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Wesley Everman
Major Professor's Signature

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HERBICIDE AND SOIL CONSIDERATIONS IN WEED CONTROL IN POTATO

By

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ABSTRACT

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The effect of soil clay content, organic matter content, and pH on flumioxazin efficacy was evaluated using a greenhouse bio-assay. Clay content was not found to affect the control of any weed species tested. Control of weed species decreased as soil organic matter content increased reducing initial and residual control. When soil pH was below 6, initial weed control was reduced with flumioxazin. However, soils with a pH of 7 had a greater effect on the residual control with flumioxazin.

Field trials were conducted at the Montcalm Research Farm near Entrican, MI in 2008 and 2009 to evaluate the effect of herbicides labeled for potatoes on three cultivars of potato mini-tubers. Imazosulfuron and treatments containing postemergence applications of rimsulfuron with or without metribuzin following preemergence applications of *S*-metolachlor plus linuron reduced yields in 2008 and 2009. In 2009, treatments of dimethenamid-p, *S*-metolachlor, pyrasulfatole, and pendimethalin alone reduced yields. Results from this study indicate greater yield losses occur when multiple stress factors are present. Several herbicides were observed to be safe when applied preemergence including linuron, metribuzin, and rimsulfuron.

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CHAPTER 1

LITERATURE REVIEW

INTRODUCTION

The potato (*Solanum tuberosum* L.) is a staple food crop grown throughout the world ranking fourth in global agricultural production. Potatoes play a major role not only in the economy, but also in the diet of many Americans. Management of the potato requires a holistic approach that addresses production efficiency, economic viability, environmental compatibility, and social responsibility (Rowe and Powelson 2008). A growing concern in potato production is the management of weeds with increasing restrictions on herbicide use and the development of herbicide resistance in weeds. To manage weeds in potatoes researchers continually evaluate new herbicides. Flumioxazin recently has been labeled for use in potatoes and could provide growers with a highly effective alternative to traditional herbicides. However, potatoes are grown on a wide range of soils which could impact weed control with flumioxazin.

SOIL APPLIED HERBICIDE EFFICACY AND PERSISTENCE

Herbicides can vary greatly in chemical and physical properties and can differ despite similar functionality in plants (Kah and Brown 2006). Each property of an herbicide contributes to a cumulative effect on its existence in the soil as a solid, liquid, or gas, impacting herbicide sorption and persistence in the soil (Monaco et al. 2002). Solubility of an herbicide can greatly influence its mobility in a soil (Koskinen and Moorman 1992). Elliott et al. (1999) attributed differences in presence of herbicides in tile drainage water to herbicide solubility with the less soluble diclofop found in lower concentrations than the highly soluble dicamba. Vapor pressure of herbicides indicates their relative tendency to volatilize from the soil. Herbicides with vapor pressure greater than 10^{-2} Pa are prone to be lost from soils due to volatilization, contributing to significant amounts of herbicide transfer (Koskinen and Moorman 1992). Due to its high vapor pressure of 1.47×10^{-2} Pa (Senseman 2007), trifluralin was reported to volatilize 60 to 71% of the initial amount applied within the first 5 days of application when not incorporated (Majewski et al. 1993).

Herbicide adsorption is also dependent on the chemical structure of an herbicide, as this determines its tendency to form chemical and physical bonds with soil particles (Calvet 1980; Leistra 1980). Soil interactions with ionic and ionizable herbicides generally are attributed to a multitude of bond types including high energy (>80 kJ/mol) chemical bonds such as covalent, ionic, and ligand exchange, and low energy (<80 kJ/mol) physical bonds such as hydrogen and van der Waals forces (Calvet 1980). The collective effect of the bonds contributes to the binding of an herbicide in soil. However, the properties of an herbicide and effect on sorption to a soil are dependent on the properties of the soil to which they are applied.

Soil interactions. Soils are diverse heterogeneous mixtures of particles derived from geological weathering of parent rock material and the biological organisms, past and present, associated with it (Hillel 1998; Havlin et al. 2005). Clay content and type in a soil can greatly impact its cation exchange capacity (CEC) due to negative charges caused by isomorphic substitutions (Calvet 1980; Havlin et al. 2005). Aluminum and iron hydroxides can also bind herbicides by anionic exchange, but generally are only important in highly weathered soils (Kah and Brown 2006; Koskinen and Moorman 1992). Soil organic matter (SOM) has been attributed by many researchers to be the greatest factor in herbicide adsorption (Monaco et al. 2002; Wauchope et al. 2002; Weber et al. 2007). Depending on the organism from which the SOM was derived, soil pH, climate, and the microbial community, the type and proportion of functional groups on the SOM can vary affecting sorption of herbicides (Walker and Austin 2003; Benoit et al. 2008). Imidazolinone herbicide adsorption to organic soil was found to be correlated with the amount of carboxylic groups in the SOM (Gennari et al. 1998).

Although not a physical property of the soil, solution pH can alter the activity of the soil's constitutive particles (Calvet 1980; Sposito et al. 1999; Kah and Brown 2006). The effect of solution pH on clay particles is minor due to changes in edge charges; however the effect of soil pH on soil SOM can be immense (Sposito et al. 1999; Kah and Brown 2006). At pH values above the SOM hydroxyl groups pKa (5 to 7), H^+ disassociates and increases the ability of the SOM to bind cations (Stevenson 1972). At soil pH values lower than 5, Ferreira et al. (2001) found SOM to increase in hydrophobicity, which could increase herbicide adsorption.

Persistence. By considering the chemical properties of a herbicide and the soil to which it is applied, a relative understanding of adsorption by the soil can be attained. Few herbicides are permanently charged, like paraquat, and can react strongly with soil particles depending on charge polarity (Iglesias et al. 2009). Conversely, ionizable herbicides can form numerous interactions with soil particles often varied by soil pH (Kah and Brown 2006). Soil solution pH significantly influences ionizable herbicides because it alters the herbicide speciation in a soil. Soil clay content and SOM affect ionizable herbicide binding by providing negative sites for cationic exchange and the combined effect of the two fractions can explain the adsorption of the majority of ionizable herbicides in soil (Schmidt and Pestemer 1980; Diehl et al. 1995; Monaco et al. 2002). However, non-ionizable herbicides have limited interactions with soil particles (Calvet 1980; Kah and Brown 2006). Binding of non-ionizable herbicides are attributed instead to hydrophobic binding which is the result of a decrease in entropy due to partitioning of the hydrophilic herbicide in the hydrophobic regions of soil (Calvet 1980; Koskinen and Moorman 1992). Understanding the multitude of interactions between herbicides and the soil allows us to study its concentration in different phases and availability for weed control.

Once an herbicide is applied to the soil, it rapidly interfaces with soil particles and reaches a relative equilibrium (Monaco et al. 2002). Herbicide that is not sorbed to the soil and is in solution is generally accepted as herbicide available for weed uptake and control (Peter and Weber 1985; Monaco et al. 2002). Therefore, as herbicide adsorption increases subsequent weed control decreases. Herbicide distribution in soils is described both by K_d and K_{oc} values, a measurement of amount of herbicide in solution compared to herbicide adsorbed to soil particles (Wauchope et al. 2002). Distribution values are useful for describing relative binding of an herbicide in given soil; however, they do not explain individual components of herbicide adsorption, but rather the summation. Nonetheless, distribution values give a basic understanding of herbicide adsorption in the soil, providing information about how transfer and degradation processes will affect its persistence.

Weed control with soil-applied herbicides is not only a function of herbicide adsorption, but also of its persistence in the soil. Herbicides need to persist long enough to provide adequate weed control but not too long so as to interfere with subsequent crops or the environment. The persistence of an herbicide in a soil is a function of its loss from the soil system and degradation. Herbicide can be lost from a system due to volatilization, leaching, surface runoff, and loss of soil with sorbed herbicide. Herbicide breakdown, dependent on the compound, is due to the combination of chemical decomposition, photodecomposition, and biological decomposition. Chemical decomposition of herbicides is due to abiotic processes such as hydrolysis and can cause significant dissipation of some herbicides (Kwon et al. 2004). Photolysis can cause rapid breakdown of herbicides such as the dinitroanalines, and can also be responsible for significant loss from the soil if not properly incorporated (Monaco et al. 2002). Lastly, microbial metabolism is responsible for the dissipation of most organic herbicides and can vary dependent on the microbial community, density, climate, and soil type (Hurle and Walker 1980; Rice et al. 2002). Soils high in organic matter are reported as having greater microbial activity (Goyal et al. 1999; Kah and Brown 2006). However, greater amounts of organic matter increase herbicide adsorption, making the herbicide unavailable for microbial degradation, causing an overall conflicting response. Precipitation and temperature influence microbial activity and their influence may help explain fluctuation in herbicide efficacy and carry over. Overall, the degradation and persistence of a soil-applied herbicide is due to a myriad of factors and their interactions.

Flumioxazin. Flumioxazin is a preemergence herbicide labeled for use in many crops including alfalfa, cotton, peanuts, potato, and soybeans. An herbicide in the protoporphyrinogen oxidase inhibiting family of herbicides, flumioxazin is used in cropping systems to manage glyphosate and acetolactate synthase inhibiting herbicide resistant weed species due to its unique mode of action (Clewis et al. 2007; Everman et al. 2009). Westhoven et al. (2008) found that, with the addition of flumioxazin and cloransulam-methyl, control of glyphosate-resistant common lambsquarters (*Chenopodium album* L.) increased from 81 to 96%, compared to an early postemergence application of glyphosate plus 2,4-D. In a greenhouse study, flumioxazin at 71 g ai ha^{-1} provided greater than 96% control of glyphosate-resistant marestail (*Conyza canadensis* L.) 8 wks after treatment. In juneberry, residual weed control with flumioxazin 8 wks after treatment at 140 g ai ha^{-1} was greater than 88% for all species with 99% control of redroot pigweed (*Amaranthus retroflexus* L.)(Hatterman-Valenti 2005). Complete control of redroot pigweed was reported 50 days after treatment when flumioxazin was tank mixed with clomazone at multiple rates, however flumioxazin applied alone at a rate of 71 g ai ha^{-1} only provided 73% control of yellow nutsedge (*Cyperus esculentus* L.) in sweetpotato (Kelly et al. 2006).

Grass control with flumioxazin is often variable and unacceptable. Niekamp and Johnson (2001) reported that flumioxazin at 71 and 110 g ai ha^{-1} provided only 18 and 36% control of giant foxtail (*Seteria faberi* L.), respectively, compared to control at another location of 62 and 81% for the low and high rate, respectively. The authors attributed differences in control to higher weed population at one location compared to the other. Flumioxazin at 53 g ai ha^{-1} only provided 63% control of barnyardgrass (*Echinochloa crus-galli* L.) 4 wks after treatment and at 105 g ai ha^{-1} provided 68 to 78% control of giant foxtail (Taylor-Lovell et al. 2002; Wilson et al. 2002). For this reason additional preemergence grass herbicides are included for use with flumioxazin such as *S*-metolachlor which increased control of barnyardgrass from 63% to 97% (Wilson et al. 2002).

Weed control efficacy with flumioxazin could vary due to interactions with the soil solution. Flumioxazin is a non-ionic herbicide with a water solubility of 1.79 mg L^{-1} and soil half life of 5 to 19 days determined by batch equilibrium experiments (Ferrell and Vencill 2003; Senseman 2007). Microbial degradation is an important factor determining persistence of flumioxazin in the soil (Ferrell and Vencill 2003). When soil pH is above 7 hydrolysis of flumioxazin could become the major process of degradation (Kwon et al. 2004). Batch equilibrium and field experiments have been conducted to better understand the adsorption of flumioxazin. Researchers have found the adsorption of flumioxazin to be correlated with SOM and certain types of clay particles (Ferrell et al. 2005; Alister et al. 2008). Adsorption of flumioxazin to SOM is mainly attributed to hydrophobic binding, while its adsorption to clay particles is due to surface iron and aluminum hydroxides attracting the electronegative region on the flumioxazin molecule (Ferrell et al. 2005).

MANAGEMENT OF POTATOES

Weed control is important in potato production to reduce competition for nutrients, light, and water, and to eliminate potential problems at harvest. Competition with redroot pigweed and barnyardgrass from time of planting to harvest at a density of 1 plant m^{-1} of row has been shown to reduce marketable yields by 22 to 33% and 19 to 21%, respectively (VanGessel and Renner 1990). Weeds not only directly reduce yields through competition but perennial species such as quackgrass (*Elymus repens* (L.) Gould) and yellow nutsedge have been reported to lower tuber quality by growing into the tuber (Lutman 1992; Boydston et al. 2008). Weed presence also may impede harvest by interfering with digging of tubers and soil separation, requiring additional management in correcting these problems (Lutman 1992; Boydston et al. 2008).

Growers achieve weed control in potatoes by utilizing cultural, mechanical, and chemical control. Cultural control of weeds is achieved by promoting early and full development of the crop canopy often through proper fertilization and cultivar selection (Boydston et al. 2008; Colquhoun et al. 2009). Cultivation often is used in potato management to manage shallow rooted weeds (Bellinder et al. 2000; Boydston et al. 2008; Felix et al. 2009). Felix et al. (2009) demonstrated the potential of using WeedCast, a weed emergence prediction model, to effectively time cultivation in potatoes to maximize weed control. However, control of weeds by cultivation can be greatly improved when combined with applications of herbicides (Renner 1992; Bellinder et al. 2000). Control of weeds is achieved with timely applications of preemergence and postemergence herbicides. *S*-metolachlor applied preemergence alone at 1.12 kg ai/ha provided 96% control of annual grass species 56 days after application (Richardson et al. 2004). Treatments of *S*-metolachlor at 1.12 kg ai/ha plus metribuzin at 0.45 kg ai/ha provided 89 and 94% control of common lambsquarters and common ragweed (*Ambrosia artemisiifolia L.*), respectively (Richardson et al. 2004). Eberlein et al. (1994) found that postemergence applications of rimsulfuron at 27 g ai/ha at one location controlled hairy nightshade (*Solanum physalifolium Rusby.*) and redroot pigweed 94 and 100%, respectively.

Cultivar Sensitivity. A challenge of using herbicides for weed control in potatoes is avoiding crop injury. Potato cultivars have variable sensitivity to herbicides attributed to differences in absorption, translocation, or metabolism of the herbicide (Hinks 1977; Bailey et al. 2003). Herbicide sensitivity to metribuzin is reported to be an inheritable trait with a relative high frequency in selected progeny making it a prevalent recurring trait (De Jong 1983). Herbicide sensitivity is of great concern to breeders because diploid species utilized as sources for novel genes have been shown to be sensitive to linuron and/or metribuzin (Bradeen and Mollov 2007). Metribuzin was found by Friesen and Wall (1984) to cause injury and yield reductions on 22 different potato cultivars. This included yield reductions of 'Alaska Red' by 68% with preemergence applications of metribuzin at 1 kg ai/ha. Hutchinson et al. (2005) reported sensitivity of the cultivar 'Ranger Russet' to preemergence applications of flumioxazin from 53 to 140 g ai/ha, which caused total yield reductions of 13 to 20%.

Potato mini-tubers. Unique to managing potatoes is the utilization of whole or cut potato tubers as the seed source for commercial production. Potatoes grown from tuber pieces have increased vigor as compared to plants grown from true seed and additional benefits such as production of "true-to-type" plants (Struik and Wiersema 1999). However, potato tuber pieces may harbor harmful pathogens such as *Phytophthora infestans* and potato virus Y (PVY) (Allen et al. 1992; Bus and Wustman 2007; Whitworth and Davidson 2008). Planting infected tuber pieces may result in the spread of disease. Depending on the pathogen's infection cycle, the spread of disease can be influenced by cultural practices and the incidence of insect pests. PVY can spread rapidly via aphid vectors (Basky and Almási 2005; Valkonen 2007), which increases the importance of removing contaminated seed. Potato seed certification programs were initiated to regulate the sale and production of seed potatoes to prevent the spread of diseased seed.

Seed certification laws were created at the national and state level requiring seed lots to meet standards to be certified. Seed certification standards required growers to maintain lots with low pathogen incidence and the initial production of seed through tissue culture. Technological advancements and increased availability of tissue culture have allowed for the production of *in vitro* plantlets to create pathogen-free pre-nuclear (seed planted to generate nuclear or first generation seed) plant material (Struik and Wiersema 1999). Over time, production of early generation material has changed and potato plantlets are now used to produce micro- and mini-tubers as the preferred initial seed source for commercial production. Production of potato mini-tubers has received much attention and consideration, resulting in research with the intent to maximize production and quality of mini-tubers (Ranalli et al. 1994; Struik and Lommen 1999).

Although mini-tubers are similar to cut seed pieces used in production, there are unique difficulties in managing them. Researchers have observed agronomic differences when planting mini-tubers as opposed to cut seed pieces, such as reduced stem number, delayed emergence, and reduced canopy closure (Struik and Lommen 1999). Research done by Ranalli et al. (1994) showed that 51 days after planting, plants grown from mini-tubers provided only 37.8% canopy closure, 34.6% less cover than plants grown from cut seed pieces, thus reducing the crop's ability to compete with weeds (Monaco et al. 2002). Mini-tubers have a lower level of carbohydrate reserves and a greater surface area to volume ratio compared to cut seed pieces. These differences cause plants grown from mini-tubers to emerge later (Ranalli et al. 1994; Struik and Lommen 1999), have generally only one stem (Ahloowalia 1994; Struik and Lommen 1999), and produce smaller sprouts (Lommen 1994). Mini-tubers producing smaller sprouts and plants which are less vigorous could be more susceptible to herbicide injury (Scott and Phillips 1971).

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CHAPTER 2

EFFECT OF SOIL CLAY AND ORGANIC MATTER CONTENT AND SOIL PH ON THE EFFICACY OF FLUMIOXAZIN

Abstract: The effect of soil clay content, organic matter content, and pH on flumioxazin efficacy was evaluated using a greenhouse bio-assay. Clay soils used in the study were 0, 10, 20, 30, 40, 50, 60 and 70% clay by mass adjusted by adding kaolin clay to sand. Organic soils used in the study were 0, 0.5, 1, 2, 4, 8, 16, and 32% organic matter by mass adjusted by adding organic soil (82% organic matter) to sand. Varying soil pH values were achieved by acidifying (H_3PO_4) or neutralizing (NaOH) a control soil (pH of 4.76) to a pH of 4, 5, 6, 7, 8 and 9. Seeds of barnyardgrass (*Echinochloa crus-galli* L.), giant foxtail (*Seteria faberi* Herrm.), redroot pigweed (*Amaranthus retroflexus* L.), and velvetleaf (*Abutilon theophrasti* L.) were incorporated into the top 1.3 cm of each soil at a density of 100 seeds per pot. Emerged plants were counted and removed in both treated and not-treated pots 2 wks after planting, and each following wk for 6 wks. Efficacy of flumioxazin was evaluated by calculating percent emergence of weeds in treated soils compared to emergence of weeds in non-treated soils. Clay content was not found to affect flumioxazin control of any weed species tested. Control of barnyardgrass, giant foxtail, and velvetleaf was reduced as soil organic matter content increased. Control of redroot pigweed was not affected by organic matter. Soil pH below 6 reduced flumioxazin control of giant foxtail and velvetleaf but did not affect control of barnyardgrass or redroot pigweed. Results indicated herbicide use rate needs to be adjusted depending on soil characteristics and targeted weed species.

Nomenclature: Barnyardgrass, *Echinochloa crus-galli* L.; flumioxazin; giant foxtail, *Seteria faberi* Herrm.; redroot pigweed, *Amaranthus retroflexus* L.; velvetleaf, *Abutilon theophrasti* L.

Key words: kaolinite, adsorption, hydrophobic binding.

INTRODUCTION

Interactions between a soil-applied herbicide and the soil medium are complex. A relative equilibrium is reached soon after application of an herbicide to the soil (Wauchope et al. 2002; Ferrell et al. 2005). The portion of herbicide not sorbed to the soil particle surface is generally considered as herbicide available for weed control (Walker 1980; Peter and Weber 1985). Therefore, if herbicide adsorption increases, subsequent weed control decreases. However, the amount and types of particles in a soil and the soil pH can greatly affect herbicide adsorption.

Herbicide adsorption in a soil is often evaluated experimentally by deriving a K_d value, a measure of the amount of herbicide in solution to herbicide adsorbed to soil particles (Wauchope et al. 2002). A K_d value is often adjusted for soil organic matter (SOM) due to the magnitude of its role in herbicide binding (Monaco et al. 2002; Wauchope et al. 2002; Weber et al. 2007). SOM can differ greatly in functional group type and abundance, depending on the origin of the SOM, soil pH, climate, and the microbial community, altering sorption herbicides (Walker and Austin 2003; Benoit et al. 2008). SOM is not the sole sorbent for many herbicides. Soil clay particles due to their net negative charge can interact with herbicides in many ways. They are reported as the major adsorption surface for certain herbicides (Monaco et al. 2002).

Flumioxazin, a non-ionic protoporphyrinogen oxidase inhibitor, is labeled for preemergence use in many crops including alfalfa, cotton, peanuts, potato, and soybeans (Niekamp 2001; Wilson et al. 2002; Ferrell et al. 2005). Flumioxazin has been used widely in cropping systems to manage glyphosate and acetolactate synthase resistant weed species due to its unique mode of action (Clewis et al. 2007; Westhoven et al. 2008; Everman et al. 2009). Flumioxazin efficacy has been shown to vary between and within studies on different weed species (Taylor-Lovell et al. 2002; Grey and Wehtje 2005; Norsworthy et al. 2009). Observed differences in weed control with flumioxazin could be due to variations in the chemical and physical properties of the soil to which it is applied.

Non-ionizable herbicides such as flumioxazin form relatively few associations with soil particles (Calvet 1980; Koskinen and Moorman 1992). Adsorption of non-ionizable herbicides to soil particles is mainly attributed to hydrophobic binding, which is the result of a decrease in entropy due to partitioning of the hydrophilic herbicide in the hydrophobic regions of soil (Calvet 1980; Kah and Brown 2006). SOM and the interlayer of clays provide conditions necessary to adsorb flumioxazin due to the hydrophobicity of the particles. However, SOM and clay particles to some degree are subject to alterations in chemical and physical structure due to solution pH. Soil pH, depending on clay type can affect clay edge charges or binding of base cations by replacement with H^+ the pH effect on SOM can be diverse and is due to affects on speciation of SOM functional groups (Sposito et al. 1999; Kah and Brown 2006). Ferreira et al. (2001) found SOM to increase in hydrophobicity at soil pH values lower than 5. This could increase flumioxazin adsorption.

Batch equilibrium and field experiments have been conducted to evaluate adsorption of flumioxazin. Researchers found the adsorption of flumioxazin to be correlated with SOM and certain types of clay particles (Ferrell et al. 2005; Alister et al. 2008). However, these experiments focused extensively on herbicide adsorption, with effects on weed control only implied. Field studies are often conducted To determine the effect of soil type on weed control, , but are complicated due to soil variations within a plot, differences in weather, spatial variation in weed population and density, and a lack in range of soil parameters tested (Walker 1980; Kah and Brown 2006; Price et al. 2008). Therefore, a greenhouse study was conducted to evaluate the effect of clay content, SOM and soil pH to determine their effect on the efficacy of flumioxazin.

MATERIALS AND METHODS

Three separate greenhouse studies were conducted in 2008 at Michigan State University to investigate the effect of clay content, SOM or soil pH on flumioxazin residual control. The studies were arranged utilizing a randomized complete block design with a factorial arrangement of treatments, four replications, and were repeated in time. Factors included: three soil characteristics, four weed species, and two herbicide treatments. Base soil components utilized in the study were collected from the top 13 cm of respective soils in uniform areas with no history of flumioxazin application. Soil components were autoclaved prior to use to ensure soil sterility as flumioxazin is susceptible to rapid microbial degradation. Soil particle size distribution, pH, CEC, and SOM content were determined for each soil used (Table 1).

Preparation of Soil. A kaolin clay[1] hereafter referred to as clay, was added to sand[2] on a dry weight to weight basis to achieve a titration of soils. Soils ranged from 0% clay to 70% clay with interpolated soils varying 10% for 8 total test soils. Organic soil was obtained from the Michigan State University Muck Farm in Laingsburg and is described as a Houghton muck soil derived from reed sedge plant materials containing 82% organic matter by mass. The organic soil was passed through a 2-mm sieve to remove large debris prior to mixing and was added to sand on a dry weight to weight basis to achieve 0.5, 1, 2, 4, 8, 16, and 32% SOM. A base soil of pH 4.76 from a blueberry field consisting of a Pipestone-Kingsville soil (complex, sandy, mixed, mesic Typic Endoaquods) was adjusted to desired pH values of 4, 5, 6, and 7 using NaOH and H_3PO_4. As with the organic soil, the base soil was passed through a 2-mm sieve prior to acid or base treatment to remove debris and large particles. Calculated amounts of acid and base were dissolved in 3 L of de-ionized water and added to 8 kg of soil to make a soil solution. The soil solution was mixed thoroughly and spread over a large surface area to allow for rapid drying to prevent prolonged anaerobic conditions. Soil was mixed every 3 hours until gravimetric water had evaporated. Soils adjusted with NaOH were subjected to salinity analysis by determining electrical conductivity using a 1:1 soil to water ratio. Conductivity of soils ranged from 0.4 to 0.7 mmhos cm^{-1}, this was considered to be non-saline for a soil type of loamy sand and able to support normal crop production (Whitney 1998). Soil pH was tested after completion of the experiment to determine pH stability and was found to vary for all soils by 0.02 to 0.16.

Weed species evaluated consisted of velvetleaf (*Abutilon theophrasti* Medik.), barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.), and giant foxtail (*Setaria faberi* Herrm.). These were collected from local populations in corn and soybean fields at the Michigan State University Agronomy Farm. The redroot pigweed seed (*Amaranthus retroflexus* L.) was obtained from a commercial source[3]. Seeds of each species were planted at a density of 100 seeds per pot to obtain a target population of 50 seedlings. Soil was added to 7 by 7 by 6.4 cm pots with the top 1.3 cm of soil being added after mixing with one of the four weed species. After planting soil was brought to field capacity and then either left non-treated or was treated with formulated flumioxazin[4] at 71 g ai ha^{-1} with a track sprayer delivering 187 L ha^{-1}. Pots were kept in a greenhouse maintained at 25 ± 5 C° with a 16 hour photoperiod of natural sunlight supplemented with high-pressure sodium lighting to provide 1,000 μmol m^{-2} photosynthetic photon flux. The day after application, 0.64 cm of water was added over the top of all pots to simulate incorporation by rainfall with subsequent moisture provided by sub-irrigation and weekly topical watering of 0.64 cm.

Emerged weeds were counted and removed from pots 2 wks after planting using forceps, carefully removing the growing point to minimize soil mixing. Seedling counts were taken for an additional seven wks after initial removal with 96% of weed emergence taking place between planting and the first two seedling counts. Weed control was calculated using the equation:

$$y = 100 - \left(\left(\frac{t}{n}\right)100\right)$$

where y is percent control, t is number of weeds that emerged in treated soil and n is the average emergence of weeds in the respective non-treated soil. Weed control was analyzed with SAS[5] using PROC MIXED to test for significant interactions between experiments, weed species, and soil characteristic ($P<0.05$). No significant differences were found between runs, therefore data were pooled. Due to significant species by soil interactions, and the large main effect of soil characteristic, weed control was evaluated separately by soil characteristic with comparisons amongst species. Weed control for species as affected by soil differences was fit with trend lines using Sigma Plot software[5] and was modeled using either linear or inverse first-order regression. Inverse first-order regression fit to data is described as:

$$y = b + \frac{a}{x}$$

where y is weed control achieved at level a x^{-1} with asymptote b.

RESULTS AND DISCUSSION

Weed control with flumioxazin varied by soil characteristic and weed species (Table 2). Control of weeds with flumioxazin as affected by SOM was best modeled by linear regression while the effect of pH on control was best modeled by inverse first-order regression with coefficient of determination values ranging from 0.31 to 0.78.

Comparing weed control at different clay contents, no significant differences were observed for control of any weed species (Figure 1). Flumioxazin has been shown to form relatively weak associations with clay particles. Weak adsorption of flumioxazin by clay particles has been suggested to be due to an electronegative region on the molecule causing repulsion with negative surfaces like clay particles (Ferrell et al. 2005). Therefore, due to low adsorption by clay particles, flumioxazin availability is dependent on soil water content (Ferrell et al. 2005). Since soils were maintained at or near field capacity in our study, 100% weed control was observed for all species.

SOM content effect on weed control varied by species with control decreasing as SOM content increased (Figure 2). Increasing SOM content reduced control of all species except redroot pigweed and was significantly different by species due to sensitivity to flumioxazin ($P<0.05$). Decrease in weed control as SOM increased, as determined from the slope of the regression equations, were 1.06, 0.89 and 0.69 for barnyard grass, giant foxtail and velvetleaf, respectively. Control of barnyardgrass, giant foxtail, and velvetleaf at 3% SOM, common to soils in Michigan, would be 93, 89, and 93%, respectively. Conversely, redroot pigweed was effectively controlled across the SOM contents tested. Differences in control of weed species because of SOM content is likely due to increased adsorption by hydrophobic bonding onto SOM, decreasing herbicide concentration in solution available for control (Peter and Weber 1985; Koskinen and Moorman 1992; Kah and Brown 2006).

Relative control of weed species by flumioxazin is as follows, from greatest to least control: redroot pigweed, velvetleaf, giant foxtail, barnyardgrass. These results are similar to reports by others; however, the level of control they observed at varying SOM contents differed from ours. Wilson et al. (2002) found that flumioxazin applied at 53 g ai ha^{-1} to SOM content of 0.8% provided 90 and 56% control of redroot pigweed and barnyardgrass, respectively, 4 WAT. At 0.8% SOM we observed 100 and 95% control of redroot pigweed and barnyardgrass, respectively. Niekamp and Johnson (2001) observed that flumioxazin at a rate of 71 g ai ha^{-1} applied to soil containing 2.5% SOM provided 82 and 63% control of velvetleaf and giant foxtail, respectively, 7 WAT. At 2.5% SOM we observed 93 and 90% control of velvetleaf and giant foxtail, respectively. Lastly, Taylor-Lovell et al. (2002) found 99% control of velvetleaf at 105 g ai ha^{-1} of flumioxazin while only 74 to 78% control of giant foxtail when SOM was 5.6%. At 5.6% SOM we observed 91 and 87% control of velvetleaf and giant foxtail respectively. Observed control reported in field studies was generally lower than what we observed suggesting that differences in control could be due to continual emergence of weeds in field studies whereas weed emergence in our study was during a small period of time. Differences between studies also could be due to environmental effects including rain and soil moisture which has a large impact on flumioxazin efficacy (Ferrell et al 2005.)

The effect of soil pH on weed control varied by species, but all decreased as pH decreased (Figure 3). Control of giant foxtail and velvetleaf was significantly decreased when soil pH was lowered below 6, with control reduced to 76.3 and 75.2%, respectively, at a soil pH of 4. Ferreira et al. (2001) demonstrated at a pH of 5.5 or lower, SOM increased in hydrophobicity which potentially could cause increased herbicide adsorption, which explains the reduction in control of giant foxtail and velvetleaf. In contrast, control of redroot pigweed and barnyardgrass was not affected by soil pH.

Control of redroot pigweed was 100% at pHs lower than 6 because it is susceptible to flumioxazin despite lower concentrations being available for control, which is similar to the results observed for varying levels of SOM. However, barnyardgrass was controlled at pHs less than 6, regardless of observations of its relative tolerance to flumioxazin at higher SOM. Barnyardgrass emergence being unaffected in the non-treated soil, could be due to a reduction in vigor leading to greater susceptibility to herbicide phytotoxicity causing a significant reduction in biomass at lower pH (data not shown).

Control of weed species in field studies was generally lower than that observed in our greenhouse study. Taylor-Lovell et al. (2002) found at 105 g ai ha^{-1} of flumioxazin and a soil pH of 6, 99% control of velvetleaf similar to our findings of 97%. However, they observed 74 to 78% control of giant foxtail while we observed 93% control. Niekamp and Jomson (2000) observed that flumioxazin at a rate of 71 g ai ha^{-1} to soil with a pH of 6.5 provided 82 and 63% control of velvetleaf and giant foxtail, respectively, 7 wks after treatment. At pH of 6.5 we observed 100% and 96% control of velvetleaf and giant foxtail, respectively.

Our results indicate that SOM content and pH can adversely impact the efficacy of a field dose rate of flumioxazin on weed species, while clay content does not. Although, as reported by Alister et al. (2008), the type of clay may be more important than the amount on flumioxazin adsorption, indicating our results may only apply to soils that contain predominantly kaolitic clay. However, flumioxazin has a partial electronegative charge and may form cationic bridge bonds or anionic bonds with aluminum and iron hydroxides which are common to highly weathered soils such as the soils Alister et al. (2008) studied in Chile potentially explaining the differences in their findings with ours and Ferrell et al. (2005). Understanding the effect of different soil characteristics on adsorption of flumioxazin will allow researchers to make soil and weed species specific herbicide recommendations. If the prevalent weed species is redroot pigweed a use rate of 71 g ai ha^{-1} will provide 100% control regardless of SOM content and soil pH. However, if the species of concern is giant foxtail or velvetleaf the use rate of flumioxazin may need to be adjusted appropriately depending on the SOM content and soil pH. Further testing is still necessary to evaluate how soil characteristics affect flumioxazin persistence, which determines residual weed control. Growers can achieve adequate weed control in variable soils by adapting herbicide rates to manage different weed species growing.

SOURCES OF MATERIALS

[1] Plus White Clay, Charles B. Chrystal Co., Inc., 30 Vesey Street, New York, NY 10007.

[2] Premimum play sand, The Quikrete Companies, 3490 Piedmont Road, Atlanta, GA 30329.

[3] Redroot pigweed (*Amaranthus retroflexus* L.) seed, Azlin Seed Service, P.O. Box 914, Leland, MS 38756.

[4] Flumioxazin, Valor SX 51WDG. Valent U.S.A. Corporation, P.O. Box 8025, Walnut Creek, CA 94596.

[5] PROC MIXED, Statistical Analysis Systems (SAS) software, Version 9.1. Statistical Analysis Systems Institute, Inc., P.O. Box 8000, Cary, NC 25712

Table 1. Properties of soils used to evaluate efficacy of flumioxazin.[a]

Soil	Sand	Silt	Clay	SOM	pH	CEC
Sand	97.7	0.07	2.1	0.1	10	0.6
10% Clay	88.2	0.4	11.2	0.2	9.3	1.5
20% Clay	78.8	0.6	20.4	0.2	9	2.9
30% Clay	66.5	2.6	30.7	0.2	8.8	3.7
40% Clay	56.2	3.4	40.2	0.2	8.7	4.9
50% Clay	43.7	5.4	50.6	0.3	8.7	5.4
60% Clay	29.4	9.6	60.7	0.3	8.4	6.4
70% Clay	18.8	9.6	71.1	0.5	8.3	6.9
0.5% SOM	93.3	0.7	5.4	0.6	9.1	2.8
1% SOM	92.7	0.7	5.4	1.2	8.8	3
2% SOM	91.7	0.7	5.4	2.2	7.8	17.1
3% SOM	90.9	0.7	5.4	3	7.8	24.2
4% SOM	89.8	0.7	5.4	4.1	7.3	30
8% SOM	85	1.7	5.4	7.9	7.1	35
16% SOM	77.4	1.4	5.4	15.8	6.9	75.8
32% SOM	62	0.9	5.4	31.7	6.6	121.6
pH 4	68.4	10.8	16.8	4	4.07	6.6
pH 5	69.8	11	15.4	3.8	4.93	7.2
pH 6	68.2	12.6	14.3	4.9	6.07	5.5
pH 7	70.1	10.4	16.8	2.7	7.07	7.1

[a] abbreviations: SOM, soil organic matter; CEC, cation exchange capacity.

Table 2. Seedling count of weed species averaged by soil and regression equation used to model weed control for clay, SOM and pH soils.[a]

Soil	Species	Emergence	Model[b]	r^2
		# Plants		
Clay				
	ABUTH	26	NS	NS
	AMARE	29	NS	NS
	ECHCG	88	NS	NS
	SETFA	18	NS	NS
SOM				
	ABUTH	41	$y = 94.64 - 0.69b$	0.31
	AMARE	70	NS	NS
	ECHCG	86	$y = 95.69 - 1.06b$	0.66
	SETFA	28	$y = 92.03 - 0.89b$	0.48
pH				
	ABUTH	32	$y = 139.24 - (256.33 / b)$	0.78
	AMARE	22	NS	NS
	ECHCG	65	NS	NS
	SETFA	20	$y = 126.43 - (200.38 / b)$	0.53

[a] abbreviations: SOM, organic matter; ABUTH, velvetleaf; AMARE, redroot pigweed; ECHCG, barnyardgrass; SETFA, giant foxtail; NS, not significant.

[b] regression models fit to data include linear ($y = a + bx$) and inverse first-order regression ($y = b + a/x$)

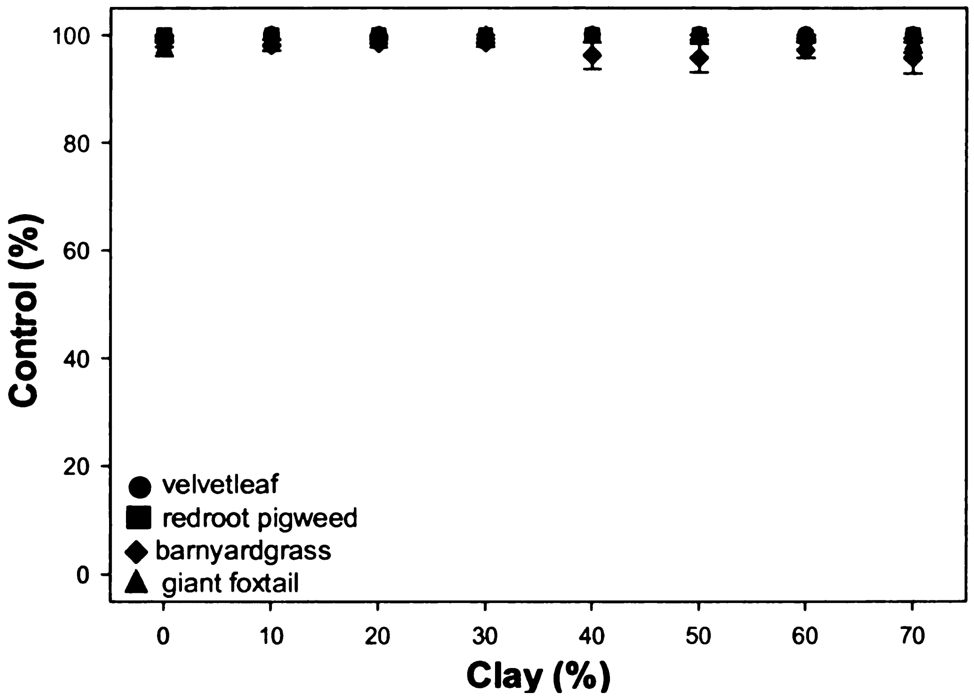

Figure 1. Efficacy of flumioxazin as affected by soil organic matter content. The vertical bars represent the standard error of means.

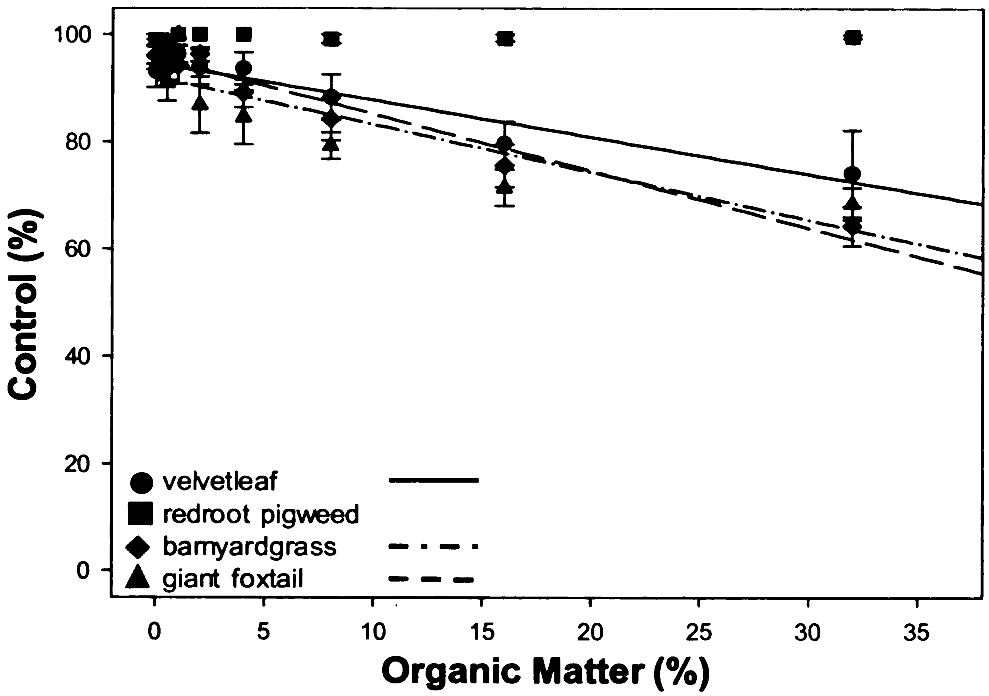

Figure 2. Efficacy of flumioxazin as affected by soil organic matter content. Fitted lines are calculated by linear regression equation for velvetleaf, barnyardgrass and giant foxtail. The vertical bars represent the standard error of means.

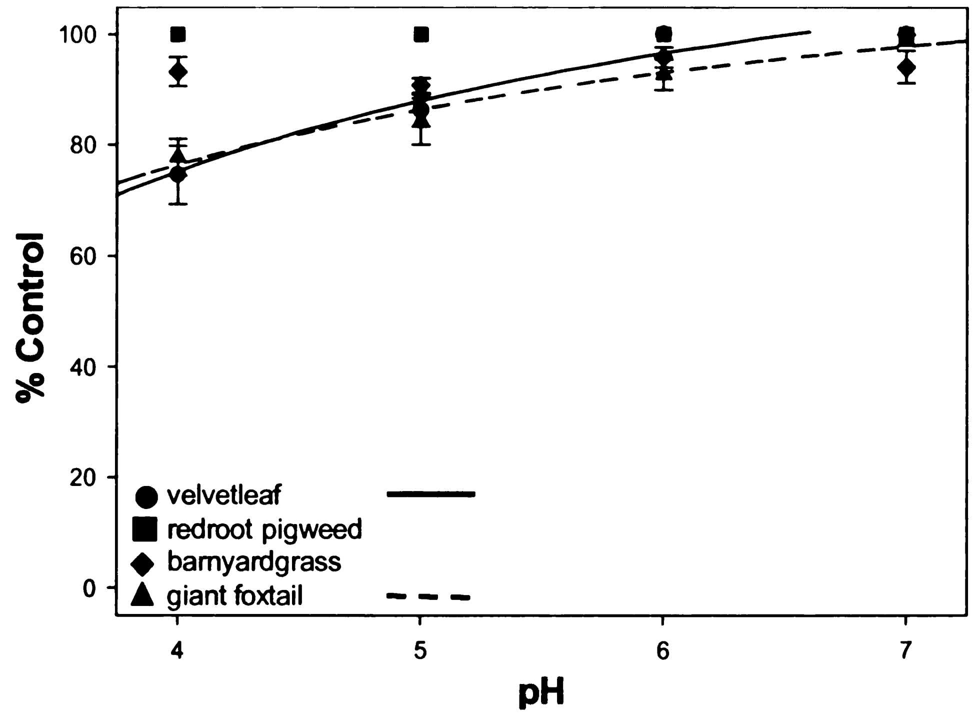

Figure 3. Efficacy of flumioxazin as affected by soil pH. Fitted lines are calculated by the inverse first-order regression equation for velvetleaf and giant foxtail. The vertical bars represent the standard error of means.

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CHAPTER 3

EFFECT SOIL ORGANIC MATTER CONTENT AND SOIL PH ON RESIDUAL CONTROL WITH FLUMIOXAZIN

Abstract: Two greenhouse studies were conducted to evaluate the effect of soil organic matter content and soil pH on flumioxazin residual weed control, utilizing artificial and field soils. Eight wks after treatment flumioxazin gave 0% control of giant foxtail (*Seteria faberi* Herrm.) and velvetleaf (*Abutilon theophrasti* L.) in all soils tested. However, eight wks after treatment 0% control was only observed for common lambsquarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.) when grown in the muck soil or when soil pH was above 7. Control of common lambsquarters and redroot pigweed was 100% for the duration of the experiment, except when soil organic matter content was greater than 3% or soil pH was 7. Control of giant foxtail and velvetleaf decreased as soil organic matter content and soil pH increased. Similar results in control were observed when comparing artificial pH soils to field pH soils, however differences in control were observed between artificial organic matter soils and field organic matter soils. Results indicate that herbicide use rate needs to be adjusted to account for soil type and prevalent weed species.

Nomenclature: Common lambsquarters, *Chenopodium album* L.; flumioxazin; giant foxtail, *Seteria faberi* Herrm.; redroot pigweed, *Amaranthus retroflexus* L.; velvetleaf, *Abutilon theophrasti* L.

Key words: persistence, efficacy, herbicide bio-assay

INTRODUCTION

Flumioxazin, a non-ionic, *N*-phenyl phthalimide herbicide, inhibits chlorophyll biosynthesis by preventing the formation of protoporphyrinogen precursors (Senseman 2007). Currently, flumioxazin is labeled for use in many crops including alfalfa, cotton, peanuts, potato, and soybeans. Flumioxazin is in the protoporphyrinogen oxidase inhibiting family of herbicides used to manage glyphosate and acetolactate synthase resistant weed species due to its unique mode of action (Taylor-Lovell et al. 2002; Clewis et al. 2007; Everman et al. 2009). Weed control with flumioxazin has been shown to vary between locations, on the same species and at the same timing (Taylor-Lovell et al. 2002; Grey and Wehtje 2005; Norsworthy et al. 2009). The differences observed in weed control with flumioxazin may be due in part to variations in the soils to which it is applied.

Interactions between an herbicide, like flumioxazin, and the soil medium are complex. After an herbicide is applied to the soil, it rapidly interfaces with soil components and reaches a relative equilibrium in the soil solution (Monaco et al. 2002). Herbicides that are not sorbed to the soil and are in solution are generally accepted as herbicides available for weed uptake and control (Peter and Weber 1985; Monaco et al. 2002). Therefore, as herbicide adsorption increases, subsequent weed control decreases; however, the amount and types of particles in a soil and the soil pH can greatly affect herbicide adsorption.

Non-ionic herbicides, such as flumioxazin, have limited interactions with soil particles (Calvet 1980; Kah and Brown 2006). Adsorption of non-ionizable herbicides in soils is mainly attributed to one phenomenon, hydrophobic binding, which is the result of decrease in entropy due to partitioning of the hydrophilic herbicide in the hydrophobic regions of soil (Calvet 1980; Koskinen and Moorman 1992). Soil organic matter (SOM) and the interlayer of clays provide conditions necessary to adsorb flumioxazin due to the hydrophobicity of the particles. Ferreira et al. (2001) found SOM to increase in hydrophobicity, when the soil pH was lower than 5, which could increase flumioxazin adsorption. SOM tends to solubilize at pH values greater than 7 and would decrease available sites for adsorption. Therefore, interactions between SOM content and pH have a large influence on flumioxazin adsorption, subsequently affecting its persistence.

Soil-applied herbicides, including flumioxazin, need to persist long enough to provide adequate weed control, but not so long as to interfere with subsequent crops or cause negative impacts on the environment. The persistence of an herbicide in a soil is a function of its loss from the soil system and degradation (Hurle and Walker 1980; Peter and Weber 1985; Monaco 2002). Herbicide can be lost from a system due to volatilization, leaching, surface runoff, and loss of soil with sorbed herbicide (Hance 1980; Monaco et al. 2002; Kah and Brown 2006). Herbicide breakdown is due to the combination of chemical decomposition, photodecomposition, and biological decomposition (Torstensson 1980; Kwon et al. 2004). Soil microbes readily degrade flumioxazin and are the main pathway of degradation when soil solution pH is not greater than 7 (Ferrell et al. 2005). When soil pH is greater than 7, hydrolysis increases and becomes the major degredation pathway (Kwon et al. 2004). Soils high in organic matter are reported as having greater microbial activity which would be expected to increase degradation of flumioxazin (Goyal et al. 1999; Kah and Brown 2006). Conversely, an increase in SOM would in turn increase herbicide adsorption, making the herbicide unavailable for microbial degradation. For this reason, determining the persistence of flumioxazin is difficult without experimentation.

Researchers have found the adsorption of flumioxazin to be correlated with SOM and certain types of clay particles using batch equilibrium and field experiments (Ferrell et al. 2005; Alister et al. 2008). However, these experiments focused extensively on herbicide adsorption. Although weed control with flumioxazin is in part affected by adsorption, it is also dependent on the interaction of the soil, soil microbes, and the weeds themselves. To determine the effect of soil type on weed control, field studies are often conducted but these are complicated due to soil variations within a study, differences in weather, spatial variation in weed population and density, and a lack in variation of soil parameters tested such as SOM or soil pH (Walker 1980; Kah and Brown 2006). Two greenhouse studies were conducted to evaluate the effect of SOM and soil pH on the residual control of flumioxazin.

MATERIALS AND METHODS

Two separate greenhouse studies were conducted in 2009 at Michigan State University to investigate the effect of 1) SOM and 2) soil pH on flumioxazin residual control. The studies were arranged in a randomized complete block with a factorial arrangement of treatments and were repeated in time. Factors included: four weed species, two herbicide treatments (treated with flumioxazin or non-treated), and five planting times (0, 2, 4, 6, and 8 wks after treatment (WAT)) with 3 replications. The soils utilized for the study were either field soils collected based on desired properties with no prior history of flumioxazin application or soils that were artificially adjusted to provide a range of values for the characteristics investigated. Soils collected from the field were taken from uniform areas in respective locations from the top 13 cm of soil. The adjusted soils will hereafter be referred to as 'lab soils'. Soil particle size distribution, pH, cation exchange capacity, and SOM content were determined for each soil used (Table 3). Field soils were investigated to determine if results from the lab soils were representative of expected field results.

Organic Matter Soils. Organic soil was obtained from the Michigan State University Muck Farm and is described as a Houghton muck soil derived from reed sedge plant materials containing 82% organic matter by mass. The organic soil was passed through a 2-mm sieve to remove large debris prior to mixing and was added to sand on a dry weight to weight basis to achieve 0, 1, and 3% SOM. Field soils of 3% SOM (Capac loam, fine-loamy, mixed, mesic Aeric Ochraqualfs) and the unadjusted organic soil were also included for comparison.

pH Soils. A base soil of pH 6 from a Capac loam (fine-loamy, mixed, mesic Aeric Ochraqualfs) in a corn-soybean rotation was adjusted to desired pHs of 5 and 7 using H_3PO_4 and $Ca(OH)_2$, respectively. As with the organic soil, the base soil was passed through a 2-mm sieve prior to acid or base treatment to remove debris and large particles. To adjust the pH, calculated amounts of acid and base were dissolved in 3 L of de-ionized water and added to 8 kg of soil to create a soil solution. Once in a solution, soil was mixed thoroughly and spread over a large surface area to allow for rapid drying to prevent prolonged anaerobic conditions. Soil was mixed every 3 hours until gravimetric water had evaporated. Field soils of pH 5 from a Capac loam (fine-loamy, mixed, mesic Aeric Ochraqualfs) and pH 7 from a Spinks loam (mixed, mesic Psammentic Hapludalfs) both from corn-wheat-soybean rotations currently planted to wheat underseeded with red clover were also included for comparison.

Weed species consisted of velvetleaf (*Abutilon theophrasti* Medik.), common lambsquarters (*Chenopodium album L.*), and giant foxtail (*Setaria faberi Herrm.*) collected from local populations in fields under corn and soybean rotations field at the Michigan State University Agronomy Farm. Redroot pigweed seed (*Amaranthus retroflexus L.*) was obtained from a commercial source[1]. Seeds of each species were planted at 150 seeds per pot except for velvetleaf which was planted at 65 seeds per pot to obtain a target population of 50 seedlings. Lab soil and field soil were added to 7 by 7 by 6.4 cm pots brought to field capacity, and were either left non-treated or were treated with formulated flumioxazin[2] at 71 g ai ha^{-1} with a track sprayer delivering 187 L ha^{-1}. Once treated, pots were placed in a greenhouse maintained at 25 ± 5 C° with a 16 hour photoperiod of natural sunlight supplemented with high-pressure sodium lighting to provide 1,000 µmol m^{-2} photosynthetic photon flux. Weed seeds were planted by randomly scattering one of the four species onto the soil surface then incorporating them with forceps to a depth of 0.5 to 1 cm at 0, 2, 4, 6, and 8 WAT. At each timing weeds were planted into treated and non-treated soil to evaluate residual control of flumioxazin and to assure that emergence of weeds in treated soils was due solely to chemical control and not changes in the soil. The day after application, 0.64 cm of water was added over the top of all pots to simulate incorporation by rainfall with subsequent moisture provided by sub-irrigation and weekly topical watering of 0.64 cm.

Data Collection and analysis. Emerged weeds were counted and removed from pots weekly using forceps carefully removing the growing point to minimize soil mixing. Seedling counts were taken for 3 wks after each respective planting with 94% of weed emergence taking place between planting and the first count at 1 wk after planting. Weed control was calculated using the equation:

$$y = 100 - \left(\left(\frac{t}{n}\right)100\right)$$

where y is percent control, t is number of weeds that emerged in treated soil and n is the average emergence of weeds in the respective non-treated soil. Weed control was analyzed with SAS[4] using PROC MIXED to test for significant interactions between runs, weed species, time after application, and soil effect on weed control ($P<0.05$). No significant differences were found between experiments, therefore data were pooled. Due to significant species by soil by time interactions, and the large main effect of soil characteristic, weed control was evaluated separately by soil characteristic with comparisons among species. Weed control for species as affected by soil differences was fit with trend lines using Sigma Plot software[3] and was modeled using either linear or logistic regression. Logistic regression fit to data is described as:

$$y = \frac{a}{1 + \left(\frac{x}{b}\right)^{c}}$$

where y is weed control achieved at level x with an upper asymptote of a (with forced upper limit of 100) and slope of c with the point of inflection b (Ratkowsky 1990; Seefeldt et al. 1995; Mueller-Warrant 1999). Time elapsed in wks until a 50% reduction in weed control was observed (I_{50}) was calculated for each soil and weed species using the respective regression equation to compare weed control between species and soils (Seefeldt et al. 1995).

Results and Discussion

Weed control with flumioxazin varied by soil type and generally decreased over time. Residual weed control was best modeled as a logistic response (24 of 40 models) with 4 models sufficiently explained by linear regression and 12 with no significant regression model (Table 4 and 5). Models that were significant ranged in coefficient of determination values from 0.72 to 0.98 but in most cases were 0.9 or higher.

Organic Soils. Organic matter content greatly influenced control of weeds species by flumioxazin (Figure 4). Weed control at 0 WAT ranged from 77.4 to 100% with I_{50} values ranging from 1.7 to 13 (Table 4). Lab soil with 0% SOM (100% sand material) had relatively no effect on weed control and not until 4 WAT was control reduced for giant foxtail and velvetleaf (Figure 4). Lab soil with 1% SOM resulted in decreased control of velvetleaf after application and by 2 WAT, control was reduced by 23.3%.

Control of giant foxtail was affected by SOM content, with reduced control at 2 WAT at 1% SOM compared to 4 WAT for 0% SOM. Control of common lambsquarters and redroot pigweed was not reduced during the duration of the experiment at 1% SOM lab soil, however control was reduced when SOM was 3% and seeds were planted 4 WAT. Initial and residual control of giant foxtail and velvetleaf was greater at 1% SOM than at 3% SOM, and was also greater in the field soil than the lab soil. Control of common lambsquarters and redroot pigweed in field soil showed no differences, however reduced control was observed as SOM changed in lab soil (Figure 4).

Digression between results of lab and field soil at 3% SOM could be due to the type of organic matter in each soil. The SOM in the organic soil used to adjust the lab soil could have a greater affinity for flumioxazin (more hydrophobic) than the SOM found in the field soil (Torrents and Jayasundera 1997; Walker and Austin 2003; Kah and Brown 2006). Differences in weed control in the two soils also could be due to the microbial populations associated with the soil with populations in the lab soils derived from the organic soil more apt to metabolize flumioxazin (Torstensson 1980) or cause a synergistic control of weeds (André and Rahe 1992). Lastly, control was greatly affected by the organic soil with I_{50} values of 7.3, 1.7, 6.9, and 1.9 for common lambsquarters, giant foxtail, redroot pigweed, and velvetleaf, respectively (Table 4). Weed control at 0 WAT for the organic soil was 80 and 77.4% for giant foxtail and velvetleaf respectively which was the lowest initial control observed for either species (Figure 4, 5).

It was observed that weed control generally decreased as SOM content increased. Control of weed species in response to SOM was similar for the larger seeded broadleaf and grass weed species (giant foxtail and velvetleaf) and the smaller seeded broadleaves (common lambsquarters and redroot pigweed). However, control of velvetleaf tended to be slightly higher than giant foxtail control with the exception of at 1% SOM lab soil, where the I_{50} value for giant foxtail was 0.58 greater than velvetleaf.

Soil pH. The residual control of flumioxazin varied greatly by soil pH and species (Figure 5). Initial weed control ranged from 90.6 to 100% and I_{50} values ranged from 2.37 to 5.93 (Table 5). For both lab and field soil at pH 5, control of common lambsquarters and redroot pigweed remained at 100% for 8 wks while giant foxtail and velvetleaf control decreased (Figure 5). Control of giant foxtail and velvetleaf at pH 5 lab and field soil, began to decrease 2 WAT with I_{50} values of 5.1 and 4.8, respectively. Minimal differences were observed between the lab and field soil at pH 5 for weed control, with the greatest difference observed in I_{50} values for giant foxtail being 0.57 WAT. Control of common lambsquarters and redroot pigweed was 100% for the duration of the study at a soil pH of 6, similar to results at a soil pH of 5. Control of giant foxtail and velvetleaf at pH 6 decreased with a 47 and 37% reduction in I_{50} values, respectively. Loss in weed control from pH 5 to 6 could be due to an increase in the ability of the microbial population to degrade the herbicide (Corbin and Upchurch 1967; Leahy and Colwell 1990; Anderson and Domsch 1992). Control of weed species at pH 7 lab and field soil were similar and only differed by I_{50} values being 0.18 to 0.48 lower for all species except giant foxtail (1.46) in the field soil. Control of common lambsquarters and redroot pigweed did not decrease until 4 WAT at pH 7, regardless of being lab or field soil. However, at pH 7 lab and field soil, control of giant foxtail and velvetleaf were similar to control at pH 6. Reduction in control of common lambsquarters and redroot pigweed but not giant foxtail and velvetleaf could be due to a slight decrease in herbicide concentration caused by hydrolysis at the higher pH (Kwon et al. 2004). This decrease in herbicide concentration however, was not enough to cause a significant reduction in control of the larger seeded weed species.

Control of all species decreased over time as soil pH increased (Figure 5). Reduction in control of common lambsquarters and redroot pigweed only occurred at the highest soil pH tested; however, control of giant foxtail and velvetleaf decreased when pH was raised from 5 to 6. Comparing species response to soil pH, it was observed that similar to SOM soils, common lambsquarters and redroot pigweed had similar responses while giant foxtail and velvetleaf responded similarly. The reason for differences between the two pairs of weed species and similarities within the pairs could be attributed to weed seed size which has been shown to influence herbicide uptake (Scott and Phillips 1971).

Initial weed control and weed control over time decreased as SOM content increased. Reductions in weed control with increasing SOM content can be attributed to several factors including an increase in available sites for hydrophobic bonding or greater amounts of microbial activity. Increasing the soil pH tended to decrease the time needed to reach a 50% reduction in control, but did not have an appreciable effect on initial control. Previous research has shown little to no differences in adsorption of flumioxazin due to soil pH (Ferrell et al. 2005; Alister et al. 2008). The authors attributed this to the non-ionic nature of flumioxazin. Our research shows that increasing solution pH decreases flumioxazin residual control, indicating that the reduction in residual control is potentially due to an effect on the microbial degradation of the herbicide. When comparing lab pH soils to field pH soils, similar control was observed, while differences in control were observed when comparing lab SOM soils to field SOM soils indicating the origin of the SOM has a critical effect on flumioxazin adsorption. By understanding the effect of different soil characteristics on flumioxazin residual control, researchers will be able to make soil and weed species specific herbicide recommendations. Adjusting herbicide recommendations due to soil type and prevalent weed species will potentially reduce herbicide use or improve weed control by matching the necessary rate to the situation.

SOURCES OF MATERIALS

[1] Premimum play sand, The Quikrete Companies, 3490 Piedmont Road, Atlanta, GA 30329.

[2] Redroot pigweed (*Amaranthus retroflexus* L.) seed. Azlin Seed Service, P.O. Box 914, Leland, MS 38756.

[3] Flumioxazin, Valor SX 51WDG. Valent U.S.A. Corporation, P.O. Box 8025, Walnut Creek, CA 94596.

[4] PROC MIXED, Statistical Analysis Systems (SAS) software, Version 9.1. Statistical Analysis Systems Institute, Inc., P.O. Box 8000, Cary, NC 25712.

Table 3. Properties of lab and field soils to evaluate flumioxazin's persistence.[a]

Soil	Sand	Silt	Clay	SOM	pH	CEC
Lab Soil pH 5	50.4	31	16.8	2.8	5.1	21
Field Soil pH 5	49.8	36.8	16.8	2.3	4.9	6.6
Field Soil pH 6	37.7	33.0	23.5	3.2	6	19.6
Lab Soil pH 7	48.2	29.4	20.8	3	7	19.7
Field Soil pH 7	40	29.6	27.8	2.6	7.1	12
Lab Soil 0% SOM	97.7	0.1	2.1	0.1	10	0.6
Lab Soil 1% SOM	92.7	0.7	5.4	1.2	8	3
Lab Soil 3% SOM	90.9	0.7	5.4	3	7.6	24.2
Field Soil 3% SOM	37.7	33	23.5	3.2	6	19.6
Muck	7.3	9.2	1.8	81.7	6.4	142.3

[a] abbreviations: SOM, soil organic matter; CEC, cation exchange capacity.

Table 4. Seedling emergence of various weed species averaged over time, I_{50}, and regression equation used to model weed control for organic matter soils.[a]

Soil	Species	Emer	I_{50}	Model[b]	r^2
LS 0% SOM					
	ABUTH	36.7	5.7	$y = 100 / 1 + (x / 5.67)^{9.85}$	0.98
	AMARE	39.7	NS	NS	NS
	CHEAL	33.5	NS	NS	NS
	SETFA	41.6	6.3	$y = 96.48 / 1 + (x / 6.29)^{10.36}$	0.98
LS 1% SOM					
	ABUTH	37.5	5.4	$y = 96.86 / 1 + (x / 5.51)^{4.29}$	0.95
	AMARE	38.9	NS	NS	NS
	CHEAL	35.5	NS	NS	NS
	SETFA	40.4	4.6	$y = 97.13 - 10.22x$	0.90
LS 3% SOM					
	ABUTH	38.9	4.4	$y = 93.63 - 10x$	0.97
	AMARE	38.3	11.6	$y = 100 / 1 + (x / 11.57)^{3.63}$	0.72
	CHEAL	35.5	13	$y = 100 / 1 + (x / 13.04)^{2.88}$	0.92
	SETFA	40.6	3.5	$y = 90.7 - 11.65x$	
FS 3% SOM					
	ABUTH	34.5	2.9	$y = 97.76 / 1 + (x / 2.92)^{1.82}$	0.81
	AMARE	32.5	NS	NS	NS
	CHEAL	32.6	NS	NS	NS
	SETFA	38.5	2.8	$y = 92.1 / 1 + (x / 3.03)^{2.4}$	0.94
Organic Soil					
	ABUTH	35	1.9	$y = 77.42 / 1 + (x / 2.44)^{2.6}$	0.95
	AMARE	38.9	6.9	$y = 100 / 1 + (x / 6.92)^{9.28}$	0.97
	CHEAL	34.8	7.3	$y = 100 / 1 + (x / 7.27)^{7.29}$	0.98
	SETFA	37.5	1.7	$y = 80.09 / 1 + (x / 1.99)^{3.12}$	0.93

[a] abbreviations: Emer, emergence; SOM, soil organic matter; FS, field soil; LS, lab soil; ABUTH, velvetleaf; AMARE, redroot pigweed; CHEAL, common lambsquarters; SETFA, giant foxtail; I_{50}, wks until a 50% reduction in control; NS, not significant.

[b] models fit to data include linear ($y = a + bx$) and logistic regression ($y = \frac{a}{1+\left(\frac{x}{b}\right)^{c}}$).

Table 5. Seedling emergence of various weed species averaged over time, I_{50}, and regression equation used to model weed control for pH soils.[a]

Soil	Species	Emer Plants	I_{50}	Model[b]	r^2
LS pH5					
	ABUTH	34.9	4.49	$y = 94.37 / 1 + (x / 4.53)^{14.76}$	0.95
	AMARE	33.1	NS	NS	NS
	CHEAL	32.6	NS	NS	NS
	SETFA	41.8	5.60	$y = 93.55 / 1 + (x / 5.74)^{5.58}$	0.9
FS pH 5					
	ABUTH	34.1	4.49	$y = 93.98 / 1 + (x / 4.53)^{14.63}$	0.98
	AMARE	34.2	NS	NS	NS
	CHEAL	32	NS	NS	NS
	SETFA	39	5.03	$y = 95.68 / 1 + (x / 5.11)^{5.55}$	0.96
FS pH 6					
	ABUTH	34.5	2.85	$y = 97.76 / 1 + (x / 2.92)^{1.82}$	0.81
	AMARE	32.5	NS	NS	NS
	CHEAL	32.6	NS	NS	NS
	SETFA	38.5	2.82	$y = 92.1 / 1 + (x / 3.03)^{2.4}$	0.94
LS pH 7					
	ABUTH	35.8	3.25	$y = 97.67 / 1 + (x / 3.27)^{9.26}$	0.97
	AMARE	34	5.86	$y = 100 / 1 + (x / 5.86)^{5.94}$	0.95
	CHEAL	34.3	5.93	$y = 100 / 1 + (x / 5.93)^{6.69}$	0.97
	SETFA	42.9	3.83	$y = 90.63 - 10.61x$	0.96
FS pH 7					
	ABUTH	35.2	2.78	$y = 99.13 / 1 + (x / 2.79)^{3.31}$	0.98
	AMARE	32	5.64	$y = 100 / 1 + (x / 5.64)^{5.71}$	0.88
	CHEAL	31.8	5.75	$y = 100 / 1 + (x / 5.75)^{5.24}$	0.87
	SETFA	38	2.37	$y = 92.98 / 1 + (x / 2.62)^{1.53}$	0.91

[a] abbreviations: Emer, emergence; FS, field soil; LS, lab soil; ABUTH, velvetleaf; AMARE, redroot pigweed; CHEAL, common lambsquarters; SETFA, giant foxtail; I_{50}, wks until a 50% reduction in control; NS, not significant.

[b] models fit to data include linear ($y = a + bx$) and logistic regression ($y = \frac{a}{1+\left(\frac{x}{b}\right)^{c}}$).

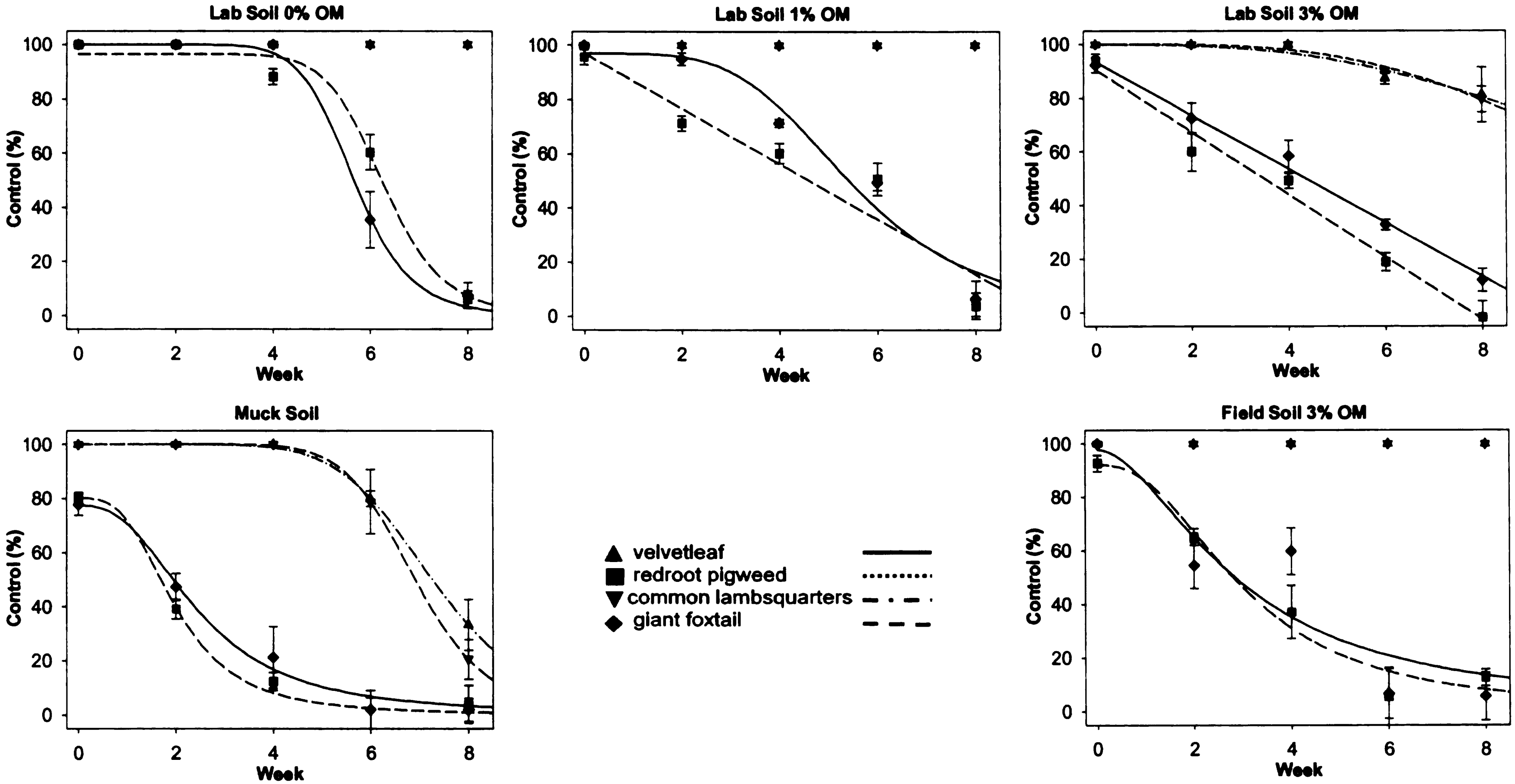

Figure 4. Weed control of velvetleaf (▲), redroot pigweed (■),common lambsquarters (▼), and giant foxtail (◆), with flumioxazin as affected by percent organic matter over time for lab and field soils. Fitted lines are calculated by linear or logistic regression for velvetleaf, redroot pigweed, common lambsquarters , and giant foxtail. Error bars represent the standard deviation of means.

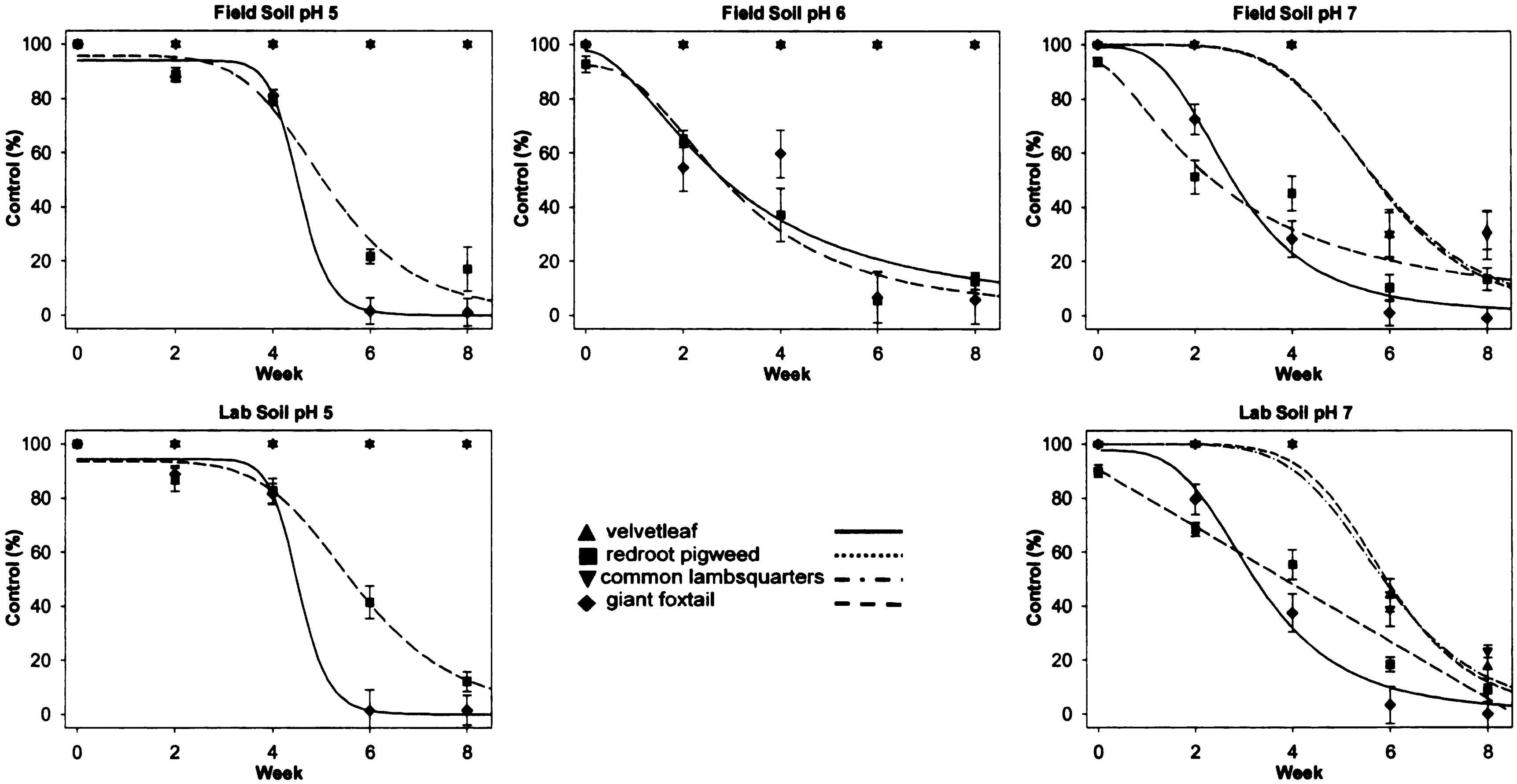

Figure 5. Weed control with flumioxazin as affected by soil pH over time. Weed control of velvetleaf (▲), redroot pigweed (■),common lambsquarters (▼), and giant foxtail (♦), with flumioxazin as affected by soil pH over time for lab and field soils. Error bars represent the standard deviation of means.

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CHAPTER 4

TOLERANCE OF POTATO MINI-TUBERS TO PREEMERGENCE AND POSTEMERGENCE HERBICIDES

Abstract: Current cultural practices for producing potatoes from mini-tubers are adopted from potatoes grown from cut seed pieces, including weed management programs. Mini-tubers are physiologically different from cut seed pieces and may differ in tolerance to herbicides labeled for potatoes. Field trials were conducted at the Montcalm Research Farm near Entrican, MI in 2008 and 2009 to evaluate the effect of herbicides labeled for potatoes on three cultivars of potato mini-tubers. Preemergence treatments of *S*-metolachlor plus linuron caused chlorosis injury in both years whereas rimsulfuron and dimethenamid-p only caused injury in 2009. Imazosulfuron applied preemergence and treatments containing postemergence application of rimsulfuron with or without metribuzin following preemergence applications of *S*-metolachlor plus linuron reduced yields in 2008 and 2009, while in 2009, treatments of dimethenamid-p, *S*-metolachlor, pyrasulfatole and pendimethalin alone reduced yields. Results from this study indicate greater yield losses when multiple stress factors are present. Several herbicides including linuron, metribuzin, and rimsulfuron were observed to be safe for plants grown from mini-tubers when applied preemergence.

Nomenclature: Dimethenamid-p; glyphosate; imazosulfuron; pyrasulfatole; linuron; metribuzin; potato, *Solanum tuberosum*; rimsulfuron; *S*-metolachlor.

Key Words: sensitivty, plant stress, delayed preemergence treatment.

INTRODUCTION

Unique to potato production is the utilization of whole or cut potato tubers as the seed source for commercial production. Potato plants grown from tuber pieces have increased vigor as compared to plants grown from true seed and additional benefits such as production of "true-to-type" plants (Struik and Wiersema 1999). However, potato tuber pieces may harbor harmful pathogens such as *Phytophthora infestans* (late blight) and potato virus Y (PVY) (Allen et al. 1992; Bus and Wustman 2007; Whitworth and Davidson 2008). Planting infected tuber pieces may result in the spread of disease. Depending on the infection cycle of the pathogen, the spread of disease can be influenced by cultural practices and the incidence of insect pests. PVY can rapidly spread via aphid vectors (Basky and Almási 2005; Valkonen 2007) increasing the importance of removing contaminated seed. Potato seed certification programs to regulate the sale and production of seed potatoes.

Technological advancements and increased availability of tissue culture have allowed for the production of *in vitro* plantlets to create pathogen free pre-nuclear (seed planted to generate nuclear or first generation seed) plant material (Struik and Wiersema 1999). Over time, production of early generation material has changed and potato plantlets are now used to produce micro and mini-tubers as the preferred initial seed source for commercial production. Production of potato mini-tubers has received much attention and consideration, resulting in research with the intent to maximize production and quality of mini-tubers (Ranalli et al. 1994; Struik and Lommen 1999). Although mini-tubers are similar to cut seed pieces used in production, there are unique difficulties in utilizing them. Researchers have observed agronomic differences when planting mini-tubers as opposed to cut seed pieces, such as reduced stem number, delayed emergence, and reduced canopy closure (Struik and Lommen 1999). Research done by Ranalli et al. (1994) showed that 51 days after planting plants grown from mini-tubers provided only 37.8% canopy closure, 34.6% less cover than plants grown from cut seed pieces reducing the crops ability to compete with weeds (Monaco et al. 2002). The potato plants are less able to compete with weeds due to the reduction in the crops growth. This makes preemergence and postemergence applications of herbicides often a necessity.

Preemergence and postemergence herbicide applications are effective methods of weed control. Researchers have noted injury and yield reductions caused by several herbicides (Bailey et al. 2002; Richardson et al. 2004; Hutchinson et al. 2005; Hutchinson et al. 2006) this indicates the importance of careful herbicide selection to control weeds and reduce crop injury to maximize yield. Potato cultivars have variable sensitivity to herbicides attributed to differences in absorption, translocation, or metabolism of the herbicide (Hinks 1977; Bailey et al. 2003). Herbicide sensitivity, specifically to metribuzin, has been reported to be an inheritable trait with a relative high frequency in selected progeny making it a prevalent recurring trait (De Jong 1983). Metribuzin was reported by Friesen and Wall (1984) to cause injury and yield reductions of 22 different potato cultivars including reduced yields of the cultivar 'Alaska Red' by 68% with preemergence applications of metribuzin at 1 kg ai/ha. Cultivar sensitivity was reported by Hutchinson et al. (2005) of the cultivar 'Ranger Russet' to preemergence applications of flumioxazin from 53 to 140 g ai/ha, which caused total yield reductions of 13 to 20%. Cultivar sensitivity adds difficulty in managing weeds in potatoes due to potential yield reductions which limit the already small number of herbicides available for them.

The physiological differences of potato mini-tubers from cut seed pieces have been recognized as a concern by researchers when utilizing cut seed piece management practices (Lommen and Struik 1994; Ranalli et al. 1994; Struik and Lommen 1999). Mini-tubers have a lower level of carbohydrate reserves and a greater surface area to volume ratio when compared to cut seed pieces. These differences have been found to cause plants grown from mini-tubers to emerge later (Ranalli et al. 1994; Struik and Lommen 1999), have generally only one stem (Ahloowalia 1994; Struik and Lommen 1999), and produce smaller sprouts (Lommen 1994). Mini-tubers producing smaller sprouts and plants which are less vigorous could be more susceptible to herbicide injury (Scott and Phillips 1971). A study was designed to evaluate the various effects herbicides have on yield and quality of seed potatoes produced by mini-tubers and whether potato mini-tubers exhibit cultivar sensitivity to herbicides.

MATERIALS AND METHODS

Field trials were conducted in 2008 and 2009 at the Montcalm Research Farm in Entrican, MI. Soil type at the farm was a Montcalm and McBride loamy sand and sandy loam (mesic Haplic Glossudalf) with a soil pH of 5.6 and organic matter content of 1.5% with the previous crop in both years being field corn. Spring tillage consisted of disking three times and field cultivating prior to planting. Cultivars planted were ‘Atlantic’, and 2 Frito-Lay (FL) cultivars ‘FL1’ and ‘FL2’, which are chipping cultivars commercially planted in Michigan. Mini-tubers planted each year were generated from the same producer and averaged 1.5 to 2 cm in diameter. Mini-tubers were planted on May 12, 2008 and on May 11, 2009 with a one row plot planter into rows 86.4 cm apart, 6.4 cm deep, at 20.3 cm spacing. Plots were 6.1 m by 2.6 m in dimension containing 3 rows per plot. Plots were hilled in both years before early bulking (9 wks after planting) and maintained weed free by hand weeding to ensure effects observed were due to treatments and not weed competition. Supplemental irrigation was applied using a center pivot system and fertilizer was applied according to Michigan State University recommendations (Warncke et al. 2009). The experimental design was a randomized complete split-strip block with 4 replications with whole plot factor as herbicide treatment and sub plot factor as cultivar. Herbicide treatments were applied with a CO_2-pressurized backpack sprayer delivering 187 L/ha at rates recommended for use in Michigan (Table 6). Preemergence herbicides were applied as a delayed application on May 28, 2008 and May 29, 2009. Postemergence treatments were applied on June 24, 2008 and July 8, 2009.

Injury ratings were visually assessed 1, 2, and 4 wks after preemergence application and rated 1 and 2 wks after postemergence application on a 0-100% scale with 0% corresponding to no injury and 100% being plant death (Frans et al. 1986). Potatoes were harvested on September 18, 2008 and on September 10, 2009. Yield was determined from 3 m of the 6.1 m row. Tubers were graded by yield and quantity of US #1 tubers (3.8cm – 8.3cm in diameter and less than 340g), smaller than US #1, larger than US #1 and tubers with defects. Data was analyzed using the MIXED procedure in SAS at a 0.05 significance level with treatment means separated by Fisher's Protected LSD. ANOVA assumptions of normality of data were met by arcsine square root transforming injury ratings and log transforming non-normal yield data. Non-transformed means are presented for clarity.

RESULTS AND DISCUSSION

Crop emergence and development varied in 2008 and 2009 due to mini-tuber dormancy and below average temperatures in 2009. Crop emergence was variable by cultivar in both 2008 and 2009. Emergence of the FL lines in 2008 was similar 1 wk after preemergence herbicide applications, but differed in their emergence relative to each other in 2009 (Table 7). The Atlantic cultivar in 2008 had yet to emerge 1 wk after preemergence herbicide application, whereas in 2009 were almost fully emerged (Table 7). Early season growth was similar in 2008 and 2009. However, in 2009 Michigan experienced its second coldest July and growing degree day accumulation after June until crop senescence was on average 150 units less than in 2008. Overall, less than ideal growing conditions in 2009 caused irregular crop growth and delayed postemergence applications by 2 wks compared to 2008.

Crop Injury. Significant year by treatment interactions were observed for all injury ratings. Additionally a year by treatment by cultivar interaction was observed for injury 2 wks after emergence in 2008. Injury observed in both years for all treatments consisted of leaf chlorosis and malformation of leaf tissue and was significant by treatment for 1 and 2 wks after emergence in both years (Table 8). Injury reported 1 wk after preemergence application in 2008 does not include the Atlantic cultivar because it had not emerged.

Greater injury was observed in 2008 than 2009 for most treatments. In 2008, the greatest injury 1 wk after preemergence application, 16%, was observed following *S*-

metolachlor applied alone whereas in 2009 injury was less than 1% for the same treatment (Table 8). Injury observed in 2008, 1 wk after preemergence application was generally higher than injury in 2009 (Table 8). Differences in injury in 2008 and 2009 could be due to delayed emergence of plants in 2009 because of a decrease in interception of chemical by growing shoots (Bailey et al. 2002). Treatments of linuron, metribuzin, pendimethalin, rimsulfuron, and imazosulfuron alone caused minimal injury 1 wk after application in both years (Table 8). There was a significant interaction of treatment and cultivar for injury 2 wks after preemergence application in 2008 but not in 2009. This is due to minimal observed injury on the Atlantic cultivar which had delayed emergence (Table 8). Significant amounts of injury were observed with treatments of *S*-metolachlor plus linuron in both FL cultivars ranging from 5 to 13% in 2008 and 5 to 8% in 2009 (Table 8). Similarly, in 2009, 5% injury was observed following application of rimsulfuron or dimethenamid-p. Early season injury following dimethenamid-p on cut seed pieces has been previously reported (Richardson et al. 2004). Treatments of linuron, metribuzin, pendimethalin, and imazosulfuron alone caused no injury 2 wks after application and through the remainder of the season. Injury in 2008 appeared to be the greatest 1 wk after preemergence herbicide treatment and decreased slightly 2 wks after treatment with injury becoming transient by 4 wks. However, injury in 2009 was less extensive 1 wk after preemergence application and increased in severity at 2 wks. Although weather differences in years caused variations in the effect of treatments on potato mini-tubers, treatments of *S*-metolachlor plus linuron sometimes caused early season injury while treatments of linuron, metribuzin, pendimethalin, and imazosulfuron alone caused no significant injury early in the season.

Crop Yield. Significant year by treatment interactions were observed for all yield parameters measured making analysis by year necessary. Treatment by cultivar interactions were not significant for yield parameters measured thus data were pooled across cultivars. No significant differences in yield or tuber quantity for larger and smaller than US #1 sized tubers were observed (data not shown). Similarly, no significant differences were observed for tubers categorized as having abnormal growths or that were odd in shape (data not shown). Herbicide treatment effects on yield of US #1 tubers were significant in both 2008 and 2009 (Table 9). Treatments of metribuzin, linuron, and rimsulfuron did not reduce yields of US #1 tubers which is consistent with previous research on cut seed piece potato production (Ackley et al.1996; Renner and Powell 1998; Bailey et al. 2002). Imazosulfuron reduced yield of US #1 tubers from the highest yielding treatment by 41.2% and 20.3% in 2008 and 2009 respectively. Reductions of US #1 tuber yield by imazosulfuron are most likely due to its effect on tuber yield per plant since it reduced tuber count per plant by 30.4% compared to the highest yielding treatment (Table 9). Although yields of US #1 tubers were reduced both years by imazosulfuron, in neither year was visual injury greater than 2%. Early season injury was observed in both years by treatments of *S*-metolachlor plus linuron applied together. However, yield reductions were only observed when *S*-metolachlor plus linuron was followed by a postemergence application of rimsulfuron alone or with metribuzin in 2008, and only when followed by rimsulfuron plus metribuzin in 2009. US #1 tuber yield per plant could account for yield reductions observed in 2008 due to *S*-

metolachlor plus linuron followed by rimsulfuron plus metribuzin which reduced tuber count by 23.9% compared to the highest yielding treatment.

Compared to the highest yielding treatment in 2009, root or shoot inhibitors including dimethenamid-p, pyrasulfatole, *S*-metolachlor, and pendimethalin applied alone reduced yields of US #1 tubers from 14.7% to 22.5% and was not consistent with early season injury. Root or shoot growth inhibitors when applied in combination with other herbicides also reduced yields of US #1 tubers in 2009 with the exception of *S*-metolachlor when applied with linuron plus metribuzin. *S*-metolachlor plus metribuzin plus pendimethalin with or without glyphosate caused the greatest yield reductions of US #1 tubers in 2009 at 24.2 and 25.5%, respectively, indicating that the combination of root and shoot growth inhibitors had a negative effect. Although tuber yield per plant was not significant in 2009, all treatments that reduced yields of US #1 tubers compared to the highest yielding treatment had 14.3 to 21.4% fewer tubers suggesting that yield reductions could be due to plants yielding fewer tubers. Total tuber yield and total number of tubers per plant were similar to treatment effects on yield and quantity of US #1 tubers (Table 10). Similarities in treatment effects on tuber yield and quantity of all tubers and US #1 tubers is important to note, due to implications on marketing the seed produced. If treatments affect only total yields and not US #1 tuber yields, a grower would still have the same amount of certified seed to sell. However, if treatments reduce the total yield and yield of US #1 tubers similarly, the grower would overall have less certified seed to market.

Despite large differences in years due to weather patterns, noticeable trends were observed in both years. Treatments of linuron, metribuzin, and rimsulfuron when applied alone were safe for weed management in potato mini-tubers, whereas imazosulfuron caused yield reductions. The varieties tested did not show significant differences in yield response to herbicide treatments in either year. Similarly, varieties tested in our study have not been reported to have differential sensitivity to herbicides when grown from cut seed pieces and only represent round chipping varieties. Further research needs to be conducted on additional varieties to determine if correlations are present for varietal sensitivity of mini-tubers and cut seed pieces.

Yield reductions in 2008 were only observed where *S*-metolachlor plus linuron were followed by a postemergence herbicide application of rimsulfuron alone or with metribuzin. However, in 2009 preemergence treatments containing root or shoot growth inhibitors reduced yields which could be due to herbicide phytotoxicity early in the season that was exaggerated by a cool growing season. Although yields were reduced by several treatments, herbicides alone and in combination are still warranted for use in mini-tubers to control weeds due to limited options and the need for season long control. Use of multiple modes of herbicide action for weed control in potatoes is becoming increasingly important as frequency of weed resistance is increasing due to long term dependency on photosystem inhibitors such as metribuzin. Knowing the impacts herbicides have on crop development will allow growers to manage their potato crop to maximize economic return.

Table 6. Herbicide treatments applied preemergence or preemergence followed by a postemergence application to potato mini-tubers.

Treatment[a]	Rate
	kg ai ha^{-1}
dimethenamid-p	0.74
pyrasulfatole	1.41
S-metolachlor	1.42
pendimethalin	0.8
linuron	0.56
metribuzin	0.56
imazosulfuron	0.45
rimsulfuron	0.03
S-metolachlor + linuron	1.42 + 0.56
S-metolachlor + linuron + metribuzin	1.42 + 0.56 + 0.12
S-metolachlor + pendimethalin + metribuzin	1.42 + 0.27 + 0.12
S-metolachlor + pendimethalin + metribuzin + glyphosate + AMS	1.42 + 0.27 + 0.12 + 0.86 + 3.8
S-metolachlor + linuron fb rimsulfuron + NIS	1.42 + 0.56 fb 0.018 + 0.47 L
S-metolachlor + linuron fb metribuzin + rimsulfuron + NIS	1.42 + 0.56 fb 0.28 + 0.018 + 0.47 L
Non-treated	

[a] Abbreviations: AMS, ammonium sulfate; fb, followed by, NIS; non-ionic surfactant.

Table 7. Interaction of year by percent vine emergence from potato mini-tubers 1 wk after preemergence herbicide application and total tuber yield, averaged across treatments.[ab]

Cultivar	2008	2009	2008	2009
	— Emergence (%) —		—— Yield (t ha^{-1})——	
Atlantic	0 d	90 a	38.6 a	29.6 b
FL1	94 a	75 b	23.9 b	16.4 c
FL2	90 a	39 c	26.7 b	17.3 c
LSD	12		6.3	

[a] Means across rows and columns followed by the same letter are not significantly different for vine emergence 1 wk after application ($P < 0.05$).

[b] Means across rows and columns followed by the same letter are not significantly different for tuber yield ($P<0.05$).

Table 8. Vine injury 1 and 2 wks after preemergence treatment and interaction of cultivar by treatment in 2008. [a-d]

Treatment	1 wk		2 wk			
	2008	2009	2008			2009
			Atlantic	FL1	FL2	
	Injury (%)					
dimethenamid-p	8 bcd	3 ab	0 f	3 def	3 def	5 bc
pyrasulfatole	4 cde	1 bc	0 f	3 def	0 f	4 cd
S-metolachlor	16 a	0 c	0 f	5 cde	2 ef	3 cd
pendimethalin	5 bcde	0 c	0 f	5 cde	2 ef	3 cd
linuron	3 de	2 bc	0 f	2 ef	2 ef	2 d
metribuzin	3 de	1 bc	0 f	0 f	0 f	2 d
imazosulfuron	2 e	1 bc	0 f	0 f	0 f	2 d
rimsulfuron	1 e	1 bc	0 f	2 ef	2 ef	5 bc
S-metolachlor + linuron	9 bc	3 ab	0 f	8 bc	10 ab	8 a
S-metolachlor + linuron + metribuzin	8 bcd	3 ab	0 f	7 bcd	5 cde	7 ab
S-metolachlor + pendimethalin + metribuzin	6 bcde	1 bc	0 f	3 def	2 ef	4 cd
S-metolachlor + pendimethalin + metribuzin + glyphosate	10 b	0 c	0 f	3 def	5 cde	3 cd
S-metolachlor + linuron fb rimsulfuron	4 cde	2 bc	0 f	2 ef	7 bcd	7 ab
S-metolachlor + linuron fb metribuzin + rimsulfuron	9 bc	5 a	0 f	10 ab	13 a	5 bc
LSD	5	2		4		2

[a] Abbreviations: fb, followed by.

[b] Injury ratings are relative to the non-treated control.

[c] Means within a column followed by the same letter are not significantly different ($P < 0.05$).

[d] Means across rows and columns for injury 2 wks after preemergence application in 2008 followed by the same letter are not significantly different ($P < 0.05$).

Table 9. Effect of herbicide treatment on US #1 tuber quantity and yield by plants grown from mini-tubers averaged across cultivars.[a-c]

Treatment[d]	2008	2009	2008	2009
	tubers plant^{-1}		t ha^{-1}	
dimethenamid-p	4.3 ab	3.4	25.2 abc	18.5 cde
pyrasulfatole	3.8 bcd	3.3	27.7 ab	18.8 bcde
S-metolachlor	4.1 abc	3.4	26.3 abc	17.9 cde
pendimethalin	3.9 bc	3.6	28.2 ab	19.7 bcd
linuron	4.0 abc	3.9	25.9 abc	22.1 ab
metribuzin	4.1 abc	4.2	28.7 ab	23.1 a
imazosulfuron	3.2 d	3.3	17.4 d	18.4 cde
rimsulfuron	4.6 a	3.8	28.8 ab	20.5 abcd
S-metolachlor + linuron	4.0 abc	3.4	29.6 a	18.6 cde
S-metolachlor + linuron + metribuzin	4.1 abc	3.7	29.6 a	21.1 abc
S-metolachlor + pendimethalin + metribuzin	3.8 bcd	3.3	26.6 ab	17.5 de
S-metolachlor + pendimethalin + metribuzin + glyphosate	4.0 abc	3.3	27.8 ab	17.2 e
S-metolachlor + linuron fb rimsulfuron	3.5 cd	3.9	21.6 cd	20.3 abcde
S-metolachlor + linuron fb metribuzin + rimsulfuron	4.1 abc	3.5	24.3 bc	19.6 bcde
Non-treated	4.0 abc	3.3	27.8 ab	17.6 de
LSD	0.7	NS	4.7	3.3

[a] Abbreviations: fb, followed by.

[b] Means within a column followed by the same letter are not significantly different ($P < 0.05$).

[c] Means within column for tuber quantity in 2009 are not significantly different ($P < 0.05$).

[d] Treatments containing glyphosate included ammonium sulfate and postemergence applications included a non-ionic surfactant.

Table 10. Effect of herbicide application on total tuber quantity and yield averaged across cultivars.[a-c]

Treatment[d]	2008	2009	2008	2009
	tubers plant^{-1}		t ha^{-1}	
dimethenamid-p	4.8 ab	3.8	27.7 abc	19.5 cde
pyrasulfatole	4.3 bc	3.8	30.1 ab	20.5 bcde
S-metolachlor	4.6 ab	3.8	28.0 abc	18.3 e
pendimethalin	4.5 abc	4.0	31.5 ab	20.6 abcde
linuron	4.7 ab	4.4	28.4 abc	22.9 ab
metribuzin	4.7 ab	4.6	32.5 a	24.0 a
imazosulfuron	3.8 c	3.7	19.8 d	19.0 cde
rimsulfuron	5.1 a	4.1	30.2 ab	22.0 abc
S-metolachlor + linuron	4.5 ab	3.9	31.7 ab	20.0 bcde
S-metolachlor + linuron + metribuzin	4.7 ab	4.2	33.0 a	21.7 abcd
S-metolachlor + pendimethalin + metribuzin	4.4 bc	3.8	30.3 ab	18.4 de
S-metolachlor + pendimethalin + metribuzin + glyphosate	4.5 abc	3.9	31.8 ab	18.9 cde
S-metolachlor + linuron fb rimsulfuron	3.8 c	4.3	23.6 cd	21.4 abcde
S-metolachlor + linuron fb metribuzin + rimsulfuron	4.6 ab	3.9	26.1 bc	20.4 bcde
Non-treated	4.5 ab	3.7	31.5 ab	18.5 de
LSD	0.7	NS	5.8	3.4

[a] Abbreviations: fb, followed by.

[b] Means within a column followed by the same letter are not significantly different ($P < 0.05$).

[c] Means within column for tuber quantity in 2009 are not significantly different ($P < 0.05$).

[d] Treatments containing glyphosate included ammonium sulfate and postemergence applications included a non-ionic surfactant.

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