growth conditions because of their high nitrogen content and water holding capacity, and are often considered the most desirable soil type for onion growth (Swaider et al. 1992). Mineral based soils, such as a sandy-loam or loamy-sand provide excellent growth conditions provided that adequate levels of OM, nutrients, and water are supplied because they are more resistant to crusting. Soils high in clay are therefore not ideal for onion production (Nonnecke 1989). In general, onion grows best at a pH range from 6 to 7. There are some exceptions, such as the muck soils of Ontario, where onion grows well at an acidic pH of 4 (Brewster 1994). As a rule of thumb, more acidic conditions are desirable with muck soils, and more basic conditions with mineral based soils.

Onion requires a continuous supply of nitrogen, phosphorus, and potassium during the growing season because onion has a limited root system that is inefficient for scavenging nutrients (Swaider et al. 1992). The amount of each of these primary nutrients to be applied varies with field history. However, onion responds well to two to three side dressing applications of nitrogen during the growing season, rather than one pre-plant bulk delivery (Nonnecke 1989). This is due to the leaching potential of nitrogen in the soil profile away from the shallow onion root system (Brewster 1994). Decoteau (2000) stated, "onion responds to side-dressing with 9 to 11 kg of nitrogen 3 wk after emergence and every 3 wk thereafter."

Onion requires a steady supply of water because of its shallow root system (Swaider et al. 1992). The onion root system develops in the upper 0 to 20 cm of the soil with a 15-cm radius around the onion bulb (Melander and Hartvig 1997). The frequency of irrigation is dependent on soil type. Muck soils have a higher water holding capacity than mineral based soils and therefore have greater water availability in the upper soil profile longer than sandy soils. Frequent, light irrigations are beneficial in mineral soils to maintain uniform upper soil moisture (Nonnecke 1989).

Overall, 15 to 31 ha-cm of water applied to onion during the growing season, depending on location (Swaider et al. 1992). Less water is used during the seedling stage than the bulbing stage. General recommendations dictate that irrigation cease when 10% of the crop canopy is down (Sell 1993), and/or 3 wk prior to harvest, aiding crop progression to maturity. If irrigation and nitrogen application continue at this time, maturity may be delayed (Brewster 1994), and unmarketable thick-necked bulbs may result (Nonnecke 1989).

Establishment, Vegetative, and Bulbing Stages

In adequate soil temperatures, germination is initiated when the cotyledon pushes through the seed coat (Swaider et al. 1992). The cotyledon then remains just inside the endosperm to absorb digested nutrients for translocation to the growing seedling. The root system continues to develop with slight elongation of a primary root and establishment of the main root system. The first narrow leaf (flag-leaf) emerges from a cavity in the cotyledons. A light irrigation may be required during establishment to avoid crusting and to provide adequate moisture for the germinating seed, thus achieving the best possible stand. (Sell 1993). After an onion seedling emerges and initiates the flag-leaf, all subsequent leaves develop inside the previous leaf and emerge from a hole in the side of the previous leaf, resulting in the onion's hollow leaf structure (Swaider et al. 1992).

The vegetative stage of crop development begins after crop establishment. During this stage plants develop a crop canopy (Brewster 1994). The larger the crop canopy, the greater the leaf area index (LAI), and the greater the capacity for light interception. These vegetative factors, combined with cultural factors such as sowing date, plant population, and maturity date, and physical factors such as moisture and temperature, equate to the resulting bulb formation and yield. Therefore, a large crop canopy, resulting from a high LAI will correlate to high light interception and overall higher crop yields.

Onion bulbing is initiated by a day length and temperature interaction (Brewster 1994). Long-day varieties initiate bulbing if a minimum photoperiod of 14 h is reached. New leaf production ceases as bulbing commences. The onion bulb is produced in the first year of growth, and if a vernalization period of 10 C is attained at maturity, the biennial onion will produce a reproductive seed stalk (Swaider et al. 1992).

Weed Control

Morphological traits of onion include a shallow root system, slow establishment period, and long, narrow, erect leaves that form a crop canopy that produces little to no shade. These morphological characteristics cause onion seedlings to be poor competitors with weeds (Ashton and Monaco 1991), and allow weeds to establish and compete with the crop (Bell and Boutwell 2001). Due to row-crop production and a poor crop canopy, weed competition is a severe problem from onion establishment through maturation (Swaider et al. 1992). Small-grade onion bulbs accounted for 90% of the total onion yield when weeds competed with onion for 6 wk after emergence (Shadbolt and Holm 1956). Volunteer potato density (*Solanum tuberosum*) of ≥ eight plants/m^2 resulted in a 90 to 100% onion yield loss when left uncontrolled (Williams et al. 2004). Low densities of uncontrolled common lambsquarters (4 plants/m^2) also resulted in a 81% yield loss compared to the weed-free check (Grundy et al. 2004). Thus, season-long weed control in onion is essential to ensure marketable yields.

Cultivation and hand-weeding are physical weed control methods in onion, but may damage the shallow onion root system. The potential injury by cultivation may outweigh the benefit for overall yield (Melander and Hartvig 1997). Accurate implement steering may minimize damage to the onion root system from cultivation. Conversely, hand-weeding is time consuming and not an economical method of weed control for onion producers (Fennimore and

Doohan 2008). In ND, cultural practices using strip-tillage or cover crops planted to protect seedling onion from the wind also supply some weed suppression benefits.

Herbicide options for weed control are limited. DCPA is the standard PRE early-season weed control option in onion and is an integral part of many onion production weed control systems. However, DCPA is not economical unless weed densities are between 4 and 15 plants/m^2, assuming 60% herbicide efficiency (Dunan et al. 1995). A combination of PRE bensulide and pendimethalin controlled nettleleaf goosefoot (*Chenopodium murale* L.), little mallow (*Malva parviflora* L.), London rocket (*Sisymbrium irio* L.), and spiny sowthistle (*Sonchus asper* L. Hill) in onion (Bell and Boutwell 2001). However, these treatments reduced onion density up to 31%. Fluroxypyr applied POST and ethofumesate PRE or POST suppressed volunteer potato (Boydston and Seymour 2002) in onion, but fluroxypyr application rates caused severe onion injury. Ghosheh (2004) concluded that a single POST oxyfluorfen application at the three- to four-leaf stage or a single PRE application did not provide adequate weed control, warranting further research into more precise weed control methods.

Bromoxynil and oxyfluorfen have labels that allow selective POST application (Boydston and Seymour 2002). However, these labels dictate onion have two true leaves for application (Anonymous 2005; Anonymous 2009). Onion appears to be very susceptible to POST herbicide injury prior to the two-leaf stage because the plant has not formed a protective leaf cuticle (Ashton and Monaco 1991). Consequently, environmental conditions that slow onion growth and establishment may result in greater early-season weed competition.

Limited herbicide registration applies not only to onion, but most horticultural crops (Bell et al. 2000; Fennimore and Doohan 2008; Gast 2008; Haar et al. 2002; Kunkel et al 2008). Barriers to expand herbicide registration in horticultural crops include an overall reduction of new active ingredients developed by the herbicide industry, the low number of horticultural crop hectares when compared with commodity crops, and liability concerns for herbicides applied to horticultural crops with limited selectivity. Low availability of registered herbicides coupled with a steady decrease in development of new herbicides has lead researchers to improve efficacy through novel approaches (Kunkel et al. 2008).

Recent research has evaluated the effect of application volume and reduced herbicide rate for single POST treatments of bromoxynil and oxyfluorfen prior to the two-leaf stage (Schumacher and Hatterman-Valenti 2007). In an experiment near Oakes, ND, bromoxynil at 80 g ae/ha applied with oxyfluorfen at 110 g ai/ha in 230 L/ha spray volume at the onion one-leaf stage provided 74% and 90% control of common lambsquarters and redroot pigweed (averaged across species) 1 week after treatment (WAT), respectively. Average control of these species decreased to 58% and 78%, respectively 7 WAT, indicating that control with a single, reduced POST application of bromoxynil or oxyfluorfen was insufficient for season-long weed control. Crop injury 3 WAT was 1% with bromoxynil and 13% with oxyfluorfen and was considered acceptable. In another study, three sequential bromoxynil applications at 70 g/ha provided 95 control of common lambsquarters, while three sequential oxyfluorfen application at 70 g/ha provided 74% control of common lambsquarters (Loken and Hatterman-Valenti 2010). These and other results have encouraged further research into the possibility of split-applied herbicide treatments in onion (Palczynski et al. 2001). However, microrates have yet to be investigated for weed control in onion.

The principles behind microrate treatments in onion are based on weed control research in sugarbeet (*Beta vulgaris* L.) (Woznica et al. 2004) that started in the 1970s because poor weed control was obtained from a single application of POST and PRE/PPI herbicides (Dexter 1994).

Research showed that less herbicide was required to control small broadleaf weeds (cotyledon to first-true leaf stage) than larger weeds (Dale 2000). Reduced herbicide rates also resulted in increased crop safety. In addition, multiple applications widened the application window allowing the grower to control multiple weed flushes. Although more herbicide treatments increased application costs, the microrate program proved to be more economical because less herbicide was applied (Dale et al. 2006). The microrate program incorporated herbicide rates reduced by approximately two to four times compared to rates recommended in conventional programs that split applications (Woznica et al. 2004), and utilized herbicides applied three or more times at 5- to 7-d intervals, starting when broadleaf weeds emerged (Zollinger et al. 2008).

Adjuvants and Leaf Cuticle

Adjuvants have been defined as substances added to a herbicide spray mixtures to improve the efficacy of the herbicide (Hazen 2000) by altering spray retention or foliar absorption at the plant cuticle (Woznica et al. 2003). Historically, adjuvant distribution has not experienced close regulation or scrutiny (Hazen 2000). However, new standards and public testing may improve the reputation of this industry.

There is no standard terminology for adjuvant classification. According to Hazen (2000), adjuvants can be placed into several specific groups, but can be most easily categorized based on end use as; "(1) those that modify the physical characteristics of the spray mixture, and (2) those that enhance the biological efficacy of the crop production chemical" (Hazen 2000). Zollinger (2000) stated that "classifying adjuvants simply as surfactants, oils, and fertilizers could reduce grower confusion". Like Zollinger, Woznica et al. (2003) described adjuvants as oils, surfactants, and nitrogen fertilizers. These descriptions attempted to simplify adjuvant classification as much as possible, and are interrelated. Fertilizers fall into category (1) because they aid in overcoming herbicide antagonism from high concentrations of the ions Ca, Mg, or Na in the spray water. Surfactants and oils fall into category (2) because of the increased efficacy these adjuvants provide herbicides at the adjuvant site of action (the leaf cuticle) (Hazen 2000, Zollinger 2008).

The effectiveness of POST herbicides is affected by a myriad of interactions between the herbicide, adjuvant, plant species, leaf surface properties, spray water quality, physical characteristics of the spray droplet, and the environment (Zollinger 2000; Woznica et al. 2003). These interactions are not easily separated and occur simultaneously, making it difficult to isolate the effect of individual factors on herbicide uptake (Schönherr and Bauer 1992).

Specifically, these interactions take place at the plant leaf cuticle, the plant's barrier to the environment. The leaf cuticle is composed of generally non-polar epicuticular wax (outermost layer) and polar cutin (underneath the epicuticular wax) (Manthey et al. 1990). The ultimate success of POST herbicide movement into a plant depends on penetration of this barrier and absorption into plant cells beneath (Hatterman-Valenti et al. 2006). Consquently, in onion, POST herbicide crop safety is directly influenced by cuticular thickness (Ashton and Monaco 1991). Therefore, research is necessary to find the safest herbicide plus adjuvant combinations that provide adequate crop safety and excellent weed control for onion producers.

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CHAPTER 3. GREENHOUSE SCREENING TRIAL: OXYFLUORFEN OR BROMOXYNIL WITH ADJUVANTS FOR WEED CONTROL IN ONION

Abstract

Early-season weed competition may cause substantial yield losses in onion. Oxyfluorfen and bromoxynil are POST herbicide options for weed control once onion has developed two leaves, which often takes 4 to 6 wk. Microrate applications of oxyfluorfen at 35 and 18 g ai/ha and bromoxynil at 35 and 18 g ae/ha with adjuvants were evaluated for onion safety and weed control under controlled greenhouse conditions. Oxyfluorfen at 35 g/ha plus organosilicone surfactant (OSS) caused 42% onion injury at 12 d after three sequential applications. Onion treated with bromoxynil at 18 g/ha plus high surfactant oil concentrate (HSOC) had lower onion fresh weight (0.7 g) compared to methylated seed oil (MSO) (1.2 g) or petroleum oil concentrate (POC) (1.3 g) at the same bromoxynil rate. The addition of nonionic surfactant to bromoxynil, averaged across bromoxynil rates, provided 17 and 39% control of redroot pigweed and common lambsquarters, respectively, and provided 49% control of common lambsquarters when added to the 35 g/ha oxyfluorfen rate. Redroot pigweed control with oxyfluorfen at 35 or 17 g/ha plus any tested adjuvant was excellent (≥ 93%). Screening results suggested the use of POC or MSO with either oxyfluorfen or bromoxynil for subsequent field trials because of similar common lambsquarters and redroot pigweed control and onion safety.

Nomenclature: Oxyfluorfen; bromoxynil; onion, *Allium cepa* L.; redroot pigweed, *Amaranthus retroflexus* L.; common lambsquarters, *Chenopodium album* L.

Key words: herbicide, reduced-rate, early-season.

Introduction

Onion seedlings are slow to emerge from the soil, have a slow growth rate exacerbated by cool temperatures, and are very poor competitors with weeds (Brewster 1994). These combined factors give several weed species a distinct advantage during the early part of the growing season. Cultivation is not advised to control weeds because of potential onion root damage (Melander and Hartvig 1997). In ND, there are seven herbicides labeled for broadleaf weed control in onion, and only oxyfluorfen and bromoxynil provide control once weeds have emerged (Loken and Hatterman-Valenti, 2011). However, oxyfluorfen and bromoxynil labels dictate POST application to onion starting at the two-leaf stage (established) due to crop safety concerns (Anonymous 2005; Anonymous 2009), which can take from 4 to 6 wk from planting. DCPA, ethofumesate, and bensulide are PRE weed control options for onion. Unfortunately, DCPA may only be economical at weed densities between 4 and 15 plants/m^2, assuming 60% herbicide efficiency (Dunan et al. 1995). Ethofumesate applied PRE at 0.6 kg ai/ha resulted in greater onion yields due to increased crop safety than ethofumesate applied PRE at 1.1 kg/ha and was described as a promising treatment, but required further evaluation of herbicide interactions with irrigation methods and soil type, and corresponding effects on onion injury (Boydston and Seymour 2002). Bensulide may reduce onion stand and vigor when environmental conditions are not favorable (Anonymous, 2010), and lacks broad-spectrum control (Bell and Boutwell 2001).

Reduced-rate herbicide application technology has been researched for weed control and crop safety benefits in several crops. Phenmedipham was applied at half the labeled rate (0.56 to 0.84 kg ai/ha) to sugarbeet in 1972 with a subsequent application 5- to 7-d later (Dexter 1994). Superior weed control and crop safety were achieved with the phenmedipham split application compared to the full-labeled rate. Weed control and subsequent soybean yield with split applications of bentazon, chlorimuron, imazaquin, or imazethapyr (280, 2, 40, and 30 g ai/ha, respectively) was not different than full-labeled rates (Steckel et al. 1990). Weed control of common lambsquarters (99%) in field pea with imazethapyr (15 g ai/ha) was not different than the full-labeled rate (75 g ai/ha) 28 days after treatment (DAT) (Sikkema et al. 2005). Weed control did decline to 80% by 56 DAT, but was still considered commercially acceptable with resulting field pea yields similar to the weed-free check.

Herbicide rate reduction has also been evaluated in onion. A single reduced-rate application of bromoxynil or oxyfluorfen (80 g ae/ha and 110 g ai/ha, respectively) provided 74% and 90% control of common lambsquarters and redroot pigweed (averaged across species) respectively, 1 wk after treatment (WAT) (Schumacher and Hatterman-Valenti 2006). Control of these species decreased to 58 and 78% control, respectively, 7 WAT, indicating this single bromoxynil or oxyfluorfen application was insufficient for season long control. Microrates demonstrated early-season control of common lambsquarters and redroot pigweed in ND (Loken and Hatterman-Valenti 2010). Bromoxynil (70 g/ha) applied three times at 5- to 7-d intervals provided 99 and 97% control, respectively, of common lambsquarters and redroot pigweed. Oxyfluorfen (70 g/ha) applied at the same parameters provided 78 and 95% control of common lambsquarters and redroot pigweed, respectively. Onion treated with microrates of oxyfluorfen had greater large-grade yields than the hand-weeded check. Nonetheless, further research was suggested to evaluate potential herbicide rate reduction when adjuvants were added.

An adjuvant is generally defined as a substance added to a herbicide spray mixture to improve the efficacy of the herbicide (Hazen 2000) by altering spray retention or foliar absorption at the plant cuticle (Woznica et al. 2003). While there is no standard terminology for adjuvant classification, attempts have been made to categorize adjuvants based on end use as; "those that modify the physical characteristics of the spray mixture, and those that enhance the biological efficacy of the crop production chemical" (Hazen 2000). Classifying adjuvants as surfactants, oils, and fertilizers has also been proposed to simplify selection and reduce confusion (Zollinger 2000; Woznica et al. 2003). Fertilizer adjuvants act to overcome hard water antagonism in carrier solutions with high concentrations of the ions Ca, Mg, or Na. Surfactants and oil-based adjuvants provide increased herbicide efficacy at the adjuvant site of action (the leaf cuticle) (Hazen 2000; Zollinger 2011).

The objectives of the greenhouse experiment using microrate applications of bromoxynil and oxyfluorfen plus adjuvants were (1) to evaluate onion safety, (2) to evaluate control of common lambsquarters and redroot pigweed, and (3) to select the adjuvant(s) for further evaluation in field trials.

Materials and Methods

Experiments evaluated bromoxynil[1] and oxyfluorfen[2] (aqueous capsule suspension) individually for onion safety and efficacy when applied as microrates with adjuvants for control of common lambsquarters and redroot pigweed. The two herbicides were used individually in experiments due to time constraints with application timings and data collection. Five adjuvants, each from different adjuvant classes, were tested with each herbicide. The adjuvant classes and rates were: organosilicone surfactant[3] (OSS) at 0.25% v/v; methylated seed oil[4] (MSO) at 0.5% v/v; high surfactant oil concentrate[5] (HSOC) at 0.5% v/v; petroleum oil concentrate[6] (POC) at 1.2 L/ha; and nonionic surfactant[7] (NIS) at 0.25% v/v. The herbicide-adjuvant combinations were applied across three herbicide rates that corresponded to zero, 0.06X, and 0.13X of the lowest labeled rate for each herbicide at the onion two-leaf stage. Oxyfluorfen application rates were 0, 18, and 35 g/ha and bromoxynil application rates were 0, 18, and 35 g/ha. These rates were chosen to express the effect of the adjuvant, rather than the herbicide. The untreated checks were treatment combinations of no herbicide and no adjuvant. Experimental design was a randomized complete block (RCBD) with a factorial arrangement of rates and adjuvants with three replications.

The onion variety 'Sedona' at three seeds per pot along with 40 to 50 redroot pigweed and common lambsquarters seeds each were planted at the same time into 10 x 10 cm square pots with potting soil[8]. Greenhouse temperatures were maintained at 21 ± 5 C, and natural daylight was supplemented to 15 h per day with a light intensity of 400 $\mu E/m^2/s$. The potted onion, redroot pigweed, and common lambsquarters plants were maintained with normal greenhouse practices and weeds were thinned to three plants of each species per pot prior to herbicide treatment.

Herbicide treatments began when common lambsquarters and redroot pigweed reached the cotyledon stage, which coincided with onion at the loop stage. Three sequential applications were made at 4 d intervals. The herbicides were applied using a chain-driven chamber sprayer[9]. A single TeeJet[10] 8001 flat-fan spray nozzle was used at an application speed of 2.6 km/h to apply a spray volume of 187 L/ha at 276 kPa. Visual evaluations were made 12 d after the third sequential herbicide application using a 0 to 100% scale for crop injury and weed control. For crop injury, 0% was when no visible onion injury was observed, 50% was when half of the onion stand was eliminated, and 100% was complete onion death and no onion were present. For weed control, 0% was when no weeds were controlled, 50% was when the weed stand was reduced to half of the untreated, and 100% was when all weeds were dead. Onion, redroot pigweed, and common lambsquarters plant fresh weights were also taken 12 d after the third application. Two runs of each experiment were completed and combined because mean square errors were within a factor of ten. Data were analyzed using ANOVA in SAS[11]. Mean squares were equated to expected mean squares to determine the proper F-tests. Treatment means were separated where appropriate using Fisher's protected LSD at the 0.05 level of significance.

Results and Discussion

Evaluation 12 d after Three Sequential Oxyfluorfen Applications.

There was a significant adjuvant-by-rate interaction for onion injury, common lambsquarters control, and common lambsquarters fresh weight (Table 1; Table A1). Onion injury tended to increase with increasing oxyfluorfen rates, with the greatest onion injury from oxyfluorfen applied at 35 g/ha plus OSS (42%) 12 d after the third application. Onion injury with oxyfluorfen applied at 35 g/ha plus any other tested adjuvant was 18% or less and was considered an acceptable injury level for further field trial evaluation. Onion injury from oxyfluorfen applied at 18 g/ha was greatest with MSO (14%), suggesting enhanced oxyfluorfen efficacy even with the lowest oxyfluorfen rate. Methylated seed oil adjuvants are aggressive at dissolving cuticular leaf waxes resulting in greater herbicide absorption (Zollinger et al. 2011).

Common lambsquarters control with the 35 g/ha oxyfluorfen rate plus an adjuvant provided better control than the 18 g/ha rate plus an adjuvant, except with NIS (Table 1; Table A1). The oil-based adjuvants and OSS tended to provide better control with oxyfluorfen at 35 g/ha than NIS or no adjuvant. Common lambsquarters fresh weights inversely corresponded to visual evaluations. Common lambsquarters treated with oxyfluorfen at 35 g/ha plus OSS, MSO, or HSOC, or oxyfluorfen at 18 g/ha plus OSS had the lowest fresh weights.

Redroot pigweed control with oxyfluorfen applied at 35 g/ha with or without an adjuvant did not differ from oxyfluorfen applied at 18 g/ha with an adjuvant (control 93% or better)

Table 1. Effect of adjuvant-by-rate interaction on onion injury, and common lambsquarters control and fresh weight in greenhouse experiments 12 d after three sequential oxyfluorfen applications.

	Oxyfluorfen rate (g ai/ha)								
	Onion Injury			Common lambsquarters control			Common lambsquarters fresh weight		
Adjuvant[a]	0	18	35	0	18	35	0	18	35
	---------- % --------			---------- % ----------			------------ g ------------		
OSS	0	6	42	0	57	82	3.2	1.2	0.3
MSO	0	14	11	0	53	64	2.6	1.0	0.8
HSOC	1	6	18	0	60	68	4.1	1.0	0.7
POC	0	1	12	0	19	69	3.8	2.1	1.0
NIS	0	6	11	0	36	49	4.0	2.0	1.6
None	0	1	13	0	7	28	3.6	4.9	2.2
$LSD_{0.05}$	---------- 7 ---------			--------- 19 ----------			------------ 1.0 ----------		

Abbreviations: [a] OSS, organosilicone surfactant at 0.25% v/v; MSO, methylated seed oil at 0.5% v/v; HSOC, high surfactant oil concentrate at 0.5% v/v; POC, petroleum oil concentrate at 1.2 L/ha; NIS, nonionic surfactant at 0.25% v/v.

(Table 2; Table A2), indicating the potential to further reduce oxyfluorfen rates when using an adjuvant for redroot pigweed control. Redroot pigweed control with oxyfluorfen is better than control of common lambsquarters (Egel 2007).

Table 2. Effect of adjuvant-by-rate interaction on redroot pigweed control in greenhouse experiments 12 d after the third oxyfluorfen application.

		Oxyfluorfen rate[b]		
		Redroot pigweed control		
Adjuvant[a]	Rate	0	18	35
		--------------------- % control ---------------------		
OSS	0.25% v/v	0	98	99
MSO	0.5% v/v	0	93	99
HSOC	0.5% v/v	0	98	100
POC	1.2 L/ha	0	94	100
NIS	0.25% v/v	0	95	99
None	0	0	78	98
$LSD_{0.05}$		------------------------- 7 -------------------------		

[a] OSS, organosilicone surfactant; MSO, methylated seed oil; HSOC, high surfactant oil concentrate; POC, petroleum oil concentrate; NIS, nonionic surfactant.
[b] Rates expressed as g ai/ha.

Evaluation 12 d after Three Sequential Bromoxynil Applications.

Bromoxynil did not injure onion (Table A3). There was a significant bromoxynil rate-by-adjuvant interaction for onion fresh weight, common lambsquarters fresh weight, and common lambsquarters control. Onion fresh weights tended to increase with increasing bromoxynil rates because weeds were controlled better as rates increased (Table 3; Table A4). Common lambsquarters fresh weights were lowest when bromoxynil was applied at 35 g/ha plus any adjuvant and at 18 g/ha plus an oil-based adjuvant or OSS.

Table 3. Effect of adjuvant-by-rate interaction on common lambsquarters control, and onion and common lambsquarters fresh weight in greenhouse experiments 12 d after three sequential bromoxynil applications.

	Bromoxynil (g ae/ha)								
	Onion fresh weight			Common lambsquarters control			Common lambsquarters fresh weight		
Adjuvant[a]	0	18	35	0	18	35	0	18	35
	g			%			g		
OSS	0.4	0.7	1.1	7	74	96	3.6	0.4	0
MSO	0.4	1.2	1.0	3	69	78	3.8	0.6	0.4
HSOC	0.5	0.7	1.0	16	86	93	2.1	0.4	0.2
POC	0.4	1.3	1.1	0	55	97	3.7	1.4	0
NIS	0.4	0.8	0.8	3	42	94	3.0	2.4	0.1
None	0.5	0.5	0.5	0	5	24	3.6	3.3	1.9
$LSD_{0.05}$	0.3			27			1.2		

Abbreviations: [a] OSS, organosilicone surfactant at 0.25% v/v; MSO, methylated seed oil at 0.5% v/v; HSOC, high surfactant oil concentrate at 0.5% v/v; POC, petroleum oil concentrate at 1.2 L/ha; NIS, nonionic surfactant at 0.25% v/v.

Visual evaluations of common lambsquarters control confirmed fresh weight trends (Table 3; Table A4). Bromoxynil applied at 35 g/ha plus an adjuvant and at 18 g/ha plus OSS or HSOC had the greatest common lambsquarters control. Bromoxynil applied at 35 g/ha without an adjuvant did not differ from the untreated check, indicating the overall benefit of an adjuvant with bromoxynil at reduced rates.

There was no adjuvant-by-bromoxynil rate interaction for either redroot pigweed control or fresh weight (Table A5). Adjuvant did not influence redroot pigweed control with bromoxynil either (Table A5). As would be expected, control was dependent on the presence of bromoxynil in the treatment (Table 4; Table A5). Redroot pigweed fresh weight corresponded to weed control, and fresh weight was reduced as long as bromoxynil was included in the application.

Table 4. Effect of rate averaged across adjuvants on redroot pigweed control and fresh weight in greenhouse experiments 12 d after three sequential bromoxynil applications.

Bromoxynil rate	Redroot pigweed	
g ae/ha	% control	fresh weight (g)
0	4	2.3
18	54	0.7
35	78	0.3
$LSD_{0.05}$	29	0.9

Based on the results of both the oxyfluorfen and bromoxynil screening trials, MSO and POC were selected for further field evaluation with oxyfluorfen and bromoxynil. HSOC was not selected due to the high level of onion injury (42%) with oxyfluorfen (Table 1). In contrast, NIS was not selected because of poor weed control with oxyfluorfen at either 35 or 18 g/ha or bromoxynil at 18 g/ha (Table 1 and 3). Including HSOC with either oxyfluorfen or bromoxynil provided acceptable weed control of both common lambsquarters and redroot pigweed, but was not selected because onion fresh weight was less when compared to remaining adjuvants (Table 1 and 3). Onion treated with bromoxynil at 18 g/ha plus HSOC had lower fresh weight in comparison to bromoxynil at 18 g/ha plus POC or MSO (Table 3). MSO and POC adjuvants with all oxyfluorfen and bromoxynil application rates tended to have similar weed control and onion safety with few exceptions.

Sources of Materials

[1] Buctril®, Bayer CropScience LP, 2 T.W. Alexander Dr., Research Triangle Park, NC 27709.

[2] GoalTender®, Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268-1189.

[3] Silwet® L-77 Surfactant, Helena Chemical Company, 225 Schilling Blvd., Suite 300. Collierville, TN 38017.

[4] Destiny®, Winfield Solutions, P.O. Box 64589, St. Paul, MN 55164-0589.

[5] Destiny® HC, Winfield Solutions, P.O. Box 64589, St. Paul, MN 55164-0589.

[6] Herbimax®, Loveland Products Inc., P.O Box 1286, Greeley, CO 80632-1286.

[7] Preference®, Winfield Solutions, P.O. Box 64589, St. Paul, MN 55164-0589.

[8] Sunshine Mix No. 2, Sun Gro Horticulture, Inc., 15831 N.E. 8th St., Suite 100, Bellevue, WA 98008.

[9] Research Track Sprayer, DeVries Mfg. Corp., 28081 870th Ave., Hollandale, MN 58045.

[10] TeeJet nozzles, TeeJet Spraying Systems Company, P.O. Box 7900, Wheaton, IL 60189-7900.

[11] SAS version 9.3, Statistical Analysis Systems Institute, SAS Circle, P.O. Box 8000, Cary, NC 25712-8000.

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CHAPTER 4. POSTEMERGENCE HERBICIDES WITH ADJUVANTS FOR EARLY-SEASON WEED CONTROL IN ONION

Abstract

A laboratory experiment evaluated the effect of temperature and onion growth stage on ^{14}C-oxyfluorfen absorption. Increasing the air temperature increased ^{14}C-oxyfluorfen absorption, regardless of growth stage. In addition, field experiments were conducted to evaluate multiple applications of bromoxynil and oxyfluorfen applied at reduced rates for early-season weed control in onion. In the field, onion treated with bromoxynil provided 12% better weed control and 9 t/ha greater large-grade onion yield than onion treated with oxyfluorfen. Increasing herbicide rates increased weed control, decreased weed density, and increased large-grade onion yield. The inclusion of either methylated seed oil (MSO) or petroleum oil concentrate (POC) adjuvants with reduced-rate herbicide applications improved weed control 28% compared to no adjuvant. Weed density was least when MSO or POC was added to the reduced-rate herbicide application, while onion stand was greatest when MSO or POC was added to the reduced-rate herbicide application. Four or five sequential reduce-rate applications provided 16% better weed control than three applications. The inclusion of pendimethalin, glyphosate, or the combination of the two, applied PRE with sequential reduced-rate applications of bromoxynil or oxyfluorfen cannot be recommended. Results suggested that sequential reduced-rate applications of bromoxynil with either MSO or POC can increase early-season weed control and subsequent onion yield.

Nomenclature: Onion, *Allium cepa* L.; oxyfluorfen; bromoxynil.

Key words: Reduced-rate, microrate, common lambsquarters.

Introduction

Weeds are a major problem facing ND onion producers and are currently managed with PRE and POST herbicides, cover-crops, and/or expensive hand labor. Common lambsquarters (*Chenopodium album* L.) is listed as the tenth most abundant early-season weed in ND (Zollinger et al. 2003), and is one of the most important weeds to control in commercial onion production (Anderson 2007). A review of herbicide labels and extension publications describes POST common lambsquarters control with oxyfluorfen and bromoxynil, the only two herbicides that have ND labels allowing POST application (starting at the onion two-leaf stage). Common lambsquarters is listed on the Buctril®[1] label (bromoxynil) as being controlled "in the seedling stage" at 280- to- 426 g/ae ha (Anonymous 2005). The *2011 North Dakota Weed Control Guide* (Zollinger 2011) and the *Midwest Vegetable Production Guide for Commerical Growers* (Egel 2007) rate common lambsquarters control with Buctril® as "good". Common lambsquarters is listed as "controlled" when weeds are in the two- to four-leaf stage on the GoalTender®[2] (oxyfluorfen) label at 140 g/ai ha (Anonymous 2009). The *Midwest Vegetable Production Guide for Commerical Growers* (Egel 2007) and the *2011 Weed Control Guide for Vegetable Crops* (Zandstra 2011) rate common lambsquarters control with GoalTender® as "fair". GoalTender® also has supplemental labels that allow application of 140 g/ha at the one-leaf stage in Texas, New Mexico, Arizona, and California (Anonymous 2008a; Anonymous 2008b; Anonymous 2008c; Anonymous 2010). However, there are no POST options for weed control in ND onion prior to the two-leaf stage, and labeled PRE herbicides often do not provide sufficient weed control leading up to the two-leaf stage.

Reduced-rate herbicide applications have been evaluated in onion as an option for weed control during establishment. A single reduced-rate application of bromoxynil or oxyfluorfen (80 g/ha and 110 g /ha, respectively) to one-leaf onion provided 74% and 90% control of common lambsquarters and redroot pigweed (*Amaranthus retroflexus* L.) (averaged across species) respectively, 1 wk after treatment (WAT) (Schumacher and Hatterman-Valenti 2007). Control of these species decreased to 58 and 78% control, respectively, 7 WAT, indicating this single bromoxynil or oxyfluorfen application was insufficient for season long control. Single applications of bromoxynil or oxyfluorfen (emulsifiable concentrate formulation[3]) at 70 g/ha to flag-leaf onion did not reduce onion stand or injure onion, but also did not provide acceptable weed control 7 WAT (Umeda and MacNeil 1999). Microrates demonstrated early-season control of common lambsquarters and redroot pigweed starting at the onion loop-stage (Loken and Hatterman-Valenti 2010). Bromoxynil (70 g/ha) applied three times at 5- to 7-d intervals provided 99 and 97% control, respectively, of common lambsquarters and redroot pigweed. Zandstra and Wallace (1989) suggested that oxyfluorfen may injure onion at recommended rates, so using reduced rates may be justified if weed control can be maintained. Oxyfluorfen (70 g/ha) applied three times at 5- to 7-d intervals provided 78 and 95% control of common lambsquarters and redroot pigweed, respectively (Loken and Hatterman-Valenti 2010). Large-grade yield with oxyfluorfen and bromoxynil was greater than the hand-weeded check and similar to the hand-weeded check, respectively. Concluding remarks indicated a need for future research to evaluate reduced-rate herbicide plus adjuvants and the corresponding effect on onion safety and weed control.

Applying microrates has also lead to further investigation regarding the optimal number of sequential herbicide applications for weed control and crop safety. More than one microrate application was usually necessary in sugarbeet because weeds continued to emerge in the early-season and one application did not provide adequate weed control (Dale and Renner 2005). Three applications of bromoxynil or oxyfluorfen at reduced rates provided better common lambsquarters and redroot pigweed control than two applications (Loken and Hatterman-Valenti 2010), but further evaluation of additional sequential applications and their effect on crop safety, weed control, and yield are necessary.

Selectivity of POST herbicides is known to be a function of differential spray retention, absorption, translocation, and metabolism (Boldt and Putnam 1980), and onion appears to be very susceptible to POST applied herbicides prior to the two-leaf stage because the plant has yet to form an effective cuticular barrier to herbicide absorption (Ashton and Monaco 1991). Both Goaltender® and Buctril® labels caution against herbicide applications at the onion two-leaf stage during cool weather conditions (Anonymous 2005; Anonymous 2009). Research regarding the effect of onion growth-stage and temperature on bromoxynil or oxyfluorfen absorption is difficult to find. However, broccoli (*Brassica oleracea* L. var. *italica*) and collard (*Brassica oleracea* L. var. *acephala*) cultivars were injured less by oxyfluorfen applied POST at 140 g/ha under warmer temperature regimes than cooler temperature regimes (day/night 25/20 and 15/10 C, respectively), but leaf wax content was unaffected (Harrison and Peterson 1999). In another study, decreased oxyfluorfen spray retention was attributed to increasing epicuticular wax content with increasing onion seedling age (Akey and Souza Machado 1984).

The objectives of this research were: 1. to evaluate the effect of temperature and growth stage on oxyfluorfen absorption in onion; 2. to evaluate the addition of methylated seed oil (MSO) or petroleum oil concentrate (POC) to microrate applications of bromoxynil or oxyfluorfen and their effect on onion safety, weed control, and onion yield; 3. to evaluate the effect of additional sequential microrate applications on onion safety, weed control, and onion yield.

Materials and Methods

^{14}C-Oxyfluorfen Absorption Experiment.

An experiment was conducted to evaluate the effect of temperature and onion growth stage on oxyfluorfen absorption. Translocation was not evaluated because oxyfluorfen, a contact herbicide, is known to have limited movement within the plant (Fadayomi and Warren 1977). Onion were seeded into 10-cm pots containing potting soil[4], grown in the greenhouse at 21 ± 2 C, thinned to one plant per pot after emergence, and watered each day. Natural daylight was supplemented to 15.5 h/d with a light intensity of 400 $\mu E/m^2/s$. Plants of uniform size were selected for treatments to be applied at the onion flag-leaf, one-leaf, and two-leaf stages to the largest respective leaf (flag-leaf treated at the flag-leaf stage; first true leaf treated at the one-leaf stage; first true leaf treated at the two-leaf stage). Onion plants were transferred from the greenhouse to the growth chamber 48 h before ^{14}C-oxyfluorfen application for temperature treatments of 15, 25, or 35 C. The chambers were maintained at 45% relative humidity and a 15.5/7.5-h day/night period.

A 1-cm^2 portion of the largest leaf of each onion plant received three 1-µl droplets containing a mixture of 535.4 Bq ^{14}C-oxyfluorfen (specific activity 10.2 mCi/mmole; labeled on the Cl-ring) in methanol:water (33:67 v/v) plus 0.17% v/v MSO[5]. ^{14}C-oxyfluorfen applied in this procedure was equivalent to a 70 g/ha field rate. Onion leaves were kept in a horizontal position with wire to enable herbicide droplet retention and subsequent absorption. Immediately after application, plants were returned to the same temperature treatments for 24 h prior to assay. Onion treated leaves were rapidly dipped 10 times into 15 ml of scintillation cocktail ‘A’ [1:1

v/v, toluene:ethanol plus 5 g/L PPO (2,5-diphenyoxazole)] and 0.5 g/L dimethyl-POPOP [1,4-*bis*-2-(4-methyl-5-phenyloxazolyl) benzene] to remove unabsorbed ^{14}C-oxyfluorfen. Samples were assayed using a liquid scintillation spectrophotometer[6] (LSS).

The experimental design was a randomized complete block with a split plot arrangement. Temperatures were considered whole plots and onion growth stages were considered subplots. The experiment was conducted twice. Data were analyzed using SAS[7]. Mean square errors within a factor of ten were considered homogeneous and were thus pooled across experiment repetitions. Treatment means were separated where appropriate using Fisher's protected LSD at the 0.07 level of significance, which is an acceptable level of significance for ^{14}C research (Rod Lym, personal communication).

Field Experiments.

Adjuvant efficacy field experiments evaluated the use of MSO[5] or POC[8] with bromoxynil or oxyfluorfen (aqueous capsule suspension[2]) applied in multiple sequential applications at reduced rates (microrates) for weed control and onion safety. Adjuvant efficacy experiments were conducted at Absaraka, Carrington, and Oakes, ND in 2008 and at Absaraka, ND in 2009 for a total of four environments (Table 1). Yield data were not collected from Absaraka in 2009 due to flooding, so yield data were averaged across the three remaining environments. Sequential application field experiments evaluated the most effective number of consecutive microrate herbicide applications for weed control during crop establishment. Sequential application experiments were conducted at Absaraka, Carrington, and Oakes, ND in 2008 and at Great Bend, ND in 2009 for a total of four environments (Table 1). Microrate system field experiments evaluated the use of PRE applications of pendimethalin and/or glyphosate followed by POST microrate applications including tank-mixes of bromoxynil, oxyfluorfen, clethodim, and MSO for weed control and onion safety. Microrate system field experiments were conducted at Oakes, Hample, and Great Bend, ND in 2010 (Table 1).

Table 1. Onion planting dates and specifications, previous crop, soil properties, and harvest dates in field experiments evaluating adjuvant efficacy, sequential herbicide applications, and microrate herbicide systems at multiple ND locations.

Location	Planting date	Previous crop	Paired-row spacing[a]	Soil type	Organic Matter	pH	Harvest date
			cm		%		
Oakes 2008[b]	Apr 23	Barley	41	Embden/Hecla sandy loam	2.4	6.7	Sep 24
Absaraka 2008	May 5	Soybean	36	Northern spottswood sandy loam	2.0	7.2	Oct 17
Carrington 2008	May 1	Wheat	36	Heimdal-Emerick/Fram-Wyard loam	2.9	7.9	Oct 3
Absaraka 2009[c]	May 19	Soybean	36	Northern spottswood sandy loam	2.0	7.2	--[d]
Great Bend 2009[e]	May 20	Corn	36	Bearden-Kindred silty clay loam	4.0	7.9	Sep 30
Oakes 2010[f]	Apr 15	Soybean	41	Embden/Hecla sandy loam	2.4	6.7	Sept 13
Hample 2010	Apr 9	Soybean	46	Swendona fine sandy loam	5.0	6.7	Aug 30
Great Bend 2010	Apr 17	Fallow	36	Bearden-Kindred silty clay loam	4.0	7.9	Sept 13

[a] Row spacing measured to the center of each paired-row with 10 cm between each row pair.
[b] 2008 locations had both adjuvant efficacy and sequential application experiments.
[c] Absaraka 2009 location was adjuvant efficacy experiment.
[d] Onion not harvested. Stand destroyed due to flooding.
[e] Great Bend 2009 location was sequential application experiment.
[f] 2010 locations were microrate system experiments.

Adjuvant Efficacy Field Experiment.

Herbicides were applied at 0.25X, 0.13X, and 0.06X, where "X" was the lowest labeled herbicide rate, with four sequential applications. Herbicide microrate treatments included bromoxynil and oxyfluorfen, each at 70, 35, and 18 g/ha. These herbicides were selected based on the results of previous field research (Loken and Hatterman-Valenti 2010). Herbicide applications began in the field when weeds reached the cotyledon stage with sequential applications every 7 d (Table 2). Two checks were used in this experiment for comparison to the microrate, a hand-weeded check and a weedy check (untreated).

Table 2. Onion growth stage during herbicide treatments evaluating adjuvant efficacy at four ND locations.

	Herbicide application				
	Microrate application				
Location	First	Second	Third	Fourth	Standard[a]
	---------- crop stage ----------				
Oakes 2008	loop	flag to 1 leaf	1 to 2 leaf	2 leaf	4 leaf
Absaraka 2008	pre to loop	loop to flag	1 leaf	1 to 2 leaf	3 leaf
Carrington 2008	pre to loop	loop to flag	1 leaf	2 leaf	5 leaf
Absaraka 2009	pre[b]	loop to flag	loop to 1 leaf	1 to 2 leaf	3 leaf

[a] Conventional herbicide standard; bromoxynil (POST) at 280 g ae/ha and oxyfluorfen (POST) at 1120 g ai/ha.

[b] Onion not yet emerged from the soil.

Sequential Application Field Experiment.

Herbicides were applied at 0.13X (bromoxynil and oxyfluorfen at 35 g/ha), where “X” was the lowest labeled herbicide rate, with three, four, or five sequential applications. The 0.13X rate was chosen to express the sequential application effect, rather than the herbicide rate. Previous onion weed control research concluded that three microrate applications provided better weed control than two, so two sequential applications was not included as a treatment (Loken and Hatterman-Valenti 2010). Herbicide applications began in the field when weeds reached the cotyledon stage with sequential applications every 7 d (Table 3). Two checks were used in this experiment for comparison to the microrate, a hand-weeded check and weedy check (untreated).

Microrate System Field Experiment.

Preemergence herbicide treatments included pendimethalin at 1.1 kg ai/ha as an early-PRE, glyphosate at 1.1 kg ae/ha as a late-PRE, and pendimethalin plus glyphosate as a late-PRE.

Table 3. Onion growth stage during herbicide treatments evaluating sequential herbicide applications at four ND locations.

	Herbicide application					
	Microrate application					
Location	First	Second	Third	Fourth	Fifth	Standard[a]
	-- crop stage					--------------------------------------
Oakes 2008	loop	flag to 1 leaf	1 to 2 leaf	2 leaf	3 leaf	4 leaf
Absaraka 2008	pre[b] to loop	loop to flag	1 leaf	1 to 2 leaf	2 leaf	3 leaf
Carrington 2008	pre to loop	loop to flag	1 leaf	1 to 2 leaf	2 leaf	5 leaf
Great Bend 2009	loop	loop to flag	1 to 2 leaf	2 leaf	2 to 3 leaf	3 leaf

[a] Conventional herbicide standard; bromoxynil (POST) at 280 g ae/ha and oxyfluorfen (POST) at 1120 g ai/ha.
[b] Onion not yet emerged from the soil.

DCPA (11.2 kg ai/ha) was applied as an early-PRE for the conventional standard check. A no-PRE control was also included for comparison. Early-PRE applications were made just after planting and late-PRE applications were made just prior to onion emergence to maximize residual duration with pendimethalin and emerged weed control with glyphosate. Postemergence herbicide treatments included tank-mixes of three different microrates. The “high” microrate was bromoxynil plus oxyfluorfen plus clethodim at 70 + 70 + 35 g/ha, repectively, with MSO at 0.5% v/v. The “medium” microrate was the same herbicides at 70 + 35 + 35 g/ha, respectively, with MSO at 0.5% v/v. The “low” microrate was the same herbicides 35 + 35 + 35 g/ha, respectively, with MSO at 0.5% v/v. Herbicide applications began in the field when weeds reached the cotyledon stage with sequential applications every 7 d (Table 4). Five checks were used in this experiment for comparison to the PRE plus microrate treatments; a bromoxynil microrate check, an oxyfluorfen microrate check, a conventional herbicide standard check, a hand-weeded check, and a weedy check (untreated). The bromoxynil and oxyfluorfen microrate checks (bromoxynil or oxyfluorfen plus clethodim plus MSO applied at 70 + 35 + 0.5% v/v, respectively) were included to compare the effect of each broadleaf herbicide applied alone to the combination of the two.

Table 4. Onion growth stage during herbicide treatments evaluating microrate herbicide systems at three ND locations.

	Herbicide application						
	PRE		Microrate application				
Location	Early[a]	Late	First	Second	Third	Fourth	Standard[b]
	------------------ crop stage ------------------						
Oakes 2010	pre[c]	pre to loop[d]	loop	flag to 1 leaf	1 leaf	2 leaf	3 leaf
Hample 2010	pre	pre to loop	loop to flag	1 to 2 leaf	2 leaf	3 leaf	4 leaf
Great Bend 2010	pre	pre	loop	flag to 1 leaf	2 leaf	2 to 3 leaf	3 to 4 leaf

[a] Application timing intended just before onion emergence.
[b] Conventional herbicide standard; bromoxynil (POST) at 280 g ae/ha and oxyfluorfen (POST) at 1120 g ai/ha.
[c] Onion not yet emerged from the soil.
[d] Herbicide application late; 10 % onion emerged at Oakes; 25% onion emerged at Hample; 5% emerged at Great Bend.

Management Practices for Field Experiments.

Herbicide microrate applications were made using a CO_2-pressurized backpack sprayer equipped with 8002[9] flat-fan nozzles spaced at 48 cm mounted on a 1.4-m-wide boom. Mid-season standard weed control treatments, in-season nitrogen, and grass control applications were made with a tractor mounted sprayer equipped with 8002 flat-fan nozzles spaced at 48 cm on a 10-m boom, except at Oakes where the boom length was 2.8 m. All applications were made with an operating pressure of 210 kPa, a speed of 5.5 km/h, and a spray volume of 187 L/ha. Reduced application volumes were chosen based on the research of Schumacher and Hatterman-Valenti (2007) in onion.

Best management practices were used for planting[10, 11], fertility, irrigation, and pest control at each location. 'Teton' onion was seeded in four, paired-rows at 543,000 seeds/ha in the adjuvant efficacy and sequential application field experiments. 'Sedona' onion was seeded in four, paired-rows at 543,000 seeds/ha in the microrate system field experiment because 'Teton' seed was discontinued. Nitrogen (28% UAN) was applied in-season at 2-wk intervals (beginning when onion was between the two- to three-leaf stage) and did not total greater than 133 kg/ha. Grass weeds were controlled as needed with clethodim at 140 g ai/ha plus petroleum oil concentrate (POC) at 1% v/v or fluazifop-P at 210 to 280 g ai/ha plus a nonionic surfactant[12] at 0.5% v/v. Late-season broadleaf weeds were controlled with a standard POST applications of bromoxynil and oxyfluorfen at 280 g/ha + 1120 g/ha during the two- to five-leaf stage.

Onion yields were obtained by harvesting 1.5 m of the middle two rows in each four-row plot for the adjuvant efficacy and sequential application field experiments, and 2.1 m of the middle two rows in each four-row plot for the microrate system field experiment (total plot length was 6 m), and grading according to USDA standards by size and quality (USDA 1997). Prior to grading, onion were allowed to cure for at least 2 wk in a well-ventilated storage room. Grades were determined by bulb diameter: cull (< 2.5 cm); small (2.5 to 5.7 cm); medium (5.7 to 7.6 cm); and large (> 7.6 cm). Split and diseased bulbs were graded as culls regardless of diameter.

At the adjuvant efficacy and sequential application field experiments, common lambsquarters was the first broadleaf weed to emerge each season and was the dominant broadleaf weed species at each location with a mean density of 118 plants/m^2. Other broadleaf species including redroot pigweed (*Amaranthus retroflexus* L.), hairy nightshade *(Solanum sarrachoides* S.), kochia (*Kochia scoparia* L.), and common purslane (*Portulaca oleracea* L.) were either not present or had low densities across each location. Common lambsquarters control was representative for the other minor weeds controlled and will be the focus of this discussion. At the 2010 microrate system field experiment, common lambsquarters and hairy nightshade (*Solanum sarrachoides*) were the dominant weed species at Oakes. Common lambsquarters and redroot pigweed were the dominant weed species at Great Bend. The Hample experiment was conducted in a cooperating local onion grower's field. Weed densities at Hample were very low except for volunteer glyphosate-tolerant soybean. These dominant species were evaluated.

Visual evaluations were used to assess overall early-season broadleaf weed control after all herbicide applications were made. These evaluations were taken approximately 3 wk after the fourth microrate application for the adjuvant efficacy field experiment or 2 wk after the fifth microrate application for the sequential application field experiment using a 0 to 100% scale for crop injury and weed control. For crop injury, 0% was when no visible onion injury was observed, 50% was when half of the onion stand was eliminated, and 100% was complete onion death and no onion were present. For weed control, 0% was when no weeds were controlled, 50% was when the weed stand was reduced to half of the untreated, and 100% was when all weeds were dead. In each plot, weed densities were counted in a 0.1 m^2 quadrate 3 wk after the fourth microrate application for the adjuvant efficacy field experiment or 2 wk after the fifth microrate application for the sequential application field experiment. These weed counts were later equated to a full m^2 for discussion purposes. At the same time, stand counts were taken of a 1-m section of one middle paired-row to evaluate onion injury. In the microrate system field experiment, weed densities were counted in a 1-m^2 quadrate 6 wk after the first microrate application in each plot. Onion stand reduction was visually evaluated using the same 0 to 100% scale 2 wk after the first microrate application.

The experimental design at each location was a randomized complete block (RCBD) with four replications and a factorial arrangement. Factors in the adjuvant efficacy field experiment were herbicide, rate, and adjuvant. Factors in the sequential application field experiment were herbicide and number of sequential applications. Factors in the microrate system field experiment were level of PRE and level of microrate. Data were also analyzed in each experiment as a RCBD without factorial arrangement for comparison to the checks. Environments were considered random effects, while herbicide, rate, adjuvant, number of sequential applications, level of PRE, or level of microrate were considered fixed effects. Each environment was first analyzed separately to test for homogeneity of mean square error among environments using SAS. Data with mean square errors within a factor of ten were considered homogeneous and were pooled across environments in the adjuvant efficacy and sequential application field experiments. Mean square errors were not within a factor of ten in the microrate system field experiment and those results are presented by environment. Mean squares were equated to expected mean squares to determine the proper denominators for *F*-tests. Treatment means were separated where appropriate using Fisher's protected LSD at the 0.05 level of significance unless otherwise specified.

Results and Discussion

^{14}C-Oxyfluorfen Absorption Experiment.

Temperature was a significant factor in this experiment, but growth stage and temperature-by-growth stage interactions were not significant. ^{14}C-oxyfluorfen absorption 24 h after treatment was greatest at 35 C and 25 C (Table 5; Table A6). Absorption at 15 and 25 C were similar, but 15 C was less when compared to the highest temperature. Increasing temperature lead to increased ^{14}C-picloram absorption in leafy spurge (*Euphorbia esula*) (Lym and Messersmith 1990), and increased ^{14}C-nicosulfuron absorption in quackgrass (*Elytrigia repens*) (Bruce et al. 1996). The results of our experiment contradict the overall findings of Akey and Souza Machado (1984) that suggested increasing seedling age resulted in increased epicuticular wax deposition and decreased spray retention at similar onion growth stages. However, it is possible that spray retention and subsequent foliar absorption were biased in this study because onion leaves were held in a horizontal position to enable ^{14}C-oxyfluorfen droplet retention. Fadayomi and Warren (1997) postulated that because there was a lack of ^{14}C-oxyfluorfen and ^{14}C-nitrofen mobility in soybean (*Glycine max*) and greenbean (*Phaseolus vulgaris*), other selectivity mechanisms besides absorption and translocation must have been responsible for selectivity differences. The results of the current study were similar to broccoli and collard tolerance findings that indicated genetic factors may play a more important role than leaf wax content in response of cole crops to POST oxyfluorfen (Harrison and Peterson 1999). Increasing temperature and corresponding greater metabolic rates may impart onion safety even though oxyfluorfen absorption was also greater at warmer temperatures.

Table 5. Effect of temperature and growth stage on onion leaf ^{14}C-oxyfluorfen absorption in laboratory studies 24 h after treatment.

Temperature	Absorption
°C	% of applied
15	31.5
25	46.2
35	66.0
$LSD_{0.07}$	25.0
<u>Growth stage</u>	
flag leaf	47.4
1 leaf	49.7
2 leaf	46.5
$LSD_{0.07}$	ns

Adjuvant Efficacy Field Experiment.

Bromoxynil and oxyfluorfen were significant factors for control of common lambsquarters and subsequent large-grade onion yield, but there were no herbicide-by-rate, herbicide-by-adjuvant, or rate-by-adjuvant interactions. Bromoxynil provided better control of common lambsquarters than oxyfluorfen when averaged across rate and adjuvant (Table 6; Table A7). Large-grade onion yield corresponded with these results as onion treated with bromoxynil had greater yields than onion treated with oxyfluorfen (Table 6; Table A8). Bromoxynil has demonstrated similar effectiveness for control of common lambsquarters and other broadleaf weeds in other studies evaluating reduced rates. Bromoxynil applied at 140 g/ha provided 88% control of six-leaf common lambsquarters 4 wk after treatment (WAT) and this control was not different from the 280 g/ha rate (97%) (Brown et al. 2007). Bromoxynil applied at 70 g/ha resulted in 95% and 93% control of seedling common lambsquarters and redroot pigweed, respectively during a midseason evaluation (Loken and Hatterman-Valenti 2010). In contrast, droughty conditions resulted in poor four-leaf common sunflower (*Helianthus* annuus) and ragweed parthenium (*Parathenium hysterophorus*) control 4 WAT (51 and 53%, respectively) when bromoxynil was applied at 240 g/ha (Rosales-Robles et al. 2005), emphasizing the need to improve herbicide efficacy, possibly with adjuvants. Adjuvants were not used with bromoxynil in any of the research above.

Table 6. Effect of herbicide, averaged across rate[a] and adjuvant[b], on percent common lambsquarters control and large-grade onion yield in adjuvant efficacy field experiments 3 wk after four sequential herbicide applications.

Herbicide	Common lambsquarters	Large-grade yield
	% control	t/ha
Oxyfluorfen	59	18
Bromoxynil	71	27
$LSD_{0.05}$	10	6

[a] Oxyfluorfen rates were 0, 18, and 35 g ai/ha; bromoxynil rates were 0, 18, and 35 g ae/ha.
[b] Adjuvants were methylated seed oil at 0.5% v/v and petroleum oil concentrate at 1.2 L/ha.

Oxyfluorfen has also been evaluated at reduced rates in other studies for common lambsquarters and broadleaf weed control. Oxyfluorfen was applied with POC at 2.3 L/ha to evaluate rate (70 and 140 g/ha) and carrier volume (47 or 190 L/ha) (Zandstra and Wallace

1989). Resulting control of common lambsquarters, onion injury, and onion yield did not differ with application rate or carrier volume during two evaluation years, with the exception of better common lambsquarters control with the greater application volume (190 L/ha) in one of the years. Overall common lambsquarters control was considered poor to fair, but common lambsquarters were, on average, 10 to 25 cm tall because applications were made at the onion three- to four-leaf stage. In comparison, microrate applications in this study were made to seedling weeds in the cotyledon stage (1-2 cm tall) and some individual treatments with oxyfluorfen provided acceptable weed control.

Herbicide application rate was a significant factor for common lambsquarters control, density, and subsequent large-grade onion yield, but there were no herbicide-by-rate, herbicide-by-adjuvant, or rate-by-adjuvant interactions. Greater herbicide rates resulted in better weed control and reduced common lambsquarters density (Table 7; Table A7). Common lambsquarters density was least when herbicides were applied at 70 g/ha. Densities were greatest when herbicides were applied at 18 or 35 g/ha. Large-grade onion yield reinforced weed control and density results as herbicides applied at 35 or 70 g/ha resulted in greater yields than the 18 g/ha rate (Table7; Table A8).

Table 7. Effect of rate, averaged across herbicide[a] and adjuvant[b], on common lambsquarters control and density and large-grade onion yield in adjuvant efficacy field experiments 3 wk after four sequential herbicide applications.

Herbicide rate[c]	Common lambsquarters		Large-grade yield
g/ha	% control	density/m^2	t/ha
18	47	86	14
35	67	60	23
70	81	29	30
$LSD_{0.05}$	10	30	8

[a] Herbicides were bromoxynil and oxyfluorfen.
[b] Adjuvants were methylated seed oil at 0.5% v/v and petroleum oil concentrate at 1.2 L/ha.
[c] Bromoxynil rates expressed as g ae/ha; oxyfluorfen rates expressed as g ai/ha.

Adjuvant was a significant factor for common lambsquarters control and density, onion stand, and subsequent large-grade and total onion yield, but there were no herbicide-by-rate, herbicide-by-adjuvant, or rate-by-adjuvant interactions. The use of either MSO or POC, averaged across herbicide and rate, increased common lambsquarters control (Table 8; Table A7 and A9). The use of MSO, averaged across herbicides and rates, decreased common lambsquarters density and increased onion stand compared to no adjuvant. Resulting large-grade and total onion yield were greater when either MSO or POC were used as a part of the treatment compared to no adjuvant (Table 8; Table A8). Similarly, reduced sugarbeet injury, increased sugarbeet yield, and acceptable weed control were reported with microrate applications of desmedipham plus phenmedipham plus triflusulfuron plus clopyralid plus MSO (45 + 45 + 4.5 + 20 g/ha + 1.5% v/v, respectively) compared to the standard check (Wilson et al. 2005). In another study, the addition of POC at 0.25% v/v to a bromoxynil plus oxyfluorfen tank mix (280 + 140 g/ha, respectively) did not increase onion injury (two-leaf) compared to the same herbicide application without POC (Cudney and Orloff 1988). Russian thistle (*Salsola iberica*) control and fresh weight (percent of control) also increased (72 to 85% and 82 to 94%, respectively) with the addition of POC.

Table 8. Effect of adjuvant, averaged across herbicide[a] and rate[b], on common lambsquarters control and density, onion stand, and large-grade and total onion yield in adjuvant efficacy field experiments 3 wk after four sequential herbicide applications.

					Yield	
Adjuvant[c]	Rate	Common lambsquarters		Onion	Large-grade	Total
		% control	density/m^2	plants/m	t/ha	
MSO	0.5% v/v	78	40	9	29	47
POC	1.2 L/ha	70	57	8	26	44
None	0	46	78	7	14	30
$LSD_{0.05}$		12	22	1	9	10

[a] Herbicides were bromoxynil and oxyfluorfen.
[b] Oxyfluorfen rates were 0, 18, and 35 g ai/ha; bromoxynil rates were 0, 18, and 35 g ae/ha.
[c] MSO, methylated seed oil; POC, petroleum oil concentrate.

Bromoxynil applied at 18, 35, or 70 g/ha did not reduce onion stand (Pr > F = 0.06) (Figure 1; Table A9), and no visual injury observations were recorded. Bromoxynil has also demonstrated onion safety in other studies. Onion injury 1 WAT and height 3 WAT were not different than the untreated check when bromoxynil (80 or 340 g/ha) was applied to onion at the one-leaf stage (Schumacher and Hatterman-Valenti 2007). Approximately 5% onion injury from bromoxynil (70 g/ha) was observed in a previous microrate study (Loken and Hatterman-Valenti 2010). However, bromoxynil at 280 g/ha (lowest current labeled rate) has injured two-leaf onion when applications are made during low light intensity and high relative humidity (Menges and Tamez 1981).

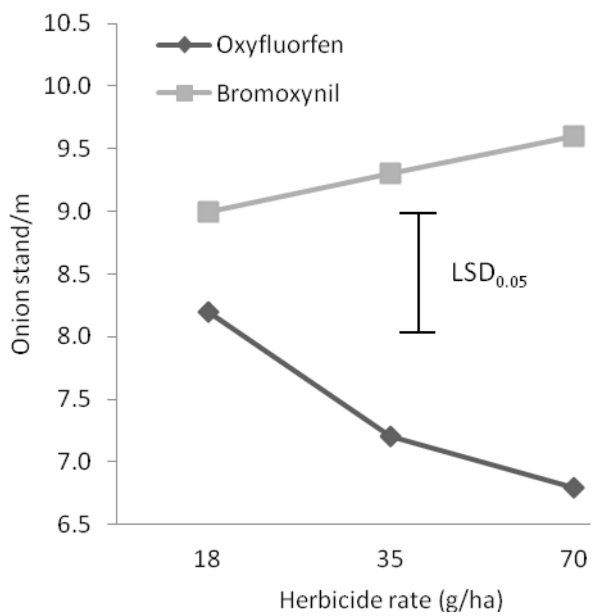

Figure 1. Effect of herbicide-by-rate interaction, averaged across adjuvants, on onion stand in adjuvant efficacy field experiments 3 wk after four sequential herbicide applications. Oxyfluorfen rates expressed as g ai/ha and bromoxynil rates expressed as g ae/ha. Adjuvants tested were methylated seed oil at 0.5% v/v and petroleum oil concentrate at 1.2 L/ha.

Onion treated with bromoxynil had better stands than onion treated with oxyfluorfen at 35 and 70 g/ha (Figure 1; Table A9). In this study, onion treated with greater oxyfluorfen rates had constricted leaves near the soil surface. Additional microrate applications caused some plant death and subsequent stand reduction. A single oxyfluorfen dose (one-leaf onion) applied at 30 or 110 g/ha caused onion injury (26 and 38%, respectively) 1 WAT (Schumacher and Hatterman-Valenti 2007). However, the injury symptoms caused by the single reduced herbicide dose did not impose any long-term effects and most onion recovered 3 WAT. Onion safety to oxyfluorfen at greater single dose rates (1200, 134, and 2500 g/ha) has been reported when applications were made to more mature, three- to four-leaf onion (Ghosheh 2004; Norsworthy et al. 2007; Qasem 2005). Maturity coupled with warmer temperatures at application, may have allowed for greater onion cuticle thickness and reduced oxyfluorfen absorption, imparting selectivity.

Herbicide and herbicide rate interacted to affect total onion yield (Figure 2; Table A8). Onion treated with bromoxynil had greater total yield than onion treated with oxyfluorfen at each rate. As rates increased, so did yield of onion treated with bromoxynil. The magnitude of the total yield difference between oxyfluorfen and bromoxynil increased at the 70 g/ha rate because total yield of onion treated with oxyfluorfen at 35 g/ha did not differ from total yield of onion treated with oxyfluorfen at 70 g/ha. This magnitude increase was attributed to increased onion injury and subsequent stand reduction from the 70 g/ha oxyfluorfen rate.

The treatment analysis with checks confirmed the findings of the factorial analysis (Table 9; Table A10 and A11). Common lambsquarters control and density tended to be greatest and least, respectively, with increasing bromoxynil rates plus MSO or POC, and was similar to the hand-weeded check. Oxyfluorfen at 70 g/ha plus MSO also provide similar common

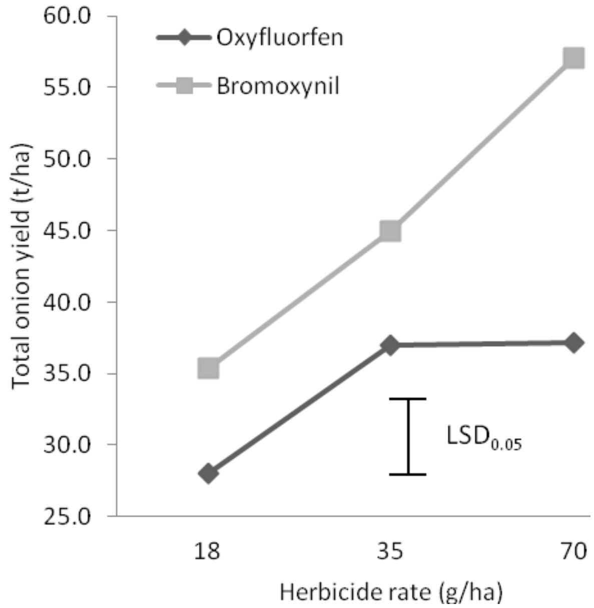

Figure 2. Effect of herbicide-by-rate interaction, averaged across adjuvants, on total onion yield in adjuvant efficacy field experiments 3 wk after four sequential herbicide applications. Oxyfluorfen rates expressed as g ai/ha and bromoxynil rates expressed as g ae/ha. Adjuvants tested were methylated seed oil at 0.5%v/v and petroleum oil concentrate at 1.2 L/ha.

lambsquarters control and density reduction compared to the hand-weeded check, but reduced onion stand to levels as low as the weedy check. Onion stand reduction tended to be greatest with oxyfluorfen applied at 35 or 70 g/ha with MSO, POC, or no adjuvant. Stand reduction tended to be least with bromoxynil plus MSO or POC. Subsequent large-grade and total onion yield were greatest with bromoxynil applied at 35 or 70 g/ha plus MSO or POC, and with bromoxynil applied at 70 g/ha without an adjuvant. These yields were greater than the hand-weeded check, due damaged onion roots from the hand weeding process. Onion treated with oxyfluorfen tended to produce large-grade and total yields that were less than those treated with bromoxynil at 35 or 70 g/ha plus MSO or POC.

Sequential Application Field Experiment.

Evaluations 2 wk after the fifth microrate application indicated that four or five

Table 9. Effect of herbicide plus adjuvant treatment on common lambsquarters control and density, onion stand, and large-grade and total onion yield in adjuvant efficacy field experiments 3 wk after four sequential herbicide applications.

Herbicide	Adjuvant [a]	Herbicide + adjuvant rate	Common lambsquarters		Onion	Yield	
						Large-grade	Total
			% control	density/m^2	plants/m	------------ t/ha ------------	
Oxyfluorfen	MSO	70 g ai/ha+ 0.5 % v/v	89	28	7	33	46
Oxyfluorfen	MSO	35 g ai/ha + 0.5 % v/v	69	67	8	22	42
Oxyfluorfen	MSO	17 g ai/ha + 0.5 % v/v	59	59	9	16	35
Oxyfluorfen	POC	70 g ai/ha+ 1.2 L/ha	77	49	7	24	36
Oxyfluorfen	POC	35 g ai/ha + 1.2 L/ha	67	68	7	26	43
Oxyfluorfen	POC	17 g ai/ha + 1.2 L/ha	43	104	9	10	26
Oxyfluorfen	None	70 g ai/ha	53	54	6	12	29
Oxyfluorfen	None	35 g ai/ha	77	87	6	12	26
Oxyfluorfen	None	17 g ai/ha	28	94	7	9	23
Bromoxynil	MSO	70 g ae/ha+ 0.5 % v/v	93	0	10	37	57
Bromoxynil	MSO	35 g ae/ha + 0.5 % v/v	93	15	9	36	5
Bromoxynil	MSO	17 g ae/ha + 0.5 % v/v	66	71	10	26	46
Bromoxynil	POC	70 g ae/ha+ 1.2 L/ha	97	5	10	40	60
Bromoxynil	POC	35 g ae/ha + 1.2 L/ha	83	32	10	33	56
Bromoxynil	POC	17 g ae/ha + 1.2 L/ha	57	83	8	20	40
Bromoxynil	None	70 g ae/ha	78	36	8	34	5
Bromoxynil	None	35 g ae/ha	43	96	8	9	25
Bromoxynil	None	17 g ae/ha	28	104	9	7	20
Hand-weeded check	None	--	96	3	9	17	39
Weedy check	None	--	0	118	7	9	18
$LSD_{0.05}$			16	47	2	13	18

[a] MSO, methylated seed oil; POC, petroleum oil concentrate.

sequential herbicide applications provided better common lambsquarters control than three sequential herbicide applications (Table 10; Table A12). These results reinforce weed emergence observations during 2008 and 2009, when it was noted that another common lambsquarters flush occurred after the third herbicide application. This weed flush was controlled in treatments with four or five sequential herbicide applications, while plots receiving only three sequential herbicide applications had poorer weed control. Increasing the number of sequential herbicide applications did not reduce onion stand.

Table 10. Effect of sequential herbicide applications, averaged across herbicide, on common lambsquarters control and onion stand with oxyfluorfen[a] and bromoxynil applied at 35 g/ha plus MSO[b] at 0.5% v/v in sequential application field experiments at 2 wk after the fifth microrate application.

No. of sequential applications	Common lambsquarters	Onion
	% control	plants/m
3	64	9
4	78	10
5	83	10
$LSD_{0.05}$	13	ns

[a] Oxyfluorfen rates expressed as g ai/ha; bromoxynil rates expressed as g ae/ha.
[b] MSO, methylated seed oil.

Bromoxynil applied four or five times provided greater common lambsquarters control than oxyfluorfen applied three times and similar weed control as the hand-weeded check (Table 11; Table A13). Common lambsquarters control with oxyfluorfen applied four or five times was similar to control provided by bromoxynil applied three, four, or five times. Common lambsquarters densities tended to be inversely proportional to the weed control ratings. Only bromoxynil applied four or five times or oxyfluorfen applied three times reduced common lambsquarters densities compared to the weedy check. Subsequent large-grade yield of onion treated with oxyfluorfen was similar to the hand-weeded check yield (Table 11; Table A14). Onion treated with bromoxynil had greater large-grade yield than the hand-weeded check.

Large-grade yield from the hand-weeded check was similar to the weedy check large-grade yield. The similarities in large-grade hand-weeded and weedy check yield were attributed to root injury incurred by the hand-weeding process. All treatments had greater total yield than the total yield of the weedy check.

Table 11. Effect of sequential herbicide applications on common lambsquarters control and density and large-grade and total onion yield with oxyfluorfen[a] and bromoxynil applied at 35 g/ha plus MSO[b] at 0.5% v/v in sequential application field experiments.

Herbicide	No. of sequential applications	Common lambsquarters		Yield	
				Large-grade	Total
		% control	density/m^2	---------- t/ha ----------	
Bromoxynil	3	68	7	29	43
Bromoxynil	4	85	2	36	55
Bromoxynil	5	90	2	29	49
Oxyfluorfen	3	60	4	25	42
Oxyfluorfen	4	71	6	24	42
Oxyfluorfen	5	77	6	27	47
Hand-weeded check		100	0	15	38
Weedy check		0	11	7	14
$LSD_{0.05}$		22	6	13	18

[a] Oxyfluorfen rates expressed as g ai/ha; bromoxynil rates expressed as g ae/ha.
[b] MSO, methylated seed oil.

Sequential herbicide applications were made at approximate 7 d intervals, weather permitting. Some applications were made when no weeds were present. A grower would be better served, from an agronomic and economic perspective, to use the microrate for weed control only when weeds are present, as illustrated by the reduced weed control with only three subsequent herbicide applications. A sugarbeet study comparing sequential calendar day (7 d) microrate applications with microrate applications based on growing degree days (GDD) as predictive tool for weed emergence and microrate applications “as-needed” (herbicide applications based on the physical appearance of cotyledon-stage weeds) reported that weed control and sugarbeet injury were similar and were reduced, respectively, by spraying “as-needed” or according to GDD (Dale and Renner 2005). Further research evaluating the use of

GDD-based or “as-needed” sequential herbicide applications is necessary with the onion microrate technique.

Microrate System Field Experiment.

In the analysis with checks (RCBD), broadleaf weed control with high, medium, or low microrates was 80% or better when a PRE application of glyphosate, pendimethalin, or the combination of the two were made at all locations, except the low microrate with pendimethalin at Oakes (78% overall control), the medium microrate with glyphosate at Hample (64% overall control), and the low microrate with glyphosate at Great Bend (63% overall control) (Table 12, Table A15, 16, and A17). This control was generally similar to the DCPA standard check, but poorer than the hand-weeded check. These results were reinforced in the factorial analysis (Table 13; Table A18, A19, and A20). Overall weed control at Oakes and Great Bend tended to be greater with glyphosate, pendimethalin, or a combination of the two than when no PRE was included in the weed control system. High and medium microrates provided better weed control than low microrates at Oakes and Great Bend, but control with the low microrate was still 73% or better. In another study, split applications of bromoxynil plus oxyfluorfen at 110 + 110 g/ha also provided superior Venice mallow (*Hibiscus trionum*) control compared to individual applications at the same rates (Westra et al. 1990). No weed control differences were detected at Hample for PRE or microrate factors.

Severe onion stand reduction was caused by PRE and microrate applications in both factorial and treatment analyses (Table 13 and 14; Table A15, A16, and A17). Westra et al. (1990) reported no onion injury when POST applications of bromoxynil plus oxyfluorfen were made to two- to three-leaf onion at full-labeled rates. Slight injury was reported when bromoxynil was applied with oxyfluorfen in two or three applications at full-labeled rates

Table 12. Effect of herbicide treatments on overall weed control 6 wk after the first microrate application at three ND locations.

Herbicide treatments[a]				Overall control		
PRE	Rate[b]	Microrate[c]	Rate	Oakes	Hample	Great Bend
	g/ha		g/ha	------------------------ % ------------------------		
Gly	1100	Brom + oxy + cleth + MSO	70 + 70 +35 + 0.5% v/v	89	84	99
Pend	1100	Brom + oxy + cleth + MSO	70 + 70 +35 + 0.5% v/v	81	85	98
Gly + pend	1100 + 1100	Brom + oxy + cleth + MSO	70 + 70 +35 + 0.5% v/v	91	85	99
None	-	Brom + oxy + cleth + MSO	70 + 70 +35 + 0.5% v/v	90	86	95
Gly	1100	Brom + oxy + cleth + MSO	70 + 35 +35 + 0.5% v/v	85	64	99
Pend	1100	Brom + oxy + cleth + MSO	70 + 35 +35 + 0.5% v/v	85	86	93
Gly + pend	1100 + 1100	Brom + oxy + cleth + MSO	70 + 35 +35 + 0.5% v/v	88	85	100
None	-	Brom + oxy + cleth + MSO	70 + 35 +35 + 0.5% v/v	76	79	75
Gly	1100	Brom + oxy + cleth + MSO	35 + 35 +35 + 0.5% v/v	83	80	63
Pend	1100	Brom + oxy + cleth + MSO	35 + 35 +35 + 0.5% v/v	78	81	95
Gly + pend	1100 + 1100	Brom + oxy + cleth + MSO	35 + 35 +35 + 0.5% v/v	81	84	91
None	-	Brom + oxy + cleth + MSO	35 + 35 +35 + 0.5% v/v	68	81	44
Checks						
None	-	Brom + cleth + MSO	70 + 35 + 0.5% v/v	65	76	69
None	-	Oxy + cleth + MSO	70 + 35 + 0.5% v/v	54	84	31
DCPA[d]	11200	Brom + oxy	280 + 140	88	84	30
Hand-weeded	-	-	-	100	100	100
Weedy	-	-	-	0	0	0
$LSD_{0.05}$				10	14	19

[a] Abbreviations: Gly, glyphosate; Pend, pendamethalin; Brom, bromoxynil; Oxy, oxyfluorfen; Cleth, clethodim; MSO, methylated seed oil.

[b] Glyphosate and bromoxynil rates expressed as g ae/ha.

[c] Microrate applications were applied four times.

[d] Conventional Standard Check, PRE application of DCPA followed by a single POST application at the two- to five-leaf stage.

Table 13. Effect of PRE herbicide and POST microrate applications on onion stand 2 wk after the first microrate application and overall weed control 6 wk after the first microrate application at three ND locations.

	Oakes		Hample		Great Bend	
Herbicide timing	Stand reduction	Overall control[a]	Stand reduction	Overall control	Stand reduction	Overall control
	%					
PRE[b]						
gly[c]	82	85	72	76	42	87
pend[d]	70	81	21	84	30	95
gly + pend	84	87	60	85	33	97
None	63	78	43	82	20	71
$LSD_{0.05}$	7	6	11	ns	14	10
Microrate[e]						
High	82	88	47	85	32	98
Medium	75	83	53	78	30	92
Low	68	77	48	82	33	73
$LSD_{0.05}$	6	5	ns	ns	ns	9

[a] Visually evaluated control of all weedy species per experimental unit.
[b] Preemergence herbicide application.
[c] Glyphosate at 1.1 kg ae/ha.
[d] Pendimethalin at 1.1 kg ai/ha.
[e] High, bromoxynil + oxyfluorfen + clethodim + MSO (70 g ae/ha + 70 g ai/ha +35 g ai/ha + 0.5% v/v); Medium, bromoxynil + oxyfluorfen + clethodim + MSO (70 g ae/ha + 35 g ai/ha +35 g ai/ha + 0.5% v/v); Low, bromoxynil + oxyfluorfen + clethodim + MSO (35 g ae/ha + 35 g ai/ha +35 g ai/ha + 0.5% v/v).

starting at the two-leaf stage with DCPA applied PRE, but this injury did not factor to reduce yield (Boydston and Seymour 2002). In contrast, microrate applications in this study were made when onion were in the seedling stages and had already received PRE applications. Initial onion stands at the Oakes location were poor including the untreated checks (Table 14). It was concluded that stands experienced greater initial reduction at Oakes because of nicosulfuron residue from the previous year, and that remaining onion stands were further reduced by herbicide treatments. When glyphosate was applied as a late-PRE, onion stand reduction was greatest at Oakes and Hample (Table 13). The late-PRE applications were intended to be made just prior to onion emergence, however at Oakes, Hample, and Great Bend some onion had already emerged (10%, 25%, and 5%, respectively) at the time of application, causing the nonselective activity of glyphosate to kill emerged onion. Stand reduction at Great Bend from PRE or microrate applications was not as severe as at Oakes or Hample, but was still considered unacceptable (Table 13). Onion plots that did not receive a PRE application averaged 43 and 20% stand reduction at Hample and Great Bend, respectively, indicating other factors contributed to reduced onion stands. The effect of microrate on stand reduction was only significant at Oakes where the high microrate caused greater stand reduction than the medium, and the medium microrate caused greater stand reduction than the low microrate. Yields corresponded to stand reduction and were poor at each environment (Table A21 and A22).

The PRE application of glyphosate, pendimethalin, or a combination of the two followed by microrates of bromoxynil plus oxyfluorfen plus clethodim plus MSO cannot be recommended at this time due to severe onion stand reduction. Further research is necessary to evaluate different combinations and rates of bromoxynil, oxyfluorfen, clethodim, and MSO when compared to these herbicides applied singly. Research should also evaluate onion safety when

Table 14. Effect of herbicide treatments on onion stand 2 wk after the first microrate application at three ND locations.

Herbicide treatments[a]				Stand reduction		
PRE	Rate[b]	Microrate[c]	Rate	Oakes	Hample	Great Bend
	g/ha		g/ha	%		
Gly	1100	Brom + oxy + cleth + MSO	70 + 70 +35 + 0.5% v/v	86	68	71
Pend	1100	Brom + oxy + cleth + MSO	70 + 70 +35 + 0.5% v/v	74	28	26
Gly + pend	1100 + 1100	Brom + oxy + cleth + MSO	70 + 70 +35 + 0.5% v/v	86	56	31
None	-	Brom + oxy + cleth + MSO	70 + 70 +35 + 0.5% v/v	76	36	29
Gly	1100	Brom + oxy + cleth + MSO	70 + 35 +35 + 0.5% v/v	86	70	39
Pend	1100	Brom + oxy + cleth + MSO	70 + 35 +35 + 0.5% v/v	71	18	36
Gly + pend	1100 + 1100	Brom + oxy + cleth + MSO	70 + 35 +35 + 0.5% v/v	83	71	30
None	-	Brom + oxy + cleth + MSO	70 + 35 +35 + 0.5% v/v	59	53	16
Gly	1100	Brom + oxy + cleth + MSO	35 + 35 +35 + 0.5% v/v	73	79	46
Pend	1100	Brom + oxy + cleth + MSO	35 + 35 +35 + 0.5% v/v	64	19	29
Gly + pend	1100 + 1100	Brom + oxy + cleth + MSO	35 + 35 +35 + 0.5% v/v	83	55	39
None	-	Brom + oxy + cleth + MSO	35 + 35 +35 + 0.5% v/v	54	40	16
Checks						
None	-	Brom + cleth + MSO	70 + 35 + 0.5% v/v	50	21	29
None	-	Oxy + cleth + MSO	70 + 35 + 0.5% v/v	56	19	11
DCPA[d]	11200	Brom + oxy	280 + 140	36	15	11
Hand-weeded	-	-	-	20	21	8
Weedy	-	-	-	15	5	8
$LSD_{0.05}$				13	19	21

[a] Abbreviations: Gly, glyphosate; Pend, pendamethalin; Brom, bromoxynil; Oxy, oxyfluorfen; Cleth, clethodim; MSO, methylated seed oil.
[b] Glyphosate and bromoxynil rates expressed as g ae/ha.
[c] Microrate applications were applied four times.
[d] Conventional Standard Check, PRE application of DCPA followed by a single POST application at the two- to five-leaf stage.

differing microrates are applied at differing onion growth stages.

Management Implications

The purpose of this research was to evaluate early-season weed control in onion. Although current labels dictate onion have two leaves prior to any POST herbicide applications, this research shows that sequential bromoxynil applications at 35 to 70 g/ha plus MSO at 0.5% v/v in a 190 L/ha spray volume can be made any time prior to the two-leaf stage to provide common lambsquarters, redroot pigweed, and hairy nightshade control, as well as crop safety. This POST herbicide application technology would be best utilized by onion growers as an adaptive management tool. Regular field scouting should be used to identify and treat cotyledon weeds as they emerge. Due to inconsistent crop safety, oxyfluorfen should not be applied in microrates until onion has two leaves or until further research indentifies safe application parameters. Preemergence herbicides should also not be applied with subsequent microrate applications because of poor crop safety.

Sources of Materials

[1] Buctril®, Bayer CropScience LP, 2 T.W. Alexander Dr., Research Triangle Park, NC 27709.

[2] GoalTender®, Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268-1189.

[3] Goal®, Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268-1189.

[4] Sunshine Mix No. 1, Sun Gro Horticulture, Inc., 15831 N.E. 8th St., Suite 100, Bellvue, WA 98008.

[5] Destiny®, Winfield Solutions, P.O. Box 64589, St. Paul, MN 55164-0589.

[6] Beckman LS 6800 liquid scintillation spectrophotometer, Beckman Coulter Inc., 4300 North Harbour Boulevard, Fullerton, CA 92864

[7] SAS version 9.3, Statistical Analysis Systems Institute, SAS Circle, P.O. Box 8000, Cary, NC 25712-8000.

[8] Herbimax®, Loveland Products Inc., P.O Box 1286, Greeley, CO 80632-1286.

[9] TeeJet nozzles, TeeJet Spraying Systems Company, P.O. Box 7900, Wheaton, IL 60189-7900.

[10] Monosem precision planter, A.T.I. Inc., Monosem, Lenexa, 17135 W. 116th Street, Lenexa, KS 66219.

[11] Milton precision planter, Starco Manufacturing, Inc., 2402 Renuana, Casper, WY 82602.

[12] Preference®, Winfield Solutions, P.O. Box 64589, St. Paul, MN 55164-0589.

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APPENDIX

Table A1. ANOVA for onion injury, and common lambsquarters control and fresh weight from greenhouse experiments 12 d after the third oxyfluorfen application.

		Onion injury		Common lambsquarters control		Common lambsquarters fresh weight	
SOV[a]	df	MS	F[b]	MS	F	MS	F
run	1	511.3	5.3	8094.7	10.2*	15.4	19.3*
rep (run)	4	96.3	0.7	792.6	3.1*	0.8	0.8
rate	2	2800.7	14.8*	34496.1	10.7	54.4	32.5*
adj	5	314.9	15.2**	2941.9	12.4**	10.8	10.3*
rate x adj	10	340.1	11.9**	803.3	3.6*	3.6	5.8**
run x rate	2	189.1	1.3	3219.7	12.5**	1.7	1.6
run x adj	5	20.8	0.1	237.5	0.9	1.1	1.0
run x rate x adj	10	28.6	0.2	224.1	0.9	0.6	0.6
error	68	143.6	-	258.5	-	1.1	-

[a] Rep, replicate; adj, adjuvant.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A2. ANOVA for redroot pigweed control from greenhouse experiments 12 d after the third oxyfluorfen application.

		Redroot pigweed control	
SOV[a]	df	MS	F[b]
run	1	33.3	1.3
rep (run)	4	13.0	0.5
rate	2	111215.5	4285.2**
adj	5	125.9	4.9**
rate x adj	10	104.7	4.0**
run x rate	2	25.7	1.0
run x adj	5	25.6	1.0
run x rate x adj	10	32.1	1.2
error	68	30.0	-

[a] Rep, replicate; adj, adjuvant.
[b] **, Significant at α=0.01.

Table A3. ANOVA for onion injury from greenhouse experiments 12 d after the third bromoxynil application.

		Onion injury	
SOV[a]	df	MS	F[b]
run	1	11.3	7.8**
rep (run)	4	0.2	0.2
rate	2	3.0	2.1
adj	5	0.8	0.5
rate x adj	10	1.6	1.6
run x rate	2	3.0	2.1
run x adj	5	0.8	0.5
run x rate x adj	10	1.6	1.1
error	68	1.5	-

[a] Rep, replicate; adj, adjuvant.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A4. ANOVA for onion and common lambsquarters fresh weight, and common lambsquarters control from greenhouse experiments 12 d after the third bromoxynil application.

		Onion fresh weight		Common lambsquarters fresh weight		Common lambsquarters control	
SOV[a]	df	MS	F[b]	MS	F	MS	F
run	1	5.8	58.0**	0.5	1.3	1070.4	9.7*
rep (run)	4	0.1	0.8	0.4	0.7	110.6	0.3
rate	2	2.5	3.7	76.2	17.3*	104478.2	39.5**
adj	5	0.4	2.6	8.4	7.2*	33485.2	21.2**
rate x adj	10	0.2	3.1*	3.0	3.2*	19896.8	4.6*
run x rate	2	0.8	4.7*	4.4	6.9**	2642.1	3.6*
run x adj	5	0.2	1.0	1.2	1.8	1576.9	0.9
run x rate x adj	10	0.1	0.4	0.9	1.5	4294.0	1.2
error	68	0.1	-	0.6	-	359.4	-

[a] Rep, replicate; adj, adjuvant.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A5. ANOVA for redroot pigweed control and fresh weight from greenhouse experiments 12 d after the third bromoxynil application.

		Redroot pigweed control		Redroot pigweed fresh weight	
SOV[a]	df	MS	F[b]	MS	F
run	1	33.3	1.3	9.0	45.0**
rep (run)	4	13.0	13.0	0.2	0.3
rate	2	111215.5	4328.4**	40.4	55.3**
adj	5	125.9	4.9*	0.6	0.9
rate x adj	10	104.7	3.3**	0.9	1.7
run x rate	2	25.7	25.7	0.7	1.1
run x adj	5	25.6	25.6	0.7	1.0
run x rate x adj	10	32.1	32.1	0.5	0.7
error	68	1764.8	-	0.7	-

[a] Rep, replicate; adj, adjuvant.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A6. ANOVA for ^{14}C-oxyfluorfen absorption in laboratory studies.

		^{14}C-oxyfluorfen absorption	
SOV[a]	df	MS	F[b]
rep	1	112.7	3.0
temp	2	1797.2	14.2[†]
error a	2	126.6	3.3
growth stage	2	16.3	0.4
temp x growth stage	4	111.4	2.9
error b	6	37.9	-

[a] Rep, replicate; temp, temperature.
[b] †, Significant at α=0.07.

Table A7. ANOVA for common lambsquarters control and density from adjuvant efficacy field experiments 3 wk after the fourth herbicide application.

		Common lambsquarters control		Common lambsquarters density	
SOV[a]	df	MS	F[b]	MS	F
expt	3	12291.6	39.0**	206510.2	47.5**
rep (expt)	12	315.2	1.5	4348.3	2.2
herb	1	10380.0	13.8*	23756.6	5.3
expt x herb	3	753.0	3.6*	4529.5	2.3
rate	2	28293.1	34.7**	78163.7	10.3*
expt x rate	6	815.8	4.0**	7623.7	3.8**
herb x rate	2	520.5	1.8	6511.0	1.4
expt x herb x rate	6	291.3	1.4	4573.6	2.3*
adj	2	26443.4	23.7**	35040.3	8.7*
expt x adj	6	1118.1	5.4**	4017.5	2.0
herb x adj	2	433.4	1.0	8085.0	4.0
expt x herb x adj	6	449.0	2.2*	2005.4	1.0
rate x adj	4	426.1	2.2	2651.4	2.0
expt x rate x adj	12	196.3	6.2**	1299.7	0.7
herb x rate x adj	4	1279.6	2.3	2710.2	0.9
expt x herb x rate x adj	12	567.4	2.8**	3037.2	1.5
error	204	206.7	-	1986.7	-

[a] Expt, experiment; rep, replicate; herb, herbicide; adj, adjuvant.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A8. ANOVA for large-grade and total onion yield from adjuvant efficacy field experiments.

		large-grade yield		total yield	
SOV[a]	df	MS	F[b]	MS	F
		-----------------------------MS x 10^7	----------------------------		
expt	2	115.4	3.8	53.7	2.1
rep (expt)	9	31.5	2.5**	25.1	1.6
herb	1	391.4	42.9**	752.7	38.2*
expt x herb	2	9.1	0.7	19.7	1.3
rate	2	425.2	12.9*	433.9	7.5*
expt x rate	4	32.9	2.6*	58.1	3.7**
herb x rate	2	37.3	4.8	88.7	12.5*
expt x herb x rate	4	7.7	0.6	7.1	0.5
adj	2	425.0	12.6*	597.1	13.3*
expt x adj	4	33.8	2.7*	45.0	2.9*
herb x adj	2	16.1	1.4	42.6	2.4
expt x herb x adj	4	11.9	1.0	18.0	1.2
rate x adj	4	24.1	3.3	59.3	2.2
expt x rate x adj	8	7.4	0.6	27.6	1.8
herb x rate x adj	4	53.4	18.1**	38.8	4.0*
expt x herb x rate x adj	8	2.9	0.2	9.7	0.6
error	153	12.5	-	5.7	-

[a] Expt, experiment; rep, replicate; herb, herbicide; adj, adjuvant.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A9. ANOVA for onion stand from adjuvant efficacy field experiments 3 wk after the fourth herbicide application.

		Onion stand	
SOV[a]	df	MS	F[b]
expt	3	587.7	20.7**
rep (expt)	12	340.7	3.8**
herb	1	251.3	16.0*
expt x herb	3	47.1	2.1
rate	2	5.1	0.3
expt x rate	6	118.4	2.7*
herb x rate	2	25.7	4.7*
expt x herb x rate	6	33.1	0.7
adj	2	65.9	6.1*
expt x adj	6	65.0	1.5
herb x adj	2	2.9	0.5
expt x herb x adj	6	35.0	0.8
rate x adj	4	3.2	0.4
expt x rate x adj	12	99.2	1.1
herb x rate x adj	4	12.3	1.5
expt x herb x rate x adj	12	96.0	1.1
error	204	7.4	-

[a] Expt, experiment; rep, replicate; herb, herbicide; adj, adjuvant.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A10. ANOVA for common lambsquarters control and density from adjuvant efficacy field experiments 3 wk after the fourth herbicide application (checks included).

		Common lambsquarters control		Common lambsquarters density	
SOV[a]	df	MS	F[b]	MS	F
expt	3	11016.3	39.2**	184692.3	42.6**
rep (expt)	12	281.4	1.5	4333.7	2.3**
trt	19	11177.6	21.3**	21416.7	4.8**
expt x trt	57	524.3	2.8**	4476.5	2.4**
error	228	189.7	-	1877.1	-

[a] Expt, experiment; rep, replicate; trt, treatment.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A11. ANOVA for large-grade and total yield from adjuvant efficacy field experiments (checks included).

		Large-grade yield		Total yield	
SOV[a]	df	MS	F[b]	MS	F
		------------------MS x 10^7------------------			
expt	2	219.0	7.3**	215.3	9.7**
rep (expt)	9	29.9	2.5*	22.1	1.5
trt	19	145.0	6.3**	210.9	4.3**
expt x trt	38	23.1	2.0**	48.6	3.2**
error	171	11.8	-	15.3	-

[a] Expt, experiment; rep, replicate; trt, treatment.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A12. ANOVA for common lambsquarters control in sequential application timing field experiments, 2 wk after the fifth herbicide application.

		Common lambsquarters control		Onion Stand	
SOV[a]	df	MS	F[b]	MS	F
expt	3	9105.4	43.1**	46.9	6.5**
rep (expt)	12	211.4	1.7	7.2	0.8
herb	1	3360.7	9.5	19.3	0.7
expt x herb	3	352.3	2.9*	26.1	2.8*
app	2	3190.2	6.7*	13.0	0.7
expt x app	6	475.1	3.9**	18.1	2.0
herb x app	2	83.3	0.2	15.0	1.8
expt x herb x app	6	572.5	4.7**	8.4	0.9
error	60	122.2	-	9.2	-

[a] Expt, experiment; rep, replicate; herb, herbicide; app, number of sequential applications.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A13. ANOVA for common lambsquarters percent control and density in sequential application timing field experiments, 2 wk after the fifth herbicide application (checks included).

		Common lambsquarters control		Common lambsquarters density	
SOV[a]	df	MS	F[b]	MS	F
expt	3	6829.0	43.1**	482.3	40.5**
rep (expt)	12	158.5	1.7	11.9	0.7
trt	7	15066.1	22.3**	186.3	3.4*
expt x trt	21	674.9	7.1**	54.7	3.0**
error	84	94.8	-	18.2	-

[a] Expt, experiment; rep, replicate; trt, treatment.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A14. ANOVA for large-grade and total onion yield from sequential application timing field experiments (checks included).

SOV[a]	df	Large-grade yield MS	Large-grade yield F[b]	Total yield MS	Total yield F
		---- MS x 10^7 ----			
expt	3	571.7	21.9**	781.2	53.3**
rep (expt)	12	26.2	2.8**	14.7	1.2
trt	7	133.7	3.9**	247.4	4.1**
expt x trt	21	34.4	3.7**	60.0	4.7**
error	84	9.4	-	12.7	-

[a] Expt, experiment; rep, replicate; trt, treatment.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A15. ANOVA for herbicide treatment and the subsequent effect on weed control and stand reduction in microrate system study at Oakes, ND (checks included).

		Common lambsquarters				Hairy Nightshade				Overall control		Stand reduction	
SOV[a]	df	biomass		Density		biomass		density					
		MS	F[b]	MS	F	MS	F	MS	F	MS	F	MS	F
		------------------------------ MS x 10^4 ------------------------------											
rep	3	6.2	1.3	0.1	1.2	1.0	1.0	0.004	0.8	0.006	1.2	0.03	3.2*
trt	16	32.0	6.8**	1.2	9.9**	9.3	8.5**	0.1	32.7**	0.2	41.4**	0.2	25.1**
error	48	4.7	-	0.1	-	1.1	-	0.005	-	0.005	-	0.008	-

[a] Rep, replicate; trt, treatment.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A16. ANOVA for herbicide treatment and the subsequent effect on weed control and stand reduction in microrate system study at Hample, ND (checks included).

		Volunteer Soybean				Overall control		Stand reduction	
SOV[a]	df	biomass		Density					
		MS	F[b]	MS	F	MS	F	MS	F
rep	3	414.7	8.2**	96.6	8.8**	229.8	2.4	514.2	2.8*
trt	16	202.8	4.0**	37.8	3.4**	1803.7	18.6**	2227.3	12.1**
error	48	50.7	-	11.0	-	97.2	-	183.5	-

[a] Rep, replicate; trt, treatment.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A17. ANOVA for herbicide treatment and the subsequent effect on weed control and stand reduction in microrate system study at Great Bend, ND (checks included).

SOV[a]	df	Common lambsquarters biomass MS	Common lambsquarters biomass F[b]	Common lambsquarters Density MS	Common lambsquarters Density F	Redroot pigweed biomass MS	Redroot pigweed biomass F	Redroot pigweed density MS	Redroot pigweed density F	Overall control MS	Overall control F	Stand reduction MS	Stand reduction F
		---- MS x 10^4 ----											
rep	3	0.2	0.1	1.4	1.9	5.4	1.1	0.1	1.3	0.03	2.0	0.008	0.4
trt	16	159.8	39.4**	9.9	13.0**	10.8	2.1*	0.09	1.1	0.4	22.2**	0.06	2.8**
error	48	4.1	-	0.8	-	5.1	-	0.08		0.02	-	0.02	-

[a] Rep, replicate; trt, treatment.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A18. ANOVA for herbicide factors and the subsequent effect on weed control and stand reduction in microrate system study at Oakes, ND.

SOV[a]	df	Common lambsquarters biomass MS	Common lambsquarters biomass F[b]	Common lambsquarters Density MS	Common lambsquarters Density F	Hairy Nightshade biomass MS	Hairy Nightshade biomass F	Hairy Nightshade density MS	Hairy Nightshade density F	Overall control MS	Overall control F	Stand reduction MS	Stand reduction F
rep	3	176.0	0.9	92.9	2.3	0.5	0.4	0.4	0.5	58.9	1.2	112.5	1.7
pre	3	1616.1	8.3**	334.9	8.1**	0.4	0.3	0.7	1.0	192.2	3.9*	1212.5	17.8**
mrate	2	1159.1	6.0**	229.4	5.6**	2.9	2.3	2.1	3.0	456.3	9.3**	594.3	8.7**
pre x mrate	6	729.7	3.8**	111.2	2.7*	0.5	0.4	0.4	0.5	85.4	1.7	113.0	1.7
error	33	193.8	-	41.3	-	1.3	-	0.7	-	49.0	-	68.2	-

[a] Rep, replicate; pre, preemergence; mrate, microrate.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A19. ANOVA for herbicide factors and the subsequent effect on weed control and stand reduction in microrate system study at Hample, ND.

SOV[a]	df	Volunteer Soybean biomass MS	Volunteer Soybean biomass F[b]	Volunteer Soybean Density MS	Volunteer Soybean Density F	Overall control MS	Overall control F	Stand reduction MS	Stand reduction F
rep	3	301.3	8.4	82.3	8.4	398.6	3.4	333.9	2.0
pre	3	36.3	1.0	1.5	0.2	195.8	1.7	5918.6	35.6**
mrate	2	169.4	4.7*	57.8	5.9**	172.4	1.5	157.8	0.9
pre x mrate	6	26.5	0.7	7.0	0.7	122.4	1.1	239.4	1.4
error	33	36.0	-	9.8	-	116.8	-	166.4	-

[a] Rep, replicate; pre, preemergence; mrate, microrate.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A20. ANOVA for herbicide factors and the subsequent effect on weed control and stand reduction in microrate system study at Great Bend, ND.

SOV[a]	df	Common lambsquarters biomass MS	Common lambsquarters biomass F[b]	Common lambsquarters Density MS	Common lambsquarters Density F	Redroot pigweed biomass MS	Redroot pigweed biomass F	Redroot pigweed density MS	Redroot pigweed density F	Overall control MS	Overall control F	Stand reduction MS	Stand reduction F
rep	3	22499.5	1.4	9939.1	2.0	2847.8	0.5	645.6	0.7	538.0	3.5*	276.9	1.0
pre	3	65339.9	4.2*	15787.6	3.2*	3779.1	0.7	1094.5	1.1	1620.0	10.5**	957.5	3.4*
mrate	2	62597.5	4.0*	10398.1	2.1	6992.5	1.3	982.9	1.0	2584.9	16.7**	20.3	0.1
pre x mrate	6	20776.1	1.3	6876.5	1.4	2862.8	0.5	573.2	0.6	650.2	4.2**	148.1	0.5
error	33	15628.1	-	4903.7	-	5292.8	-	961.3	-	156.7	-	279.6	-

[a] Rep, replicate; pre, preemergence; mrate, microrate.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A21. ANOVA for herbicide factors and the subsequent effect on onion yield in microrate system study at Oakes, Hample, and Great Bend, ND.

		Oakes REC				Hample				Great Bend			
SOV[a]	df	Large-grade		Total		Large-grade		Total		Large-grade		Total	
		MS	F[b]	MS	F	MS	F	MS	F	MS	F	MS	F
		---- MS x 10^7 ----											
rep	3	29.4	3.1*	39.1	3.1*	18.5	1.8	39.3	2.4	1.0	0.6	41.2	4.0*
pre	3	93.2	9.8**	112.1	9.0**	24.5	2.4	163.9	9.9**	2.6	1.5	24.9	2.5
mrate	2	56.2	5.9**	25.1	2.0	9.2	0.9	5.7	0.4	1.1	0.6	2.2	0.2
pre x mrate	6	25.3	2.7*	47.6	3.8**	5.9	0.6	11.5	0.7	1.0	0.6	19.4	1.9
error	33	9.5	-	12.5	-	10.2	-	16.6	-	1.8	-	10.2	-

[a] Rep, replicate; pre, preemergence; mrate, microrate.
[b] **, Significant at α=0.01; *, significant at α=0.05.

Table A22. ANOVA for herbicide treatment and the subsequent effect on onion yield in microrate system study at Oakes, Hample, and Great Bend, ND (checks included).

		Oakes REC				Hample				Great Bend			
SOV[a]	df	Large-grade		Total		Large-grade		Total		Large-grade		Total	
		MS	F[b]	MS	F	MS	F	MS	F	MS	F	MS	F
		---- MS x 10^7 ----											
rep	3	12.1	1.3	26.6	1.9	12.0	2.5	74.3	4.6**	0.7	0.6	34.6	4.1*
trt	16	76.3	8.4**	141.4	10.3**	32.2	3.2**	82.7	5.1**	1.1	0.9	22.6	2.7**
error	48	9.1	-	13.7	-	10.0	-	16.2	-	1.2	-	8.4	-

[a] Rep, replicate; trt, treatment.
[b] **, Significant at α=0.01; *, significant at α=0.05.