POSTEMERGENCE CONTROL OF ANNUAL BLUEGRASS WITH MESOTRIONE IN KENTUCKY BLUEGRASS

BY

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THESIS

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ABSTRACT

Annual bluegrass (*Poa annua* L. var Hausskn Timm) is a common grass weed species in turf. A lack of environmental stress tolerance, combined with prolific seed production and a highly competitive growth habit makes annual bluegrass difficult to maintain, but also difficult to get rid of from an established area by a turf manager. Cultural control options rely on increasing the competiveness and health of the desired turf species, such as Kentucky bluegrass, but the management demands for turf areas such as golf course fairways, tees, and greens, favor annual bluegrass. Under these conditions chemical control of the weed is currently the only viable option. The postemergence control of annual bluegrass with an herbicide is difficult. The number of herbicides available for use in cool-season turf is limited, and the ones that are available, selectively control annual bluegrass in a few turfgrass species and lack adequate selectivity.

Mesotrione is an herbicide with postemergence control of many broadleaf and grass weed species. An HPPD-inhibiting herbicide, mesotrione causes the destruction of plant tissues by increasing free radicals and reactive oxygen species through the inhibition of carotenoids and other radical scavenging compounds. Herbicide sensitivity is based upon rates of metabolism. Annual bluegrass shows sensitivity to mesotrione and may be able to be controlled by postemergence applications.

Studies were conducted at the Landscape Horticulture Research Center in Urbana, Illinois to determine whether mesotrione can be used to control annual bluegrass. Studies were initiated to determine the best rate and application frequency of mesotrione in 2010. In 2011, a series of experiments were conducted to determine the effect of nitrogen fertilization, spray volume, and adjuvants on annual bluegrass control. Conclusions from these studies include a need of multiple, frequent applications of mesotrione to control annual bluegrass; temperature influences mesotrione activity; increasing nitrogen fertility, lower spray volumes, and adding urea-ammonium nitrate solution all increase control. Utilizing these strategies can have negative consequences including possible increased levels of injury to desirable species and spray drift. Mesotrione can be used to control annual bluegrass in cool-season turf, but turf managers must balance the risks and rewards of using mesotrione.

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CHAPTER 1: INTRODUCTION

The Herbicide: Mesotrione. Mesotrione is a selective herbicide that controls many broadleaf and grass weed species in both agriculture and turf. Registered in 2008 for turf use as Tenacity®, mesotrione has been used in agriculture under the name Callisto® (Goddard, 2009). Developed by Syngenta and based upon a naturally occurring allelochemical from the Bottlebrush plant, leptospermone, mesotrione inhibits the enzyme 4-hydroxyphenylpyruvate dioxygenase (HPPD) in the biosynthesis pathway for carotenoids (Fig.1.1; Syngenta Professional Products, 2008). Carotenoids are responsible for releasing high-energy states of chlorophyll in photosynthetic tissues (Beaudegnies et al., 2009). Quenching this high-energy state prevents the production of radicals and reactive oxygen species, which cause damage to lipids and proteins that can result in the destruction of the photosynthetic complex (Beaudegnies et al., 2009). Loss of the photosynthetic complex releases chlorophyll into other areas of the tissue producing more radicals and the eventual destruction of all leaf pigments creating the characteristic white injury symptom (Beaudegnies et al., 2009). Disrupting carotenoid biosynthesis also directly blocks the production of tocopherols and plastoquinone (Fig. 1.1). Tocopherols are antioxidants that help to scavenge the plant for reactive oxygen species, and plastoquinone is an electron carrier between photosystem II and photosystem I (Beaudegnies et al., 2009). A reduction in these structures creates secondary injury and disrupts other metabolic and biosynthetic pathways. Mesotrione selectivity is based upon species dependent metabolism (Syngenta, 2008; Abit and Al-Khatib, 2009). Plants that are able to quickly metabolize and breakdown mesotrione are less susceptible to injury and control.

The Weed: Annual Bluegrass. Annual bluegrass (*Poa annua* L. var Hausskn Timm) is a problematic weed that is difficult to control in both cool and warm-season turf. Annual bluegrass reduces aesthetic and functional quality due to its lighter green color, prolific seed production, and shallow root system (McCullough and Hart, 2008). Prolific seed production, rapid seed germination, and establishment along with the ability to tolerate low mowing heights makes annual bluegrass very invasive in established turf areas. Poor tolerance to diseases, drought, and wear, makes annual bluegrass very difficult to maintain as a perennial turf (McCullough and Hart, 2008). A turf manager can choose to control the weed by either cultural or chemical means, or adopt cultural practices that will maintain annual bluegrass as a vital turfgrass component (Beard, 1970). Due to difficulty of controlling or maintaining annual bluegrass, the selective control of the weed would be a highly desirable trait for any herbicide in cool-season turf.

Contrary to the name, annual bluegrass can exist as a perennial species under highly maintained turf conditions (Branham et al., 2010). As an annual species, annual bluegrass produces a prolific amount of seed and then dies in the spring prior to summer stress, but as a perennial species less seed is produced and the plant survives multiple growing seasons (Beard, 1970). The growth habit of annual bluegrass can also vary greatly depending on the stituation. Annual bluegrass is generally considered a bunch type grass, but under turf conditions annual bluegrass has been found to have a prostrate or creeping habit of growth (Beard, 1970). The development of a creeping growth habit allows annual bluegrass to spread throughout an area faster and makes control more difficult.

The main reason annual bluegrass is considered a weed is due to its lack of tolerance to environmental stresses (Beard, 1970). Annual bluegrass is ridden with many disease and insect problems whose control require extensive use of fungicides and insecticides (Beard et al., 1978). Besides pest issues, annual bluegrass is also sensitive to cold tempeatures. Annual bluegrass will die at temperatures 5 to 10 degrees higher than other cool-season turfgrass species (Beard, 1970). High temperatures are also an issue for annual bluegrass. Optimal growth occurs at 21˚C, but reaching a tempeature of 27˚C results in a reduction in normal root functions and plants reach maturity rapidly

(Beard et al., 1978). Under dry conditions, annual bluegrass will show injury quickly and at higher levels than other species due to its shallow root system (Beard et al., 1978). With all of these issues it is easy to understand why annual bluegrass is such an undesirable turf weed. Unfortunately, annual bluegrass is an opportunistic grass which is capable of out competing other turfgrass species that are naturally weak competitors or weakened by errors in the cultural management by the turf manager (Beard et al., 1978). Turf areas with empty spaces are perfect entry points for annual bluegrass, as well as dormant grasses that are incapable of competing (Beard et al., 1978). Once the weed encroaches into the turf area, control of the weed is very difficult.

Postemergence control of annual bluegrass is divided into two areas, cultural and chemical control. The cultural control of annual bluegrass involves increasing competition of the permanent and desirable turf species utilizing cultural methods such as increasing mowing height, maintaining a proper amount of irrigation and drainage, reducing soil compaction and traffic, utilizing proper fertilization, and using well adapted turfgrass species or cultivars (Beard et al., 1978). However, under many turf areas such as golf course greens, tees, and fairways, the required cultural practices increase selection pressure away from the desired species towards annual bluegrass. Under these situations, chemical control is required. The range of postemergence herbicides for the selective control of annual bluegrass in cool-season turf is very limited. Two options are ethofumesate and bispyribac-sodium (Riecher et al., 2011). Ethofumesate is effective in controlling annual bluegrass in perennial ryegrass, but safety in Kentucky bluegrass and other cool-season turf grasses is marginal at best (Riecher et al., 2011). Bispyribac-sodium can control annual bluegrass in creeping bentgrass, perennial ryegrass, and tall fescue, but damage is common on these species and many Kentucky bluegrass cultivars (Riecher et al., 2011). With the risk of injury to desirable turf species with these herbicides, the options for postemergence control of annual bluegrass in cool-season turf are extremely limited.

Research Objective. Mesotrione is not labeled for postemergence control of annual bluegrass. However, annual bluegrass is sensitive to mesotrione and the potential exists to use mesotrione to control this weed. Determining whether or not mesotrione can control annual bluegrass would be an important discovery for turf managers. In agricultural settings, annual bluegrass control is inconsistent with mesotrione (Armel et al., 2009). In turf, several researchers have used mesotrione for preemergence annual bluegrass control (Kopec et al., 2009; Hoiberg and Minner, 2011), but few studies have been conducted on the postemergence control of annual bluegrass. Reicher et al. (2011) found that applying mesotrione at 0.11 and 0.17 $kg \cdot ha^{-1}$ in the fall combined with a follow-up application in the spring provided inconsistent annual bluegrass control.

The objective of this study was to determine if mesotrione can be utilized as a postemergence herbicide to control annual bluegrass in cool-season turf. Various application rates and timings of mesotrione were studied to determine the optimum application schedule to control annual bluegrass. The effects of various parameters such as adjuvants, nitrogen fertility, and spray volume on annual bluegrass control were also studied. Verifying whether mesotrione can or can not be used as a postemergence herbicide for annual bluegrass control will have a significant impact on turf management due to the limited control options.

Tables and Figures

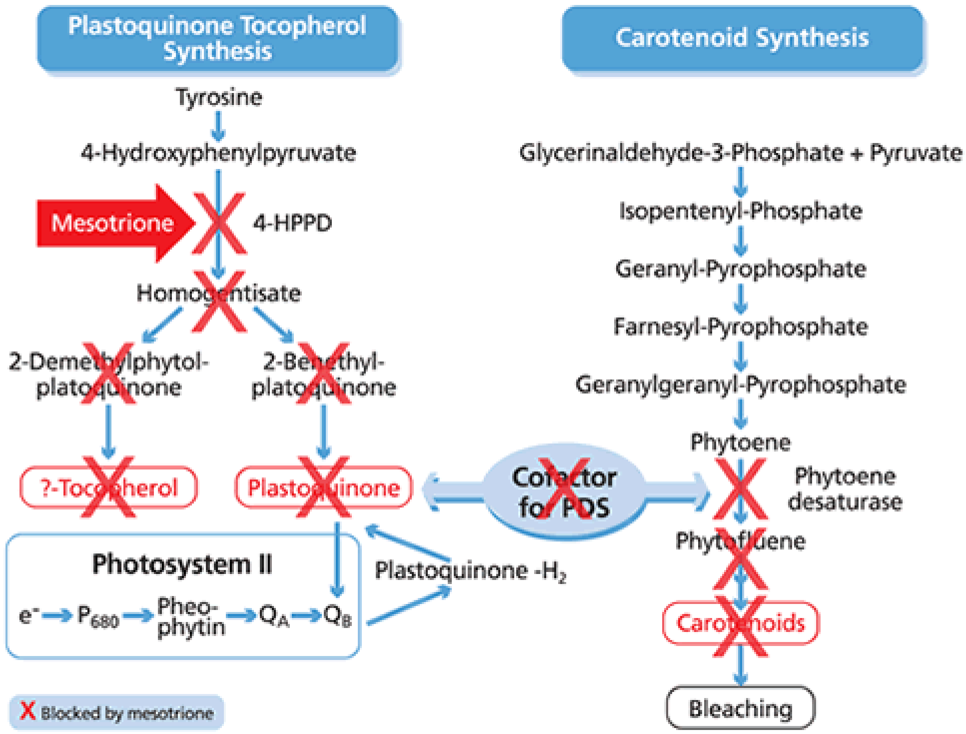

Figure 1.1. Mesotrione inhibition of the enzyme, HPPD , and carotenoid biosynthesis (Syngenta, 2008).

CHAPTER 2: DETERMINATION OF APPLICATION RATE, FREQUENCY, AND EFFECT OF TEMPERATURE ON MESOTRIONE AND THE CONTROL OF ANNUAL BLUEGRASS[1]

Annual bluegrass (*Poa annua* L. var Hausskn Timm) is a very difficult weed species to control in cool-season turf areas. Prolific seed production and germination coupled with tolerance to low mowing heights and soil compaction makes annual bluegrass (ABG) a very invasive weed, but lack of heat and drought tolerance, along with susceptibility to many pests, makes it difficult to maintain (Beard et al., 1978). Under highly maintained turf settings, ABG converts to a perennial life cycle over time requiring the use of a postemergence herbicide application for eradication (Branham et al., 2010). The selective control of ABG in cool-season turf, especially Kentucky bluegrass (*Poa pratensis* L.), can be challenging due to limited herbicide options (Reicher et al., 2011).

Mesotrione is a new herbicide for use on turf that has postemergence activity on many broadleaf and grass weed species. Mesotrione was introduced for agricultural use as Callisto®4S (Syngenta Crop Protection, Greensboro, NC) and was registered for turf use in 2008 as Tenacity®4S (Syngenta Professional Products, Greensboro, NC). Developed after the naturally occurring allelochemical, leptospermone, mesotrione works by inhibiting the enzyme 4-hydroxyphenylpyruvate dioxygenase (HPPD) of the biosynthesis pathway of plastoquinone and tocopherols (Beaudegnies et al., 2009). Tocopherols are antioxidants that scavenge for damaging radicals, and plastoquinone is an electron carrier used in photosystem II. The production of carotenoids is also terminated because of the requirement for plastoquinone as a precursor. Carotenoids are light-harvesting antenna structures responsible for quenching high energy states of chlorophyll (Beaudegnies et al., 2009). By quenching chlorophyll, carotenoids reduce the production of destructive reactive oxygen species in the plant.

[1]This chapter was accepted for publication in the journal, *HortScience*, as "Postemergence control of Annual bluegrass with mesotrione in Kentucky bluegrass."

When carotenoids are absent, lipids and proteins are damaged by radicals and reactive oxygen species, leading to the disassembly of the photosynthetic complex and eventually destruction of all leaf pigments, which gives plants the characteristic bleached look from mesotrione (Beaudegnies et al., 2009).

Mesotrione is a selective herbicide due to plant specific rates of metabolism (Mitchell et al., 2001). In grain sorghum, mesotrione-tolerant cultivars metabolized mesotrione more rapidly than susceptible cultivars (Abit and Al-Khatib, 2009). Differential rates of metabolism allow mesotrione to be used as a selective herbicide to control weed species while preserving turf species, but may also limit weed control. Species not able to metabolize mesotrione rapidly will show symptoms of injury, but may still be able to metabolize mesotrione before fatal injury occurs. This is the situation with ABG and the foundation for this research.

The current label for mesotrione use in turf states that ABG is not controlled with mesotrione (Anon., 2009). Mesotrione has been shown to provide postemergence control of ABG under agricultural settings, so there is potential to use mesotrione in turf to control ABG (Armel et al., 2009). Previous research in turf has shown that mesotrione can control ABG with preemergence applications, but control with postemergence applications occurs only in the fall (Hoiberg and Minner, 2010; Reicher et al., 2011). Further, Reicher et al. (2011) described postemergence control of ABG as inconsistent. The objective of this study was to determine the rate and application interval of mesotrione that will yield the greatest postemergence control of ABG. Finding a rate and application interval that can be used throughout the year could allow mesotrione to be an effective option for postemergence ABG control in cool-season turf.

Materials and Methods

Plant Culture. Experiments were initiated on May 27 and July 25 of 2009 and May 3, June 7, July 5, and October 11 of 2010 at the Landscape Horticulture Research Center on the University of Illinois campus. The trials were conducted in a mixed stand of Kentucky bluegrass (KBG) and ABG. The October 2010 trial was conducted on the KBG cultivar 'Odyssey', and all other trials were performed on a KBG cultivar blend of 'Total Eclipse', 'Award', and 'Excursion'. Annual bluegrass comprised more than 50% of the turf area and naturally infested the area. The turf stand was maintained at 2.2 cm and was mowed two to three times per week to simulate a golf course fairway. The soil type was a Flanagan silt loam (fine, smectic, mesic, aquic argiudolls) with a pH of 6.8, sand content of 125 $g \cdot kg^{-1}$, silt content of 588 $g \cdot kg^{-1}$, and clay content of 287 $g \cdot kg^{-1}$. The area was irrigated as needed to ensure no water stress occurred and was fertilized at 147 kg $N \cdot ha^{-1}$ per year with three applications of commercial fertilizers.

Herbicide Treatments. Turf plots measuring 1.2 m by 1.8 m were treated with mesotrione, as Tenacity® 4S (Syngenta Professional Products, Greensboro, NC) at eleven different rate and application intervals (Table 2.1). Trials in 2009 had fewer treatments than trials in 2010 because of the addition of new treatments after a year of research. All treatment rate combinations were selected to apply the maximum annual application rate of mesotrione, 0.56 $kg \cdot ha^{-1}$, permitted by the current label (Syngenta Professional Products, Greensboro, NC, 2009). As recommended by the current label, a non-ionic surfactant (Activator 90; Loveland Industries, Greeley, CO) was added at 0.25% v/v to all treatments. Treatments were applied with a CO_2-pressurized sprayer calibrated to deliver 470 $L \cdot ha^{-1}$ at 0.27 MPa. The spray boom was composed of four flat-fan nozzles (TeeJet 8002 flat fan spray nozzles; Spraying Systems Co., Roswell, GA) spaced 25 cm apart and operated at a height of 60 cm. Treatment schedules (Table 2.1) were applied at the same time of day when possible.

Data Collection. Visual ABG injury symptoms were rated weekly on a 0% to 100% scale, where 0% was completely green tissue and 100% represented complete necrosis. In the October 2010 trial, data was also collected weekly for KBG visual injury on a 0% to 100% scale because the KBG cover was much higher than the other trials. Percent control was calculated from initial and final visual estimates of ABG populations eight weeks after initial application.

Statistical Analysis. Prior to statistical analysis, data from non-treated plots were removed to stabilize variance (Corbett et al., 2004). Annual bluegrass control data from the July 2009, May 2010, and October 2010 were transformed with a logarithmic transformation to meet the assumptions of analysis of variance, while the remaining trials and data on KBG injury did not require any transformation (Kuehl, 2000). All data are presented as non-transformed, i.e, percent control. Data were analyzed using Proc Mixed (SAS, 2008), and means were separated using the least significant difference test at $\propto$=0.05. Regression analysis was conducted using Proc Reg (SAS, 2008) on ABG control, application frequency, and temperature.

Results

Annual Bluegrass Injury. There was a significant interaction between trial, treatment, and weekly injury rating, so each trial was analyzed individually. In order to summarize the data over all treatments and trials, three treatments were selected that varied in the level of ABG control (Fig. 2.1 A-C). Mesotrione at 56 g·ha^{-1} applied three times wk^{-1} for a total of ten applications resulted in high levels of ABG control, while 110 g·ha^{-1} wk^{-1} for five applications and 186 g·ha^{-1} applied three times wk^{-1} for three applications were less effective (Table 2.1). Treatments that provided ABG control produced high levels of foliar injury, and that injury persisted until the ABG died (Fig. 2.1 A-C). All treatments resulted in ABG Injury, but injury did not always result in control. Mesotrione applied at 110 g·ha^{-1} wk^{-1} for five applications and 186 g·ha^{-1} three times wk^{-1} for three applications triggered injury in ABG, but the injury eventually decreased and little to no ABG control resulted (Fig. 2.1 A-C). Applying 56 g ha^{-1} three times wk^{-1} for ten applications gave a consistent pattern of increasing ABG injury that reached a maximum at 4 to 5 weeks after initial treatment (WAIT). Even though ABG injury was severe in each trial from this treatment, control levels ranged from 40-88% (Table 2.1), indicating severe injury does not always lead to high levels of ABG control.

Annual Bluegrass Control. There was a significant interaction between treatment and trial, so each trial was analyzed individually. Mesotrione applications resulted in ABG control; however, the effectiveness of various application schedules differed substantially between trials (Table 2.1). The only trial that did not produce at least one treatment with ABG control above 80% was May 2010. All other trials produced multiple treatments with acceptable (>80%) control (Table 2.1). Applications of 56 g·ha^{-1} two or three times wk^{-1} for ten applications or 84 g·ha^{-1} two times wk^{-1} for seven applications consistently yielded superior ABG control. Applications of 56 g·ha^{-1} applied two or three times wk^{-1} for ten applications provided the highest level of control in five of six trials. Applying 84 g·ha^{-1} twice wk^{-1} for seven applications provided the highest level of control in the three trials in which it was included (Table 2.1). Other treatments were less consistent than these three treatments. For example, 186 g·ha^{-1} applied three times on a 14-day interval provided outstanding control in the October 2010 trial, but provided poor control in the May, June, and July 2010 trials. One treatment regime, 186 g·ha^{-1}, applied three times on a two-day interval provided poor control in each trial.

Kentucky Bluegrass Injury. Kentucky bluegrass injury data were not collected during the first five trials because the population of KBG was too low to accurately observe injury, however, injury data was collected in the October 2010 trial. During this trial, KBG injury was not observed from any treatment for two weeks following initial herbicide application (Table 2.2). At three weeks after initial application, injury symptoms including discoloration and slight bleaching were observed in some treatments, and at four weeks after application, all treatments showed some degree of bleaching injury (Table 2.2). After four weeks, however, the degree of bleaching decreased for the majority treatments. At the end of six weeks, treatments of 56 g·ha^{-1} applied three times wk^{-1} and 84 g·ha^{-1} applied twice wk^{-1} were the only treatments still displaying statistically significant injury (Table 2.2). Injury from these two treatments would be considered unacceptable, and the turf did not recover completely until the following spring.

Discussion

Temperature Influences Control. Differences in ABG control levels can be attributed to many factors, but the weather during each trial seems the most likely reason. Increasing temperatures have been shown to increase weed control from mesotrione (Johnson and Young, 2002). However, McGurdy et al. (2008) working with perennial ryegrass did not observe a response to temperature. Also, irradiance levels and relative humidity may influence mesotrione activity (McGurdy et al., 2008; Johnson and Young, 2002).

During these trials, air temperatures and application timing interact to dramatically affect ABG control (Tables 2.1 and 2.3). In May and October 2010, the temperatures were much lower during the first three weeks than the other trials (Table .3). In the May trial, temperatures rose beginning in the fourth week, while the temperatures in the October trial dropped further beginning in the fourth week leading to different responses to mesotrione in these two trials. In May 2010, only two treatments provided significant ABG control. These two treatments were the only treatments that had applications that extended into the fourth and fifth week of the experiment when average temperatures were much higher. In October 2010, however, the temperature dropped after the first three weeks but high levels of control were still observed in this trial, and one treatment, 186 g ha^{-1} applied three times on a 14-day interval, gave 100% ABG control but in other trials it performed poorly. These results indicate that ABG response to mesotrione differs dramatically with temperature and season, and reinforces the results of Reicher et al. (2011) who obtained acceptable ABG control with late season mesotrione applications. The decline in temperatures in the October trial may reduce the metabolism of mesotrione by ABG, allowing damaging concentrations of mesotrione to remain in the plant long enough to create high levels of control as shown by Mitchell et al. (2001).

In July 2010, the average temperature was the highest of all the trials (Table 2.3), and a number of treatments provided good to excellent control (Table 2.1). During the first three weeks following trial initiation, temperatures averaged 25.7˚C, and five treatments provided >80% control and seven >70% control under these conditions. Higher temperatures may increase control levels due to the increase in photosynthesis and other metabolic reactions, leading to an increased concentration of radical and reactive oxygen species in the plant. Since mesotrione can reduce free radical scavenging and quenching, the higher concentration of radicals will lead to more damage to susceptible plants. Mesotrione treatments that featured multiple, frequent applications yielded excellent control when temperatures were above 20˚C during the first three weeks following trial initiation (Table 2.1), conversely treatments with few applications or a long period of time between applications were not as successful in controlling ABG under warmer conditions. Metabolism of mesotrione is the most likely explanation because the rapid metabolism of mesotrione during high temperatures will reduce the concentration in the plant quickly, thus reducing herbicidal activity. Mitchell et al. (2001) showed that species are controlled better when mesotrione is metabolized slowly and a high concentration is maintained in the plant.

Application Frequency Affects Control. Application rate and frequency are the main factors that determine how much mesotrione enters the ABG plant. During the hot July 2010 trial, ABG recovered rapidly from mesotrione at 186 g·ha^{-1} applied three times on two-day intervals, while injury from 56 g·ha^{-1} applied three times wk^{-1} for ten applications steadily increased for the first two weeks of the trial and then remained injured for the rest of the trial (Fig. 2.1B). Frequent and prolonged applications overcome the rapid metabolism of mesotrione, keeping mesotrione concentrations elevated enough to cause injury leading to ABG control during periods of high temperatures. Applying mesotrione as frequently as three times per week is an attempt to overcome the rapid metabolism of mesotrione by ABG. However, best overall control appears to result from a combination of application rate, time span of applications, and temperature. The three treatment regimes that gave the most consistent and highest level of control took between 21 and 31 days to complete the applications (Table 2.1). Weekly applications of mesotrione at 186 or 110 g·ha^{-1} were, in general, not as effective as comparable rates of mesotrione applied more frequently. The exception was the October 2010 trial when 186 g·ha^{-1} applied on a 14-day interval for three applications gave outstanding control (Table 2.1).

The response of ABG to application frequency was estimated by using treatments applied at 186 g·ha^{-1} at application intervals of two to fourteen days for the trials conducted in 2010 (Fig. 2.2 A-B). The May 2010 trial was omitted due to low control levels. Significant error variances did not allow a combined analysis of all three trials, but the June and July trials were able to be combined, and the October trial was analyzed separately. When reviewing the combined June and July and the October data, application frequency is significant in both datasets (P=0.0305 Fig. 2.2B; P= 0.002 Fig. 2.2A). However, the relationship between application frequency and percent control differs for the trials in June and July compared to October. The June and July trials did not show a significant linear response (P=0.77), but instead display a quadratic response with maximum control with an application every 7.8 days (P=0.009; Fig. 2.2B). In contrast, ABG control during the October trial is linearly related to application frequency (P=> 0.0001; Fig. 2.2A). In the October trial, applications applied every two weeks gave outstanding control and the level of control decreased as applications were applied more frequently (Fig. 2.2A).

Kentucky Bluegrass Injury. Damage to KBG and other desirable turf species is undesirable, but the injury was minor on the cultivars used in our studies and recovery occurs quickly after applications cease. Since mesotrione symptoms occur in new growth, damaged tissue is quickly removed through mowing after applications cease. Further research into the addition of a safening agent may help to reduce the negative aesthetic results from mesotrione, but maintain weed control. Further research is also needed on cultivar sensitivity to mesotrione, particularly since KBG is a variable species with a wide selection of cultivars. Some research on cultivar tolerance to mesotrione in KBG has been reported (Bhowmik et al. 2007), however, not under the application regimes used in this research. The most effective application regimes for ABG control should be expected to increase the risk of injury to susceptible KBG cultivars.

Mesotrione can provide effective ABG control if multiple applications are made when air temperatures are consistently above 20˚C. Seven to ten applications at low rates of mesotrione can be used any time throughout the year to achieve high levels of control, but this is a very labor-intensive approach. Using five applications twice per week at 110 $g \cdot ha^{-1}$ or three applications at 186 $g \cdot ha^{-1}$ wk^{-1} when the temperature is above 20˚C may control ABG and is more practical for many turf managers. Good ABG control can be achieved in the fall as air temperatures are declining, but applications should be at higher rates with longer intervals between applications. A successful regimen using mesotrione to control ABG in KBG will have to be based upon desired control levels, tolerance of injury to the desired turf, amount of labor required, and time of year the herbicide will be applied.

Tables and Figures

Table 2.1. Control of annual bluegrass eight weeks after initial application from various rates and application timings of mesotrione.

				------------------------Experiment Initiation---------------------					
			Treatment duration in	May '09	July '09	May '10	June '10	July '10	Oct. '10
Rate (g·ha^{-1})	Application schedule	Total applications	days	% Annual bluegrass control					
56	M W F	10	21	85a[z]	93a	40b	96a	88a	68a
56	M Th	10	32	84ab	77b	75a	68ab	86a	100a
186	M (every two weeks)	3	28	[y]		3c	0d	27b	100a
186	M	3	14			3c	58abc	79a	82a
186	M Th	3	7			3c	20cd	70a	23b
186	M W F	3	5	0c	51c	3c	0d	31b	0b
110	M W F	5	9	38bc	95a	3c	38bc	87a	33b
110	M Th	5	14	80ab	97a	5c	76ab	90a	37b
110	M	5	28	57b	41c	15c	43bc	92a	53a
220 followed by 110	M Th	4	10			3c	85a	65a	5b
84	M Th	7	21		95 a			62a	86a

[z]Means followed by the same letter are not significantly different according to Fisher's Least Significant Difference test (P=0.05).

[y]All treatments were not used in all trials and are indicated by an empty space

Table 2.2. Kentucky bluegrass injury from mesotrione treatment combinations in October 2010.

		% Kentucky bluegrass injury[z]					
		1	2	3	4	5	6
Rate (g·ha^{-1})	Application schedule	WAA[y]	WAA	WAA	WAA	WAA	WAA
56	M W F	0.0	0.0	3.3	16.6*	25.0**	26.6**
56	M Th	0.0	0.0	0.0	13.3*	11.6*	10.0
186	M (every two weeks)	0.0	0.0	0.0	10.0*	6.6	6.6
186	M	0.0	0.0	3.3	16.6*	11.6*	6.6
186	M Th	0.0	0.0	10*	16.6*	6.6	6.6
186	M W F	0.0	0.0	6.6	13.3*	3.3	0.0
110	M W F	0.0	0.0	16.6*	20.0**	10.0*	6.6
110	M Th	0.0	0.0	0.0	10.0*	0.0	0.0
110	M	0.0	0.0	0.0	3.3	0.0	0.0
220 followed by 110	M Th	0.0	0.0	0.0	10.0*	0.0	0.0
84	M Th	0.0	0.0	0.0	16.6*	20.0**	20.0**

*,**Treatments statistically different than 0 ($P \leq 0.05$ or $P \leq 0.001$, respectively)

[y]Week after initial application

[z] Injury was rated on a scale of 0-100 with 0 representing no injury and 100 completely brown turf

Table 2.3. Average weekly air temperatures following treatment initiation.

	May-09	Jul-09	May-10	Jun-10	Jul-10	Oct-10
Number of treatments with control*	3	3	0	3	5	4
Temp. (˚C) 1 Week after application	21.1	22.0	14.8	23.3	25.4	15.3
2 Weeks after application	19.5	20.7	15.5	24.7	25.6	14.0
3 Weeks after application	22.9	24.1	17.1	25.4	26.0	10.6
4 Weeks after application	27.9	23.2	24.7	22.1	24.8	5.6
5 Weeks after application	25.0	20.3	23.1	25.4	25.4	11.9
6 Weeks after application	19.9	16.4	22.4	25.8	28.6	3.6

*Treatments above 80% control of annual bluegrass

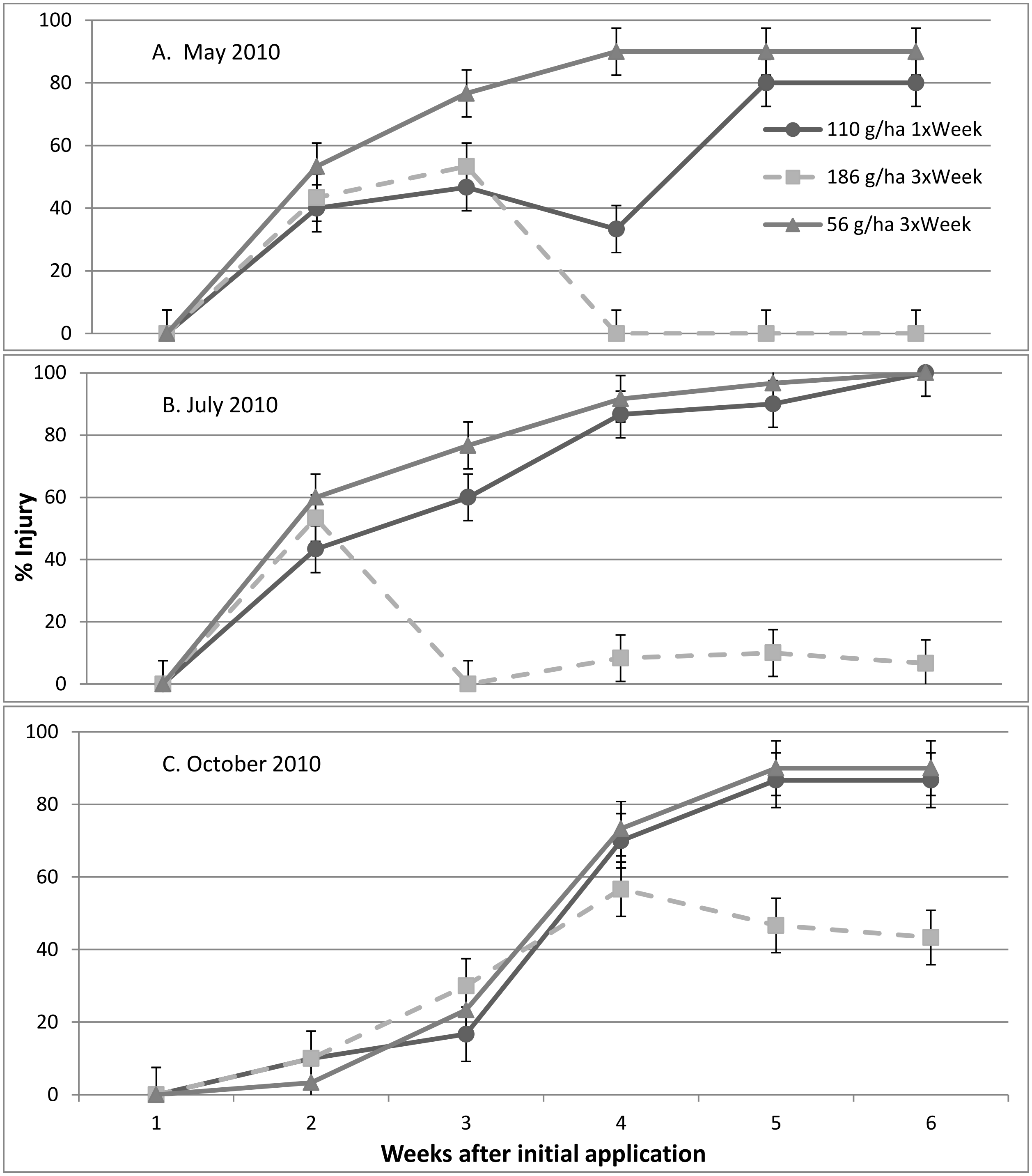

Figure 2.1. A-C. Annual bluegrass injury from mesotrione rates of 56, 110, and 186 g·ha^{-1} during May, July, and October 2010 field trials. Error bars represent pooled standard error of treatment means. Overlapping bars indicate no significant difference.

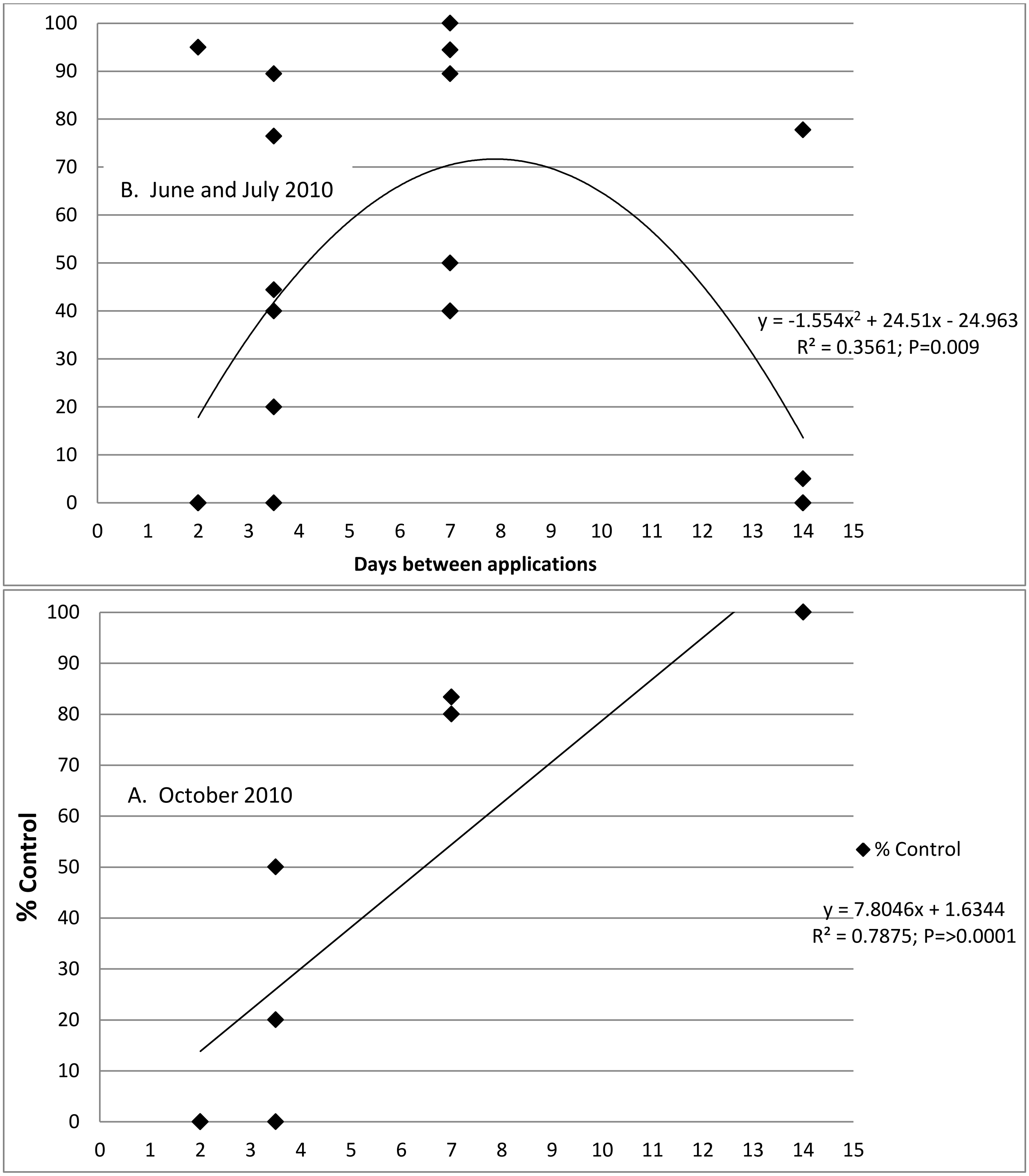

Figure 2.2. A-B. The effect of application frequency on annual bluegrass control from mesotrione applied at 186 g·ha^{-1} from the October (A); June and July 2010 (B) field trials. In the June and July trials, annual bluegrass exhibits a quadratic response with a maximum control level at 7.8 days.

CHAPTER 3: THE IMPACT OF NITROGEN FERTILIZATION ON ANNUAL BLUEGRASS CONTROL WITH MESOTRIONE

The application of fertilizer is a common management practice in turf, and it ranks with mowing and irrigation as a primary determinant of turf quality (Turgeon, 2008). Nitrogen is especially important to turf color, growth, and quality. Nitrogen is a constituent of chlorophyll, amino acids, and proteins, which causes it to be required in high quantities compared to other mineral nutrients (McCullough et al., 2011). Deficiency of nitrogen rapidly reduces plant growth and causes chlorosis (Taiz and Zeiger, 2006). Excessive amounts of nitrogen result in excessive aerial shoot growth; higher disease incidence; poor root and lateral shoot growth; environmental stress tolerance; and reduced carbohydrates reserves (Turgeon, 2008). Maintaining proper nitrogen levels by a turf manager is key to producing high quality turf.

The application of nitrogen fertilizers is regularly utilized by turf managers to prevent reductions in turf quality and growth. Nitrogen containing fertilizers can be divided into two groups, quickly and slowly available. Quickly available forms of nitrogen include inorganic salts, such as ammonium nitrate and ammonium sulfate, and organic sources such as urea (Turgeon, 2008). These fertilizers are highly soluble and have a rapid but short-term turf response (Turgeon, 2008). Slowly available nitrogen fertilizers include slowly soluble, slow release, and natural organic forms (Turgeon, 2008). They have a slow initial effect, but long-term turfgrass response and reduced levels of leaching and volatilization (Turgeon, 2008). Using a quickly or slowly-available source or a combination of both will be based upon the desired effects by a turf manager.

Besides plant growth, nitrogen fertility has been shown to interact with herbicides to influence efficacy (Brosnan et al., 2010). A significant interaction between herbicides and increasing nitrogen levels has been shown to increase herbicide performance by increasing the response rate or by decreasing the amount of herbicide required to reduce weed biomass (Kim et al., 2006). How nitrogen influences herbicide efficacy is not fully understood, but nitrogen fertility influences physiological and biochemical processes in the plant that may in turn affect the uptake, translocation, and metabolism of herbicides (Mithila et al., 2008). The nitrogen source, urea-ammonium nitrate, has been used as an additive to herbicides to increase herbicide absorption and therefore increase weed control (Nalewaja et al., 1998). Nitrogen may also negatively affect herbicide efficacy. Increased herbicide metabolism due to increased nitrogen levels may reduce herbicide efficacy when the herbicide is broken down more quickly by the plant (McCullough et al., 2011). The lack of nitrogen might also affect herbicide efficacy. Low nitrogen levels may reduce translocation because of a reduction in net assimilation of carbon in plants due to less growth, resulting in a decrease in the net export of sugars and the absorbed herbicide (Mithila et al., 2008).

Nitrogen may influence mesotrione activity on annual bluegrass. Previous studies have shown that annual bluegrass control by an herbicide can be influenced by nitrogen fertilization (McCullough et al., 2011; Brosnan et al., 2010). Annual bluegrass was controlled with 4.4 $g \cdot ha^{-1}$ of flazasulfuron and two applications of fertilizer significantly better than a single application of flazasulfuron at 17.5 $g \cdot ha^{-1}$ (Brosnan et al., 2010). Brosnan and others also found by using radioactively labeled flazasulfuron that nitrogen fertilization increased herbicide translocation by annual bluegrass (2010), and an increase in translocation of the herbicide throughout the plant can increase weed control. Alternately, increased nitrogen levels increased metabolism of bispyribac-sodium by annual bluegrass, which may result in less control of certain biotypes of annual bluegrass (McCullough et al., 2011). An increase in mesotrione metabolism by annual bluegrass, such as with bispyribac-sodium, may reduce control. Mesotrione has been shown to be influenced by nitrogen fertilization, but appears to be species dependent (Cathcart et al., 2004). Redroot pigweed grown under low nitrogen conditions required higher doses of mesotrione to achieve a 50% reduction in biomass as compared to high nitrogen conditions, but control of velvetleaf was unaffected by nitrogen level (Cathcart et al., 2004).

The effect of nitrogen fertilization on the control of annual bluegrass with mesotrione has not been studied. The objective of this study is to determine the efficacy of mesotrione on annual bluegrass under varying nitrogen fertilization levels.

Materials and Methods

Plant Culture. Experiments were conducted from June 6 to July 26 and August 17 to October 4, 2011 at the Landscape Horticulture Research Center on the University of Illinois Urbana-Champaign campus. The trials were conducted in a mixed stand of Kentucky bluegrass and annual bluegrass. Annual bluegrass comprised more than 90% of the turf stand and naturally infests the area. Kentucky bluegrass (*Poa pratensis* L. cv 'Bewitched') comprised the remainder of the turf. The turf was mowed two to three times per week at 2.2 cm. The soil type was a Flanagan silt loam (fine, smectic, mesic, aquic argiudolls) with a pH of 6.8, sand content of 125 $g \cdot kg^{-1}$, silt content of 588 $g \cdot kg^{-1}$, and clay content of 287 $g \cdot kg^{-1}$. The area was irrigated as needed to ensure no water stress occurred.

Herbicide Treatment. Turf plots measuring 1.2 m by 1.8 m were treated with mesotrione as Tenacity® 4S (Syngenta Professional Products, Greensboro, NC) at 110 $g \cdot ha^{-1}$ once a week for five applications. A non-ionic surfactant (Activator 90; Loveland Industries, Greeley, CO) was added at 0.25% v/v to all treatments. Treatments were applied with a CO_2-pressurized sprayer calibrated to deliver 470 $L \cdot ha^{-1}$ at 0.27 MPa. The spray boom was composed of four flat-fan nozzles (TeeJet 8002 flat fan spray nozzles; Spraying Systems Co., Roswell, GA) spaced 25 cm apart and operated at a height of 60 cm.

Fertilizer Treatment. Nitrogen was applied to the plots as a commercial grade fertilizer (31-0-10; 19.15% urea nitrogen, 6.97% other water soluble nitrogen, and 4.88% water insoluble nitrogen) in the first trial and a granular urea fertilizer (46-0-0) in the second trial at nitrogen rates of 24, 48, and 72 kg $N{\cdot}ha^{-1}$. Fertilizer were applied at two timings, immediately before and one week after the first application. The exact amount of fertilizer for each plot was calculated and measured prior to application. The fertilizer was broadcast uniformly across the plot using a 1.2 by 1.8 meter box with five layers of hardware cloth. The layers of wire mesh help to ensure uniform coverage.

Data Collection. Visual annual bluegrass injury symptoms were rated weekly on a 0% to 100% scale, in which 0% was completely green tissue and 100% was necrotic tissue. Percent control was calculated from initial and final visual estimates of annual bluegrass populations six weeks after application.

Statistical Analysis. Annual bluegrass control data from the two trials were analyzed using SAS 9.2 Proc Mixed (P=0.05; Statistical Analysis Software, Inc., Cary, NC). Means were separated by using Fisher's test of least significant difference (P=0.05). Regression analysis was conducted using Proc Reg (P=0.05; Statistical Analysis Software, Inc., Cary, NC) on annual bluegrass control and fertilizer rate.

Results

Annual Bluegrass Control. Data from the two trials were combined because of insignificant interactions between trial, nitrogen rate, and timing. The timing of fertilizer application was not significant (P=0.5601) nor was the interaction between timing and nitrogen rate (P=0.6996), but nitrogen rate significantly increased control of annual bluegrass (Table 3.1; P=0.0032). When no fertilizer was applied, annual bluegrass control was only 12%, but applying nitrogen at a rate of 72 kg $N{\cdot}ha^{-1}$

provided 74% annual bluegrass control (Table 3.1). Annual bluegrass control responded linearly to increasing rates of nitrogen fertilization (P=0.0006; Fig. 3.1)

Annual Bluegrass Injury. Annual bluegrass showed significantly greater injury at four and five weeks after treatment initiation when nitrogen was applied at 72 or 48 kg ha^{-1} (Fig. 3.2). Over all treatments, injury was highest three weeks after the first herbicide application, but injury response after this point depended upon fertilizer level (Fig. 3.2). Mesotrione applied with no fertilizer or at the lowest level, 24 kg $N{\cdot}ha^{-1}$, showed decreased injury after three weeks, and there was no significant difference in injury between these two treatments at four and five weeks after initial treatment (Fig. 3.2). Mesotrione applied with 48 and 72 kg $N{\cdot}ha^{-1}$ caused serious (>80%) annual bluegrass injury at three, four, and five weeks after initial treatment and resulted in higher injury levels than the other two treatments (Fig. 3.2). Injury levels from 48 and 72 kg $N{\cdot}ha^{-1}$ were similar, but the level of annual bluegrass control was different (Fig.3.2; Table 3.1).

Discussion

Nitrogen Influences Control. Nitrogen fertilization increased annual bluegrass control by mesotrione compared to mesotrione applied alone. The results of this study confirm the results of Cathcart et al. (2004) that weed control by mesotrione is increased as nitrogen levels are increased. Although this study does not directly show it, increased nitrogen levels can create an increase in physiological and biochemical reactions such as uptake, translocation, and metabolism in the plant and causes mesotrione to exert a greater effect as compared to without nitrogen fertilization (Mithila et al., 2008). An increase in absorption and translocation would increase control of annual bluegrass because higher levels of mesotrione within and dispersed throughout the plant would result in higher injury and control. An increase in herbicide metabolism would decrease annual bluegrass control with mesotrione since mesotrione susceptibility is determined by metabolism rates (Abit and Al-Khatib, 2009). Another explanation is that an increase in overall metabolism within the annual bluegrass plant creates a larger concentration of reactive oxygen species and radicals than would normally be present, and since mesotrione reduces the amount of carotenoids and other radical scavenging structures, the amount of damage that can occur is multiplied due to the lack in protective agents (Beaudegnies et al., 2009). To completely understand how nitrogen fertilization influences mesotrione, a more detailed and in-depth study needs to be conducted.

An increase in mesotrione activity on annual bluegrass due to nitrogen fertilization is a significant finding because it can help turf managers better control the weed. Since both fertilization and weed management are two common practices in turf, the beneficial relationship allows turf managers to control annual bluegrass with mesotrione and not worry about nitrogen reducing control levels. Without fertilizer, annual bluegrass control with mesotrione requires frequent applications that would require an immense amount of labor (Table 2.1). The addition of fertilizer to mesotrione applications can increase control allowing turf managers to utilize less labor-intensive application strategies by reducing the frequency of applications or number of applications required.

Tables and Figures

Table 3.1. The effect of nitrogen rate on annual bluegrass control from mesotrione applied at 110 g·ha^{-1} once a week for five applications.

Nitrogen Rate (kg N·ha^{-1})	% Annual Bluegrass Control**
0	12* c
24	34 bc
48	44 b
72	74 a

*Treatment means followed with same letter are not significantly different according to Fisher's LSD test at α=0.05

**Data are the mean of the two experiments conducted in 2011.

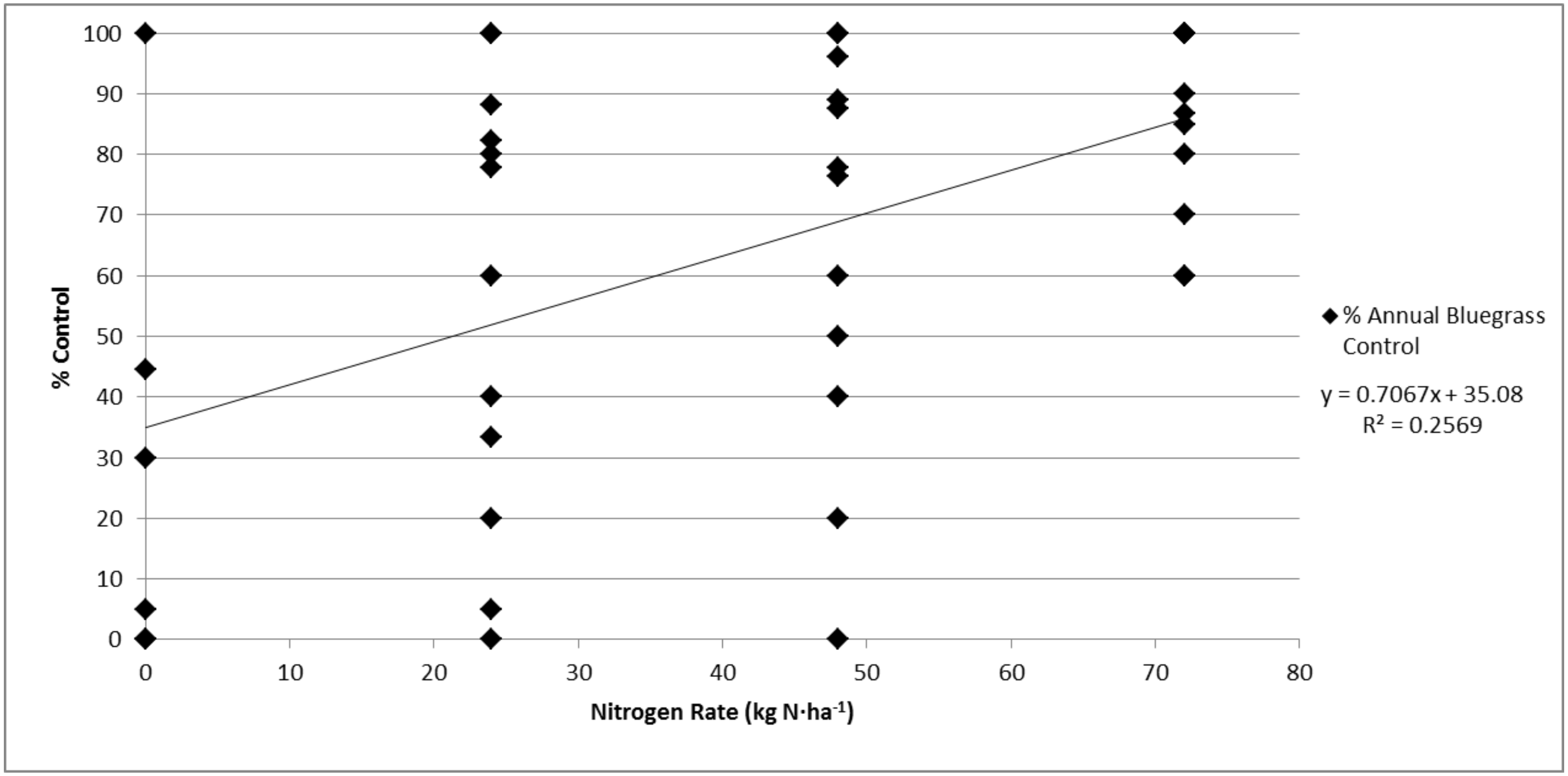

Figure 3.1. Linear relationship (P=0.0006) between annual bluegrass control and nitrogen rate from mesotrione applied once a week at 110 g·ha^{-1} for five applications.

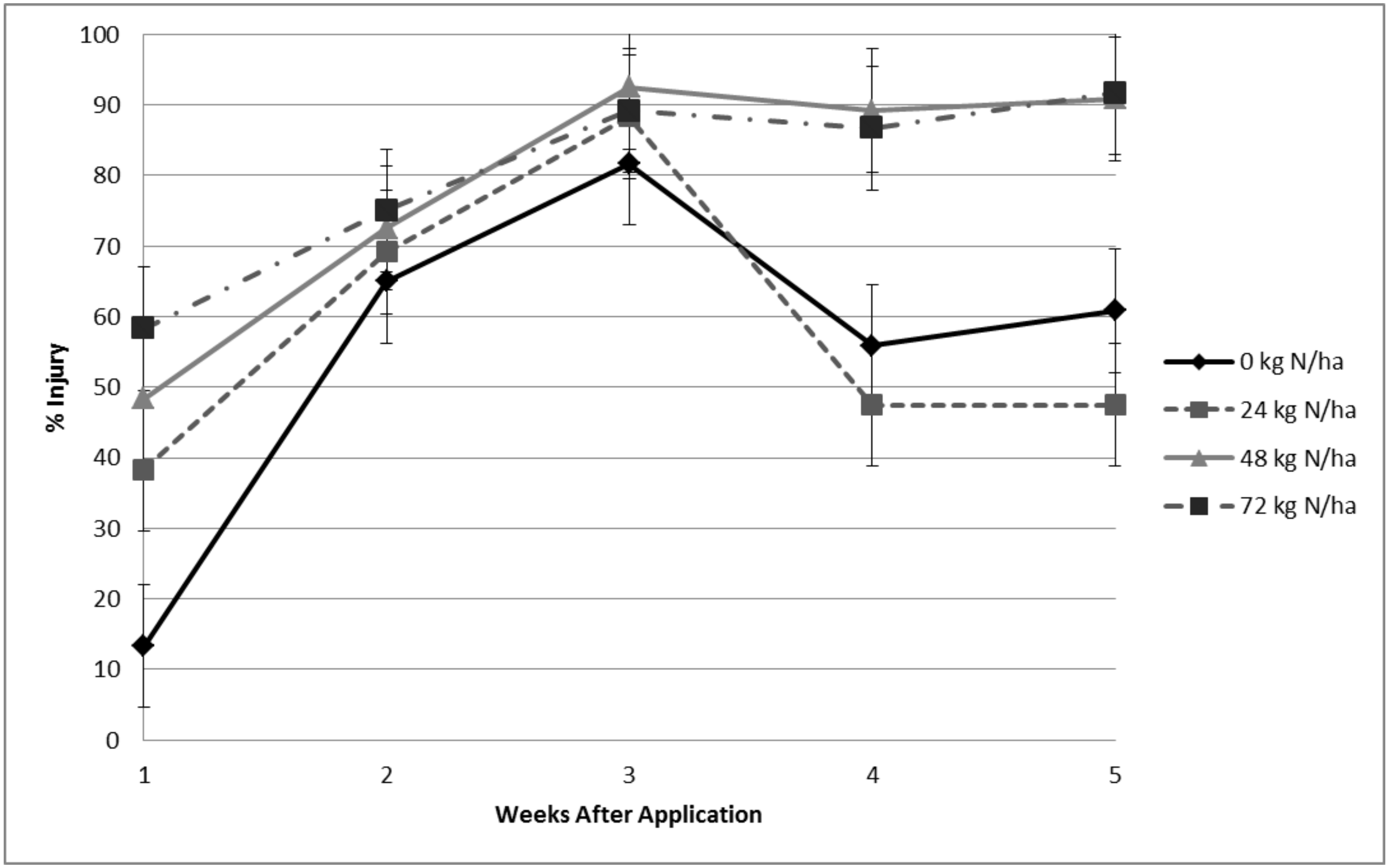

Figure 3.2. Weekly annual bluegrass injury ratings with mesotrione applied once a week at 110 g·ha^{-1} for five applications with different rates of nitrogen applied before herbicide application. Error bars represent pooled standard error with overlapping bars indicating no statistical difference.

CHAPTER 4: SPRAY VOLUME INFLUENCES CONTROL OF ANNUAL BLUEGRASS WITH MESOTRIONE

Proper application methods of herbicides can aid in controlling weed species. Factors such as adjuvant concentration, herbicide rate, and spray volume determine the overall effectiveness of postemergence herbicides (Smeda and Putnam, 1989). Spray volume refers to the total amount of solution applied to an area. The solution is comprised of the herbicide, any adjuvants or tank-mix additives, and water. Both extremes of spray volume have benefits and risks. Low spray volumes reduce application time because the sprayer requires less refilling, there is a reduced need for surfactants, and the cost of application is reduced because less fuel is required (McWhorter and Hanks, 1993). Risks of low spray volumes include the potential for the herbicide spray solution to be carried away in the wind and affect non-target species (Spillman 1984), and phytotoxic injury results more often with lower spray volumes (Buhler and Burnside, 1984). High spray volumes will reduce the risk of drift and phytotoxic injury, but requires more herbicide solution, time, and money to apply.

Many studies have observed an interaction between spray volume and herbicide efficacy (McWhorter and Hanks, 1993; Shaw et al., 2000; Smeda and Putnam, 1989; Kells and Wanamarta, 1987; Gauvrit and Lamrani, 2008). The results of these studies are all unique to each herbicide and weed studied. Knoche reviewed the results of 110 studies involving spray volume adjustments and the effect on herbicide efficacy and found that decreasing spray volume increased weed control in 24% of the studies, 44% of the studies found decreasing spray volume decreased weed control, and 32% of the studies found no change in weed control (1994). These conflicting results indicate that it is difficult to predict the effect of spray volume on weed control.

The influence of mesotrione spray volume on the control of annual bluegrass has not been studied. Currently, the label for mesotrione in turf recommends using at least 280 $L \cdot ha^{-1}$ (30 gallons per acre), and does not provide any information on the effect of using different spray volumes (Syngenta Crop Protection, 2009). The objective of this study is to determine the effect of spray volume on the control of annual bluegrass by mesotrione.

Materials and Methods

Plant Culture. The experiment was conducted in two trials beginning on August 17 and September 1, 2011 at the Landscape Horticulture Research Center on the University of Illinois Urbana-Champaign campus. The trials were conducted in an area containing Kentucky bluegrass (*Poa pratensis* L. cv. 'Bewitched'), but annual bluegrass comprised more than 90% of the turf area and naturally infests the site. The turf stand was maintained at 2.2 cm and was mowed two to three times per week. The soil type for the area is a Flanagan silt loam (fine, smectic, mesic, aquic argiudolls) with a pH of 6.8, sand content of 125 $g{\cdot}kg^{-1}$, silt content of 588 $g{\cdot}kg^{-1}$, and clay content of 287 $g{\cdot}kg^{-1}$. The area was irrigated as needed to ensure no water stress occurred and was fertilized at 146 kg $N{\cdot}ha^{-1}$ per year with three applications of commercial fertilizers.

Herbicide Treatments. Turf plots measuring 0.6 by 1.2 meters were treated with mesotrione as Tenacity® 4S (Syngenta Professional Products, Greensboro, NC) at five different spray volumes: 187, 374, 561, 748, and 935 $L{\cdot}ha^{-1}$. Treatments were applied at 186 $g{\cdot}ha^{-1}$ of mesotrione once a week for a total of three applications. A non-ionic surfactant (Activator 90; Loveland Industries, Greeley, CO) was added at 0.25% v/v to all treatments. Treatments were applied with a CO_2-pressurized sprayer calibrated to deliver each spray volume at 0.27 MPa. The spray boom was composed of a single even flat fan nozzle (TeeJet flat fan spray nozzles; Spraying Systems Co., Roswell, GA) and operated at a height of 60 cm. Different spray volumes were achieved by using different ground speeds and nozzle combinations. Ground speed was controlled by walking with a metronome at a calibrated rate. Treatments were applied at the same time of day when possible.

Data Collection. Visual annual bluegrass injury symptoms were rated weekly on a 0% to 100% scale, in which 0% was completely green tissue and 100% was necrotic tissue. Percent control was calculated from initial and final visual estimates of annual bluegrass populations six weeks after application.

Statistical Analysis. Annual bluegrass control data from the experiment did not require any transformation and met the assumptions for analysis (Kuehl, 2000). SAS 9.2 was used to analyze the data in Proc Mixed (P=0.05; Statistical Analysis Software, Inc., Cary, NC), and Proc Reg for regression analysis of spray volume and annual bluegrass control. Mean separation of the data was done using a Fisher’s test of least significant difference (P=0.05)

Results

Annual Bluegrass Control. There was no significant interaction between trial and spray volume, so the data were combined over both trials. The effect of spray volume on annual bluegrass control was found to be significant (P=>0.0001). Mesotrione applied at 186 $g \cdot ha^{-1}$ in 187 $L \cdot ha^{-1}$ gave 94% annual bluegrass control. Percent control was much lower at higher spray volumes (Fig. 4.1). Spray volumes of 374, 561, 748, or 935 $L \cdot ha^{-1}$ were not significantly different, providing control levels of 31 to 53% (Fig. 4.1). The regression line of the data indicates a slight increase in control in volumes past 700 $L \cdot ha^{-1}$ which may indicate that spray volumes above the levels studied, may provide greater control levels. However, since the volumes ranging from 374 to 935 $L \cdot ha^{-1}$ all were statistically the same, an increase in control above 935 $L \cdot ha^{-1}$ may not be equal to or greater than control levels achieved with 187 $L \cdot ha^{-1}$. Another study looking at spray volumes above 935 L·ha^{-1} may help to explain if control levels follow the upward trend or if the levels remain the same.

Annual Bluegrass Injury. Annual bluegrass injury was greatest when mesotrione was applied at 187 L·ha^{-1}, and injury was significantly greater than all other treatments at every rating (Fig. 4.2). For all other treatments, injury levels were greatest three weeks after initial herbicide application and declined from that point (Fig. 4.2). After four weeks, injury levels were significantly greater at the 187 L·ha^{-1} volume compared to all other treatments (Fig. 4.2). Using 187 L·ha^{-1} created more injury to annual bluegrass compared to higher spray volumes, resulting in greater control.

Discussion

Spray Volume Influences Mesotrione. Spray volume played a significant role in the control of annual bluegrass with mesotrione. These results match similar studies indicating that spray volume influences herbicide efficacy (Stougaard, 1999; Ramsdale and Messersmith, 2001; Smeda and Putnam, 1989). Using lower spray volumes resulted in greater annual bluegrass control from mesotrione. Lower spray volumes may increase control due to differences in herbicide deposition and absorption. Reducing spray volumes reduces droplet size which increases the amount of herbicide active ingredient, mesotrione, in each droplet (Gauvrit and Lamrani, 2008). Buhler and Burnside reported droplets with higher herbicide concentration result in more herbicide absorption (1983), indicating that many small droplets with a high concentration of mesotrione created by low spray volumes will cause the plant to absorb more mesotrione and increase control of annual bluegrass, compared to high spray volumes that are comprised of large droplets with a lower concentration of mesotrione. High spray volumes will also affect herbicide deposition on the plant surface because high spray volumes can create herbicide runoff from the plant surface (Smeda and Putnam, 1989). If the herbicide is removed from the plant surface, less will be able to be absorbed by the foliage and will reduce control.

Reduced spray volumes indicate that foliar applications provide greater control of annual bluegrass with mesotrione. Mesotrione can be absorbed by both the foliage and roots of a plant, but results from this study indicate foliar absorption is more effective. Root absorption of mesotrione is more likely when applied with high spray volumes. Goddard found that mesotrione is absorbed through the foliage of annual bluegrass more than the roots (2009). This indicates that foliar-applied mesotrione, which occurs with low spray volumes, will be absorbed better than root-applied mesotrione, or high spray volumes. Our results indicate that lower mesotrione spray volumes are more effective in controlling annual bluegrass.

Low spray volumes do have some drawbacks and risks. Low spray volumes create small droplets that are susceptible to drift. Large droplets that are typical of high spray volumes have enough mass to travel in a near vertical path and are less likely to be altered by moderate winds (Spillman, 1984). The risk of drift is of great concern because non-target species may be injured. Plants such as trees, shrubs, and other ornamentals may be injured by the drift of mesotrione. If this was to occur, a temporary reduction in aesthetic value or even death could happen to the plant. Landscaping companies or golf course superintendents would have the greatest concern over drift injuring non-target species and may result in their choice of not using low spray volumes. Besides the risk of drift, a potential to increase injury to other turf species exists. Since lower spray volumes increased injury to annual bluegrass, turf species such as Kentucky bluegrass and perennial ryegrass may be equally susceptible to an increase in injury. A balance between risk and reward must be determined by the turf manager before utilizing mesotrione to control annual bluegrass.

Tables and Figures

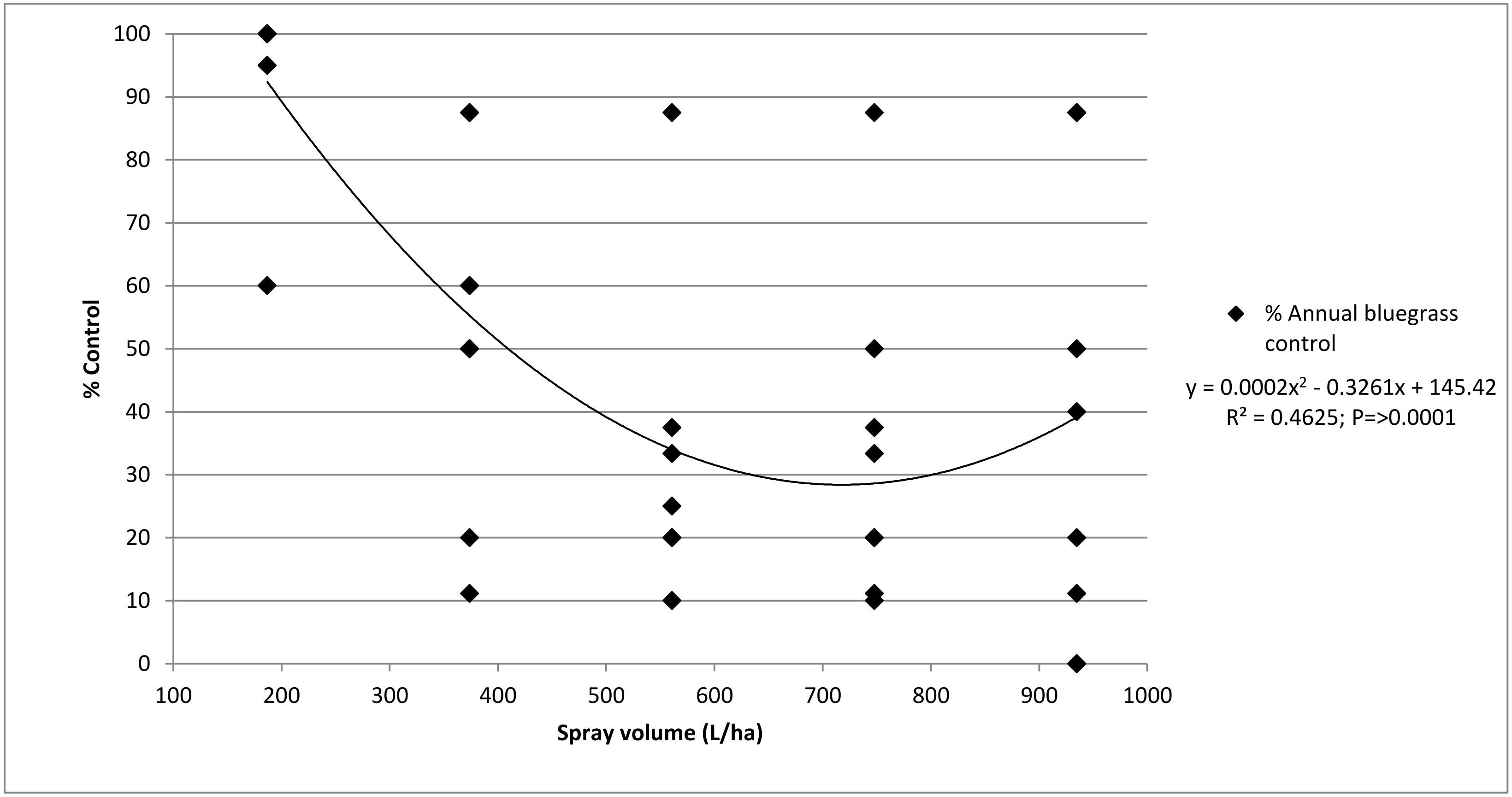

Figure 4.1. Relationship between annual bluegrass control with mesotrione applied at 186 g·ha^{-1} weekly for three applications at varying spray volumes (P=<0.0001).

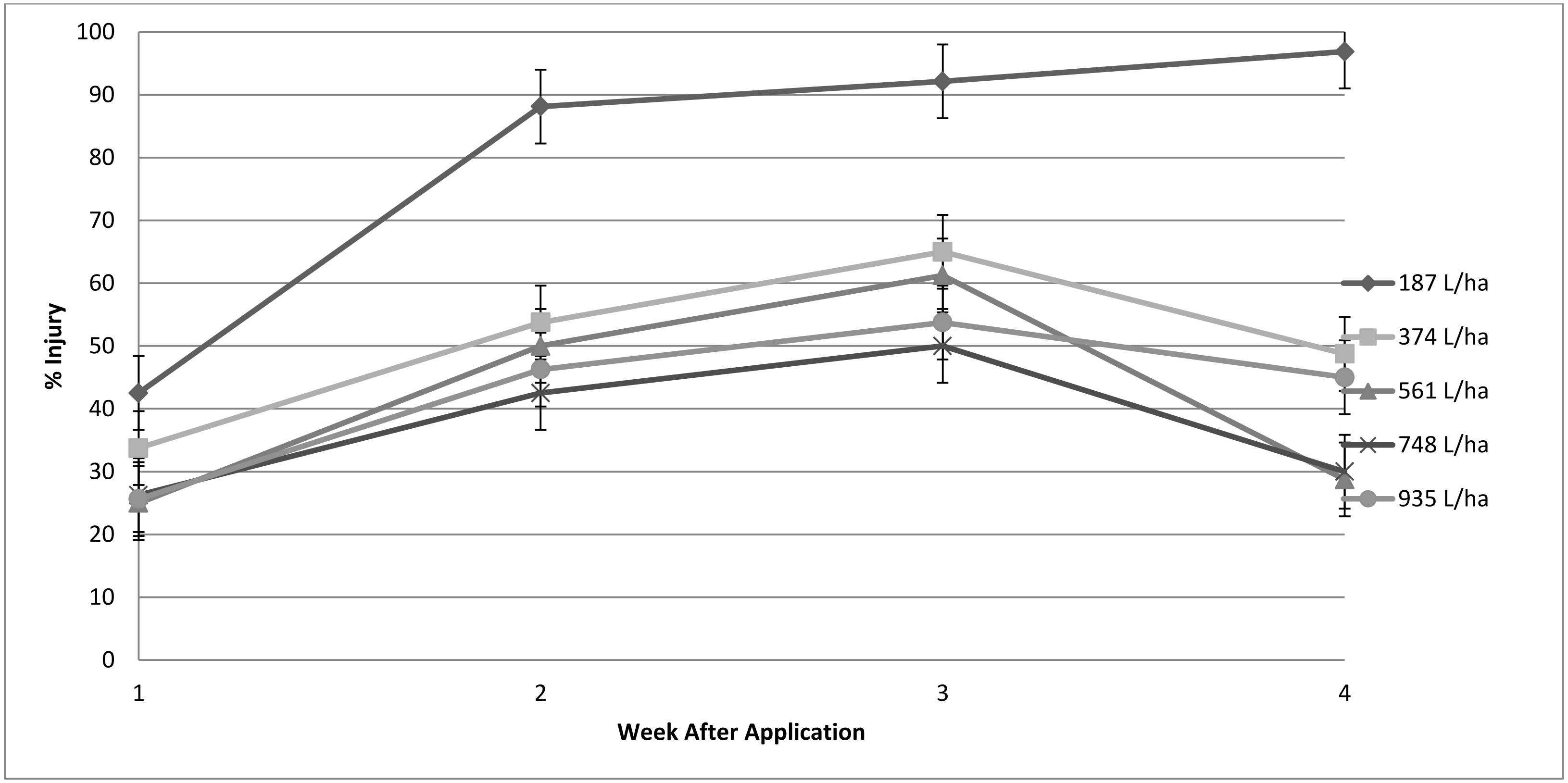

Figure 4.2. Annual bluegrass injury with mesotrione applied at 186 g·ha^{-1} weekly for three applications at varying spray volumes. Error bars represent pooled standard error. Overlapping bars indicate no statistical difference.

CHAPTER 5: MESOTRIONE AND ADJUVANT COMBINATIONS TO CONTROL ANNUAL BLUEGRASS

Adjuvants are commonly used to increase the performance of foliar-applied herbicides and can be defined as "an ingredient that aids or modifies the action of the principal active ingredient" (Hazen, 2000). The use of adjuvants dates back to 1880's when substances such as soap, animal oils, kerosene, sugar, and glue were used to try to increase pesticide efficacy (Hazen, 2000). From this point, many products have been researched and developed into present day adjuvants. Adjuvants can be classified into two groups, tank-mix modifiers and activator adjuvants (Hazen, 2000). Tank-mix modifiers are used for a unique purpose required for a pesticide spray solution such as buffering, increasing compatibility between pesticide or fertilizer formulations, reducing spray drift, or defoaming agents (Hazen, 2000). Activator adjuvants are classified as surfactants, oils, or salts (Hazen, 2000). These chemicals alter herbicide performance by manipulating the physical and chemical properties of the spray solution to modify spreading, wetting, retention, and penetration of the herbicide solution into the plant (Hazen, 2000). A surfactant aids absorption of the herbicide by reducing surface tension of the spray solution to allow a closer contact to the leaf surface (Hazen, 2000). Oils are derived from petroleum or vegetable based oils and increase penetration of the herbicide by using the characteristics of an oil to move through the cuticle of the plant (Hazen, 2000). Salts are derived from nitrogen fertilizers and increase herbicide activity, but it is unclear as to why or how salts increase efficacy (Nalewaja et al., 1998).

Adjuvant use is a common practice to increase herbicide efficacy or reduce the amount of active ingredient applied while maintaining weed control (Nalewaja et al., 1995). Many studies have shown the impact of adjuvant use on herbicide efficacy (Jordan et al., 1996; Jordan and Burns, 1997; Ramsdale and Messersmith, 2001; Zawierucha and Penner, 2001). Currently, a non-ionic surfactant (NIS) adjuvant at 0.25% v/v is recommended for mesotrione use in turf, but adjuvant choice may influence control levels (Syngenta Crop Protection, 2009). Annual bluegrass absorbed 25% of bispyribac-sodium applied, but 45%, 46%, and 75% of bispyribac-sodium was absorbed when a crop oil concentrate (COC), NIS, and methylated seed oil (MSO), respectively, were added indicating that annual bluegrass absorbs herbicides differently depending on what adjuvant is used (McCullough et al., 2008). Giese et al. (2005) reported that mesotrione provided better control of creeping bentgrass when using a NIS compared to a MSO. Also, creeping bentgrass control was increased from 78% with NIS alone to 98% by adding UAN to mesotrione with NIS (Xie et al., 2011). The objective of this study was to determine the effect of four different adjuvant classes, NIS, COC, MSO, and an organosilicone surfactant (OSL), as well as the nitrogen fertilizer, UAN, on annual bluegrass control with mesotrione. Determining the best adjuvant combination with mesotrione will allow for greater postemergence control of annual bluegrass in cool-season turf.

Materials and Methods

Plant Culture. Experiments were conducted in June 6 and August 17, 2011 at the Landscape Horticulture Research Center on the University of Illinois Urbana-Champaign campus. The trials were conducted in a mixed stand of Kentucky bluegrass and annual bluegrass. The trials were located in an area of the Kentucky bluegrass (*Poa pratensis* L. cv. 'Bewitched'). Annual bluegrass comprised more than 90% of the turf area and naturally infests the area. The turf stand was maintained at 2.2 cm and was mowed two to three times per week. The soil type for the area is a Flanagan silt loam (fine, smectic, mesic, aquic argiudolls) with a pH of 6.8, sand content of 125 $g \cdot kg^{-1}$, silt content of 588 $g \cdot kg^{-1}$, and clay content of 287 $g \cdot kg^{-1}$. The area was irrigated as needed to ensure no water stress occurred and was fertilized at 146 kg $N \cdot ha^{-1}$ per year with three applications of commercial fertilizers.

Herbicide Treatments. Turf plots measuring 1.2 m by 1.8 m were treated with mesotrione as Tenacity® 4S (Syngenta Professional Products, Greensboro, NC) at a rate of 110 $g{\cdot}ha^{-1}$once a week for a total of five applications. Treatments were applied with a CO_2-pressurized sprayer calibrated to deliver 470 $L{\cdot}ha^{-1}$ at 0.27 MPa. The spray boom was composed of four flat-fan nozzles (TeeJet 8002 flat fan spray nozzles; Spraying Systems Co., Roswell, GA) spaced 25 cm apart and operated at a height of 60 cm.

Adjuvants. A factorial treatment arrangement was used with adjuvant type as one factor and UAN as a second factor. Adjuvants added to the mesotrione solution include a NIS (Activator 90; Loveland Industries, Greeley, CO), COC (Crop Oil Concentrate; Helena Chemical Company, Collierville, TN), MSO (Premium MSO Methylated Spray Oil; Helena Chemical Company, Collierville, TN), and OSL (Kinetic; Helena Chemical Company, Collierville, TN). The NIS was added at a 0.25% v/v, MSO and COC were added at 1% v/v, and OSL was added at a 0.1% v/v. The UAN solution was 28% nitrogen and added at a 2.5% v/v rate. Herbicide and adjuvant solutions were mixed thoroughly after preparation and before application to the turf plot.

Data Collection. Visual annual bluegrass injury symptoms were rated weekly on a 0% to 100% scale, in which 0% was completely green tissue and 100% was necrotic tissue. Percent control was calculated from initial and final visual estimates of annual bluegrass populations eight weeks after application.

Statistical Analysis. A complete factorial arrangement of the data was analyzed in SAS 9.2 in Proc Mixed (P=0.05; Statistical Analysis Software, Inc., Cary, NC). The data required the use of the $\sin^{-1}$ transformation to meet the assumptions of ANOVA (Kuehl, 2000). All data presented is back transformed to the original data. Means were separated using Fisher's least significant difference test (P=0.05).

Results

Annual Bluegrass Control. The data from the two trials could not be combined due to issues of unequal error variances, so trials were analyzed individually. The use of an adjuvant was found not significant during the June trial (P=0.1349), but was found significant in the August trial (P=0.0053). The high level of control from all treatments during both trials prevented or reduced the ability to detect differences between adjuvants (Table 5.1). This may be due to the high temperatures during the two trials since mesotrione applied at 110 $g{\cdot}ha^{-1}$ does not typically result in high levels of annual bluegrass control (Table 1.1). Results from the August trial indicate that NIS provided the greatest level of control at 100% with both COC and OSL not statistically different with control levels of 99 and 98% respectively. The adjuvant MSO was the only treatment not statistically greater than not using any adjuvant at all (Table 5.1). The use of UAN solution resulted in a significant increase during both trials (P=0.0031; P=0.0003) to 98 and 99% annual bluegrass control compared to 87 and 93% control when UAN was omitted from the spray solution.

Annual Bluegrass Injury. Injury levels increased rapidly in the first and second weeks after initial herbicide application with injury levels increasing or leveling off past this point depending on the treatment (Table 5.2). The NIS and treatment without an adjuvant saw a decrease in injury between the second and third week after initial application, and the OSL treatment never achieved greater than 54% injury (Table 5.2). The other treatments did increase annual bluegrass injury weekly, but the difference between weeks and treatments was generally not significant (Table 5.2). At five weeks after initial treatment, the adjuvant with the significantly lowest level of injury was OSL (Table 5.2). This adjuvant may provide a safening effect when added to mesotrione since annual bluegrass control was still achieved (Table 5.1).

In the first and second week after herbicide application, annual bluegrass injury levels were the same between treatments with and without UAN (Table 5.2). In the third week after application treatments with UAN increased injury to annual bluegrass more than treatments without UAN, and this pattern continued into the fourth week (Table 5.2). This pattern is evident within each adjuvant, but generally only the main effect for UAN is statistically significant during weeks three and four. At four and five weeks after initial application, adding UAN either alone or with the OSL adjuvant resulted in significantly more injury than OSL alone or no adjuvant (Table 5.2).

Discussion

Mesotrione Activity As Influenced By Adjuvants. Our study showed mixed results in the use of adjuvants with mesotrione to control annual bluegrass. One trial indicates that adjuvants do not increase annual bluegrass control with mesotrione, while the second trial indicates that adjuvants do increase control. Giese et al. (2005) found that using different adjuvants resulted in different control levels of creeping bentgrass when using mesotrione, which matches the results from the August trial but not the June trial. This study did find the use of UAN to be significant which matches other studies with mesotrione (Xie et al., 2011; Li and Howatt, 2006). Since UAN is a form of nitrogen fertilizer, it is not clear whether the increase in activity is due to a nitrogen response (Chapter 4) or an effect on herbicide uptake. Mesotrione control by annual bluegrass may be influenced by adjuvant use, but contradicting results and extremely high control levels during the trials prevent determining adjuvant effectiveness. Conducting the study again using a different rate and application frequency of mesotrione may help to show if there are any differences.

The addition of UAN to mesotrione can increase annual bluegrass control. Regardless of the use of an adjuvant or choice of adjuvant, a turf manager can easily increase the control of annual bluegrass just by adding UAN to the tank-mix. The increase in control may allow lower rates of mesotrione to be used or fewer applications. The addition of UAN to mesotrione may also increase the control of other weeds making the use of mesotrione and UAN more desirable for turf managers. The use of UAN does increase injury to annual bluegrass compared to not using it and has the potential to increase injury to desirable species. Increasing injury to turfgrass species such as Kentucky bluegrass or perennial ryegrass may limit the use of mesotrione and UAN due to the risk of fatal injury and negative aesthetic results. Since this study only applied UAN at 2.5% v/v, another study utilizing different rates of UAN solution may show if annual bluegrass control can be increased further with higher rates or if injury can be reduced.

Adjuvants are a very common tool added to herbicide tank-mixes that can increase weed control by altering the spray solution to increase absorption, retention, and distribution across the leaf surface. Many studies have described the use of an adjuvant with an herbicide to be a beneficial relationship to increase weed control. The use of an adjuvant with mesotrione had mixed results in this study, but the addition of UAN did significantly increase control. Discovering UAN does increase the control of annual bluegrass is significant to turf managers because it can help to increase overall control, reduce the amount of labor required to control annual bluegrass with mesotrione, or employ lower rates of mesotrione.

Tables and Figures

Table 5.1. Annual bluegrass control during June and August field trials with mesotrione applied at 110 g·ha^{-1} weekly for five applications with and without adjuvants and UAN.

	% Control	
Adjuvant	June, 2011*	August, 2011**
None	88	89 C
NIS	91	100 A
COC	91	99 AB
MSO	99	97 BC
OSL	93	98 AB
With UAN	98	99
Without UAN	87	93

*Adjuvants not significant (P=0.1341); UAN significant (P=0.0031)

**Adjuvants significant (P=0.0053); UAN significant (P=0.0003)

ǂMeans followed by same letter not statistically different at α=0.05 using Fisher's LSD test

Table 5.2. Weekly annual bluegrass injury ratings during both trials with mesotrione applied at 110 g·ha^{-1} weekly for five applications with and without adjuvants and UAN.

	% Injury				
Adjuvant	1 WAIA	2 WAIA	3 WAIA	4 WAIA	5 WAIA
COC	13	47	48	68	85
COC + UAN	17	40	58	73	85
MSO	18	42	53	78	73
MSO + UAN	20	47	65	80	89
NIS	12	38	33	60	80
NIS + UAN	22	42	45	73	77
OSL	13	32	35	54	43
OSL + UAN	13	33	45	70	68
None	17	42	32	33	68
None + UAN	10	28	30	57	80
LSD α=0.05	11	16	15	15	18

*COC at 1% v/v, MSO at 1% v/v, NIS at 0.25% v/v, OSL at 1% v/v, and UAN at 2.5% v/v

CHAPTER 6: SUMMARY AND CONCLUSION

Mesotrione is a HPPD inhibiting herbicide that is new to turf. A selective herbicide with both pre- and postemergence activity on many broadleaf and grass weed species, mesotrione controls susceptible plants by interrupting the production of carotenoids and other radical and reactive oxygen species scavenging structures. Mesotrione selectivity is based upon plant metabolism rates, susceptible plants are not able to quickly breakdown mesotrione and injury is able to occur. Annual bluegrass, a common grass species weed in turf and nuisance to turf managers, shows susceptibility to mesotrione and may be able to be controlled by the herbicide. This level of susceptibility of annual bluegrass to mesotrione and the impact of having a postemergence control option was the foundation for this research.

The objectives of this research were to determine if mesotrione could be used as a viable chemical control option of annual bluegrass. Studies focused on finding a rate and application frequency, along with the influence of nitrogen fertilization, spray volume, and the use of adjuvants were conducted. Significant results from these studies allowed a greater understanding of mesotrione and the control of annual bluegrass. Mesotrione activity was regulated by temperature. During high temperatures (>20˚C), mesotrione activity and control levels increase, but under low temperatures control is reduced. During the spring, control of mesotrione is less compared to the fall even though the temperatures are similar. The physiological differences in annual bluegrass that occurs during these seasons may influence control with mesotrione. Multiple and frequent applications of mesotrione were found to be effective anytime of the year, but under high temperatures, applications at 110 $g \cdot ha^{-1}$ twice a week for five applications or 186 $g \cdot ha^{-1}$ weekly for three applications can also control annual bluegrass. The amount of labor required to control annual bluegrass with mesotrione with seven to ten applications multiple times a week would be difficult for most turf managers, so further studies were conducted to determine if mesotrione activity could be increased by varying other factors.

Further research observed nitrogen fertilization, spray volume, and choice of adjuvant on annual bluegrass control with mesotrione. These factors were studied because they represent simple things that a turf manager could manipulate to control annual bluegrass with mesotrione. Nitrogen fertilization was shown to increase control in a linear fashion when nitrogen levels were increased. The timing of fertilization was not significant, but using a rate of 72 kg $N{\cdot}ha^{-1}$ resulted in the greatest level of control of annual bluegrass and the same amount of injury occurred whether 72 or 48 kg $N{\cdot}ha^{-1}$ was applied. This study revealed that nitrogen fertilization can be used to increase mesotrione activity and potentially reduce the number or frequency of applications required to control annual bluegrass. Adjusting the spray volume was also found to influence mesotrione activity. Utilizing lower spray volumes was found to control annual bluegrass better than at higher spray volumes. At the lowest rate of 187 $L{\cdot}ha^{-1}$, control levels were significantly greater than at higher volumes. The final study on the influence of adjuvants and UAN had mixed results. Determining the effect of adjuvant use on annual bluegrass control with mesotrione was reduced due to contradicting results during the two trials. In one study the use of an adjuvant was found significant, while the other trial found adjuvants to be not significant. These results were due to high control levels that occurred during the trials. Repeating this study using a less effective treatment may display differences between adjuvants. The study was able to provide a significant result in the use of UAN solution. UAN was able to increase control compared to not using it. Being able to increase control levels by just adding UAN is a significant finding and can increase the control of any application strategy selected by a turf manager using mesotrione to control annual bluegrass.

Using these results to increase annual bluegrass control with mesotrione will have some negative consequences. Increasing mesotrione activity on annual bluegrass will also increase activity on desirable species such as Kentucky bluegrass and other cool-season turf species. Higher activity levels will increase injury and may limit the use of mesotrione to control annual bluegrass. Also, utilizing low spray volumes increases the risk of herbicide drift and damaging non-target species as well. This would be of great concern to applications on golf courses and landscapes that have other plants such as trees, shrubs, and other ornamentals. The results from this study can be used by a turf manager to formulate a mesotrione regime to control annual bluegrass, but also control potential risks.

Prior to this study, postemergence applications of mesotrione only resulted in mild injury to annual bluegrass. The results of this study show that mesotrione can be used to control annual bluegrass. The risk of injury to desirable turf species and the amount of labor required may limit a turf manager’s selection of mesotrione. Our results indicate that mesotrione when applied frequently can provide a high level of annual bluegrass control. By fertilizing with nitrogen, reducing spray volumes to 187 $L \cdot ha^{-1}$, and adding UAN at 2.5% v/v, even greater herbicidal activity and annual bluegrass control is possible.

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