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ENHANCING POSTEMERGENCE WEED CONTROL PROGRAMS
IN CORN AND SOYBEAN WITH FLUTHIACET AND FLUMICLORAC

presented by

JASON C. FAUSEY

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of the requirements for

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ENHANCING POSTEMERGENCE WEED CONTROL PROGRAMS IN CORN AND SOYBEAN WITH FLUTHIACET AND FLUMICLORAC

By

Jason C. Fausey

A DISSERTATION

Submitted to
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Department of Crop and Soil Sciences

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ABSTRACT

ENHANCING POSTEMERGENCE WEED CONTROL PROGRAMS IN CORN AND SOYBEAN WITH FLUTHIACET AND FLUMICLORAC

BY

Jason C. Fausey

The recently developed cyclic imide herbicides fluthiacet and flumiclorac control one of the most troublesome broadleaf weeds, velvetleaf. These herbicides selectively control velvetleaf and other broadleaf weeds by inhibiting the protoporphyrinogen IX oxidase enzyme. Studies examined the physiological basis for fluthiacet and flumiclorac selectivity in five plant species. Enhanced herbicide metabolism contributed to the tolerance of redroot pigweed to fluthiacet and wild mustard to flumiclorac. Decreased herbicide retention, absorption, and translocation; and increased herbicide metabolism contributed to corn tolerance to these herbicides. Soybean tolerance resulted from decreased herbicide retention and increased herbicide metabolism.

Experiments examined the effect temperature, light intensity, time to initial light exposure, relative humidity, and the presence of dew have on fluthiacet and flumiclorac efficacy. Increasing temperature from 10 to 40 C and increasing light intensity from 0 to 1000 μmol m^{-2} s^{-1} increased herbicide activity. Time to initial light exposure and relative humidity did not affect fluthiacet and flumiclorac activity. The presence of dew reduced herbicide activity.

Studies evaluated broadleaf weed control with fluthiacet and flumiclorac applied alone

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and in tank mixtures. Velvetleaf, common lambsquarters, redroot pigweed, common ragweed, common cocklebur, eastern black nightshade, and wild mustard growth in the greenhouse were reduced by 50% from 0.1, 2.9, 0.9, 1.1, 0.8, 0.4, and 1.2 g ha^{-1} of fluthiacet and 0.7, 3.0, 2.4, 3.3, 3.0, 3.4, and 74.1 g ha^{-1} of flumiclorac, respectively. Adjuvants enhanced common lambsquarters, redroot pigweed, common ragweed, and velvetleaf control with fluthiacet by 53, 57, 29, and 29% and with flumiclorac by 36, 62, 41, and 34%, respectively, in the greenhouse. In field studies, soybean injury and broadleaf weed control were equivalent when fluthiacet or flumiclorac was applied with a crop oil concentrate or a nonionic surfactant. Velvetleaf control with these herbicides was greatest in the field when applied to 5 cm tall plants. However, season-long velvetleaf control with both herbicides was greatest when applied to 45 or 60 cm tall plants. In field studies, fluthiacet and flumiclorac tank mixtures with atrazine, dicamba, 2,4-D, and primisulfuron plus prosulfuron controlled common lambsquarters, redroot pigweed, and velvetleaf season-long. Similarly, tank mixing fluthiacet or flumiclorac with imazethapyr provided season-long common lambsquarters, redroot pigweed, common ragweed, and eastern black nightshade control.

Field studies evaluated the performance of annual weed control programs that included fluthiacet and flumiclorac. Experiments revealed these herbicides are effective applied in a tank mixture with other postemergence herbicides. Alternatively, these herbicides provide excellent weed control when applied postemergence following a preemergence herbicide application.

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INTRODUCTION

Velvetleaf (*Abutilon theophrasti* Medik.) is one of the most troublesome weeds in agricultural crops. Acceptable postemergence velvetleaf control in corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) was difficult before the development of fluthiacet and flumiclorac. These herbicides provide unprecedented postemergence velvetleaf control and offer several advantages over other commercial postemergence herbicides including low use rates, short half-lives, rapid burndown, resistance management, and the ability to broaden the spectrum of other corn and soybean herbicides when applied in a tank mixture. Additionally, each herbicide provides a varying degree of activity on common lambsquarters (*Chenopodium album* L.), kochia (*Kochia scoparia* L.), *Amaranthus* species, *Solanaceae* species, and other broadleaf weeds. Understanding the mechanism of selectivity would provide information that may be used to maximize fluthiacet and flumiclorac efficacy of marginally controlled weeds.

To determine the most effective way to use fluthiacet and flumiclorac, research will determine the basis of selectivity, evaluate the effect environmental conditions at application have on efficacy, examine the effect adjuvant selection has on efficacy, examine tank mixture interactions, and establish an optimal system that incorporates these herbicides into corn and soybean weed control programs.

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CHAPTER 1

Physiological Basis for Fluthiacet and Flumiclorac Selectivity in Five Plant Species

ABSTRACT

Greenhouse and laboratory studies were conducted to determine the physiological basis for fluthiacet and flumiclorac selectivity in five plant species. These herbicides selectively control weeds postemergence by inhibiting protoporphyrinogen oxidase (Protox). Injury symptoms include rapid desiccation and necrosis, similar to diphenyl ether and bipyridinium herbicide injury. Species sensitivity was evaluated by comparing the dry weight reduction from postemergence fluthiacet and flumiclorac applications. Velvetleaf was sensitive to both herbicides, redroot pigweed was more sensitive to flumiclorac than fluthiacet, wild mustard was sensitive to fluthiacet yet tolerant to flumiclorac, and corn and soybean were tolerant to both herbicides. Studies evaluated the effects of herbicide retention, absorption, translocation, or metabolism on fluthiacet and flumiclorac selectivity. Enhanced herbicide metabolism contributed to the tolerance of redroot pigweed to fluthiacet and wild mustard to flumiclorac. Decreased herbicide retention, absorption, and translocation; and increased metabolism contributed to corn tolerance to fluthiacet and flumiclorac. Decreased herbicide retention and increased

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herbicide metabolism provided soybean tolerance to these herbicides.

Nomenclature: Fluthiacet, [[2-chloro-4-fluoro-5-[(tetrahydro-3-oxo-1*H*, 3*H*-[1,3,4]thiadiazolo[3,4-a]pyridazin-1-ylidene)amino]phenyl]thio]acetate; flumiclorac, pentyl[2-chloro-4-fluoro-5-(1,3,4,5,6,7-hexahydro-1,3-dioxo-2*H*-isoindol-2-yl)phenoxy]acetic acid; velvetleaf, *Abutilon theophrasti* Medik. #[1] ABUTH; redroot pigweed, *Amaranthus retroflexus* L. # AMARE; wild mustard, *Brassica kaber*, (D.C.) L.C. Wheeler # SINAR; corn, *Zea mays* L.'Pioneer 3751' # ZEAMA; soybean, *Glycine max* (L.) Merr. 'Conrad' # GLYMA.

Key Words: Absorption, metabolism, protoporphyrin, retention, translocation, ABUTH, AMARE, SINAR, ZEAMA, GLYMA.

Abbreviations: ALA, δ-aminolevulinic acid; DA, 4,6-dioxoheptanoic acid; DAT, days after treatment; HAT, hours after treatment; LSS, liquid scintillation spectrometry; MES, 2-(N-morpholino) ethanesulfonic acid; NIS, nonionic surfactant; Proto, protoporphyrin IX; Protogen, protoporphyrinogen IX; Protox, protoporphyrinogen oxidase; TLC, thin layer chromatography; v/v volume per volume.

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[1]Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available from WSSA, 810 East 10th Street, Lawrence, KA 66044-8897.

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INTRODUCTION

Fluthiacet and flumiclorac are recently developed cyclic imide herbicides that selectively control broadleaf weeds postemergence in corn and soybean (Porpiglia et al. 1994; Kamoshita et al. 1993). Fluthiacet and flumiclorac have a similar mode of action to diphenyl ether, oxadiazole, and triazolinone herbicides despite their different chemical structures (Sato et al. 1991). These herbicides inhibit the protoporphyrinogen oxidase (Protox) enzyme in susceptible plant species which leads to an uncontrolled nonenzymatic oxidation of protoporphyrinogen IX (Protogen) to protoporphyrin IX (Proto) (Anonymous 1995; Duke et al. 1991; Mito et al. 1991). Proto, a photodynamic tetrapyrrole intermediate, is a potent photosensitizer generating singlet oxygen in the presence of molecular oxygen and light (Duke et al. 1991). Injury in plants treated with Protox-inhibiting herbicides includes rapid light-dependent chlorophyll bleaching, desiccation, and necrosis (Wright et al. 1995). Although detectable in sensitive plant species 30 minutes after herbicide exposure, Protox inhibition requires light to initiate herbicidal activity (Duke et al. 1990).

Predicting herbicide efficacy is challenging. Environmental conditions at application (Doran and Anderson 1976), herbicide rate (King and Oliver 1992), weed size (Kells et al. 1984), interactions with other herbicides (Hatzios and Penner 1985), and the addition of an adjuvant (Roggenbuck et al. 1990) influence herbicidal activity. Enhanced herbicidal efficacy generally reflects increased herbicide absorption (Harrison and Wax 1986); however, increased herbicide absorption does not always correlate with increased efficacy (Starke et al. 1996). Ritter and Coble (1981) reported that soybean tolerance to

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the diphenyl ether herbicide acifluorfen (5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoic acid) was explained by less rapid herbicide absorption and translocation coupled with increased metabolism. Similarly, acifluorfen caused widespread cell membrane disruption decreasing weed control by reducing systemic herbicide absorption and translocation (Westberg and Coble 1992).

Temperature and relative humidity influence Protox-inhibiting herbicides translocation and efficacy. Increasing relative humidity from 50 to 85% enhanced acifluorfen, fomesafen (5-[2-chloro-4-(trifluoromethyl)phenoxy] (methylsulfonyl)-2-nitrobenzamide), and lactofen ((±)-2-ethoxy-1-methyl-2-oxoethyl-5-[2-chloro-4-(trifluoromethyl)phenoxy] -2-nitrobenzoate) activity on prickly sida (*Sida spinosa* L.), pitted morningglory (*Ipomoea lacunosa* L.), entireleaf morningglory (*Ipomoea hederacea* var. *integriuscula* L.), and common cocklebur (*Xanthium strumarium* L.) (Wichert et al. 1992). However, Higgins et al. (1988) reported that acifluorfen and lactofen translocation and metabolism in pitted morningglory was negligible.

Weeds prevent crops from reaching their yield potential. Fluthiacet and flumiclorac effectively control velvetleaf, one of the most troublesome broadleaf weeds in corn and soybean. However, research investigating the physiological basis for fluthiacet and flumiclorac selectivity is limited. Studies have not determined the mechanism of selectivity for these herbicides. Conceivably, research could increase control of marginally controlled weed species though crop tolerance may limit the potential to increase fluthiacet and flumiclorac efficacy. Therefore, the objective of this research was to determine the physiological basis for fluthiacet and flumiclorac selectivity in velvetleaf, redroot pigweed, wild mustard, corn, and soybean.

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MATERIALS AND METHODS

Herbicide Effect on the Porphyrin Pathway

Electrolyte Leakage. Experiments evaluating the effects fluthiacet and flumiclorac have on membrane integrity of velvetleaf, redroot pigweed, wild mustard, corn, and soybean leaf disks used the electrolyte leakage assay procedure described by Duke et al. (1984). Treatments included technical grade fluthiacet or flumiclorac alone or with 4,6-dioxoheptanoic acid[2] (DA) or δ-aminolevulinic acid[2] (ALA). DA and ALA were used as a herbicide antagonist and synergist, respectively. Five-mm diameter leaf disks were excised and washed for 2 h in a 1% sucrose, 1 mM 2-(*N*-morpholino) ethanesulfonic acid[2] (MES) solution with a pH of 6.8. Fifty leaf disks were placed in 13 by 100-mm test tubes containing 3 ml of fresh sucrose/MES solution with various rates of herbicide, antagonist, and synergist (see Tables 2 and 3). Leaf disks were added to the test tubes and incubated at 25 C in darkness for 16 h followed by exposure to 1000 μmol m^{-2} s^{-1} at 25 C for 24 h.

The experiment was a completely randomized design with six replications and repeated. Electrolyte leakage from the leaf disks was monitored 0, 12, and 24 h after initial light exposure using a conductivity meter[3]. Results are expressed as the change in conductivity from the 0 h light exposure.

General Greenhouse Methods

Velvetleaf and wild mustard seed were collected at the Michigan State University

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[2] Sigma Chemical Company, St. Louis, MO 63178.

[3] Omega Engineering Inc., Stamford, CT 06907-0047.

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Research Farm in East Lansing. Redroot pigweed seed was obtained from a commercial seed supplier[4]. The corn variety 'Pioneer 3751'[5] and soybean variety 'Conrad' were used in the following studies.

Seeds were planted in BACCTO[6] potting soil in 946-ml plastic pots. Environmental conditions were maintained within a greenhouse at 27 ± 5 C. Plants were grown under a 16-h photoperiod of natural and supplemental high pressure sodium lighting with a photosynthetic photon flux density of 1000 μmol m^{-2} s^{-1}. Plants were thinned to 1 plant pot^{-1}, fertilized with 50 ml of a water-soluble fertilizer solution (400 ppm N, 400 ppm P_2O_5, and 400 ppm K_2O), and watered as needed.

Species Sensitivity. Experiments compared velvetleaf, redroot pigweed, wild mustard, corn, and soybean sensitivity to fluthiacet and flumiclorac. Treatments included an untreated control, 2 g ha^{-1} fluthiacet, and 15 g ha^{-1} flumiclorac. Herbicides were applied with 0.25% (v/v) nonionic surfactant[7] (NIS). At application, velvetleaf plants were 10 cm tall with five to six leaves; redroot pigweed plants were 10 cm tall with seven to eight leaves; wild mustard plants were 8 cm tall with four to five leaves; corn plants were 20 cm tall with four leaves; and soybean plants were 13 cm tall with two fully developed trifoliolates. Herbicides were applied with a continuous belt-linked sprayer fitted with an

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[4]Seed, V & J Seed Farms, P.O. Box 82, Woodstock, IL 60098.

[5]Corn, Pioneer Hi-Bred International, Inc., Des Moines, IA 50301.

[6]BACCTO professional planting mix, Michigan Peat Co., P.O. Box 98129, Houston, TX 77098.

[7]Activator-90, nonionic surfactant, a mixture of alkyl polyoxyethylene ether and fatty acids, Loveland Industries Inc., P.O. Box 1289, Greeley, CO 80632.

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8001E flat-fan nozzle[8] traveling at 1.53 km h^{-1} and delivering 234 L ha^{-1} at 193 kPa of pressure.

The experiment was a completely randomized design with four replications. Plants were visually evaluated 3, 7, and 14 d after treatment (DAT). Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 indicating plant death. Evaluations represented visual stunting, chlorosis, and necrosis. Dry weight reduction was determined 14 DAT by harvesting the aboveground plant material. Dry weight reduction was calculated as 100[1 - (plant dry weight/untreated plant dry weight)].

Herbicide Retention. Experiments were conducted to determine fluthiacet and flumiclorac foliar spray retention on velvetleaf, redroot pigweed, wild mustard, corn, and soybean using a modified Boldt and Putnam (1980) procedure. Treatments included 2 g ha^{-1} fluthiacet or 15 g ha^{-1} flumiclorac plus 0.25% (v/v) NIS[7] and 2.5 g L^{-1} Chicago sky blue dye[2]. Herbicides were applied with a continuous belt-linked sprayer fitted with an 8001E flat-fan nozzle[8] traveling at 1.53 km h^{-1} and delivering 234 L ha^{-1} at 193 kPa of pressure. At application, velvetleaf plants were 10 cm tall with five to six leaves; redroot pigweed plants were 10 cm tall with seven to eight leaves; wild mustard plants were 8 cm tall with four to five leaves; corn plants were 20 cm tall with four leaves; and soybean plants were 13 cm tall with two trifoliolates.

The experiment was a completely randomized design with four replications. Following herbicide application, aboveground plant segments were harvested and rinsed with distilled water containing 0.25% (v/v) NIS[7]. Plant leaf area was determined while the

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[8]Teejet flat-fan nozzles, Spraying Systems Co., North Avenue and Schmale Road, Wheaton, IL 60532.

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rinsate absorbance was measured with a spectrophotometer at 625 nm. Whole plant retention was calculated from a standard curve, and results are expressed as a percent of the theoretical maximum retention. Theoretical maximum retention was calculated as 100[1 - (herbicide concentration retained/maximum retention: based on the plant leaf area)].

Herbicide Absorption, Translocation, and Metabolism. Experiments compared fluthiacet and flumiclorac absorption, translocation, and metabolism in velvetleaf, redroot pigweed, wild mustard, corn, and soybean. Herbicide absorption, translocation, and metabolism were determined in a single plant treated with ^{14}C-radiolabeled fluthiacet or flumiclorac. Plants were grown in the greenhouse as previously described to the growth stages in the spray retention experiment. The youngest fully developed leaf was chosen for the ^{14}C-radiolabeled herbicide treatment; the 4^{th} true velvetleaf and wild mustard leaf, the 6^{th} true redroot pigweed leaf, the 2^{nd} true corn leaf, and the middle soybean leaflet of the 1^{st} trifoliolate.

Velvetleaf, redroot pigweed, wild mustard, corn, and soybean plants, except the leaf chosen for ^{14}C treatment, were sprayed with 2 g ha^{-1} fluthiacet or 15 g ha^{-1} flumiclorac plus 0.25% (v/v) NIS[7]. Herbicides were applied as previously discussed in the spray retention experiment. The leaf chosen for ^{14}C treatment was covered with cellophane during the broadcast herbicide application to prevent spray interception. The cellophane was removed immediately following herbicide application.

The spray retention study determined the quantity of spray solution intercepted during a broadcast herbicide application. All hand-treated leaves received a herbicide treatment that simulated a broadcast herbicide application. To ensure sufficient radioactivity for the n

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metabolism analysis, a minimum of 2.7×10^3 Bq was applied to the treated leaf.

The radiolabeled spotting solution contained phenyl-labeled ^{14}C-fluthiacet (1.5×10^3 kBq mg^{-1} specific activity, 95.4% purity) or tetrahydrophthaloyl-1, 2-labeled ^{14}C-flumiclorac (9.5×10^3 kBq mg^{-1} specific activity, 94.9% purity) with the appropriate formulation blank, NIS[7], and water volumes. Treatments consisting of fifteen, 2 μl droplets of solution totaling 2.7×10^3 Bq were applied to the adaxial leaf surface.

Unabsorbed ^{14}C fluthiacet or flumiclorac was removed by gently swirling the treated leaf in a 20 ml liquid scintillation vial containing 3 ml of methanol : water (1:1) solution for 60 seconds. Leaves were rinsed with an additional 0.5 ml of solvent as they were removed from the scintillation vial. The rinse solution was radioassayed by liquid scintillation spectrometry (LSS). Fluthiacet and flumiclorac absorption was calculated by dividing the recovered ^{14}C-herbicide by the quantity of ^{14}C-herbicide applied.

Radiolabeled plants were harvested 2, 4, and 12 h after treatment (HAT) and divided into three sections; the treated leaf, above the treated leaf, and below the treated leaf. These parts were immediately frozen and stored at -30 C until further analysis. Preliminary experiments found that only treated leaves contained sufficient ^{14}C herbicide concentrations to conduct metabolism analysis; therefore, the other leaf sections were separately combusted in a biological sample oxidizer[9], and the evolved radiolabeled herbicide was sustained within a ^{14}C trapping cocktail. Cocktail samples were assayed with LSS to quantify herbicide translocation above and below the treated leaf. ^{14}C translocation out of the treated leaf was calculated as the ^{14}C recovered above and below the treated leaf divided by the total ^{14}C recovered in the plant.

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[9] R. J. Harvey Instruments Corp., 123 Patterson St., Hillsdale, NJ 07642.

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Fluthiacet and flumiclorac metabolism was investigated in the ^{14}C treated leaf. Leaves were ground in a tissue homogenizer[10] with 20 ml of an acetonitrile : water (6:4) solution. The homogenate was vacuum-filtered, and the residue was rinsed with an additional 20 ml of solvent. Rinsate volumes were recorded and two, 1 ml aliquots were radioassayed with LSS to determine the extractable ^{14}C. The filter paper and residue were air dried and combusted to determine the unextractable ^{14}C. Total radioactivity within the treated leaf was calculated by adding the extractable and unextractable ^{14}C.

The filtrate was evaporated to 2 ml with a rotary evaporator at 35 C, and the solution was transferred to a 13 by 100 mm test tube and concentrated to 100 to 150 μl under an air stream in a 40 C water bath. Fifty μl of the concentrated extract were spotted on 20 by 20 cm silica gel (60 F 254) thin layer chromatography (TLC) plates[11] for metabolite separation. Plates were developed in a 13 cm solvent front in toluene : ethyl acetate : acetic acid (5:7:1 v/v/v). Radioactive positions, proportions, and their corresponding R_f values were determined by scanning TLC plates with a radiochromatogram scanner[12].

TLC separations revealed parent fluthiacet, flumiclorac, and three metabolites for each herbicide (Table 1). To determine metabolite biological activity, the previously discussed procedures were followed using nonradioactive herbicide treated plants. Nonradioactive metabolites were separated on the TLC plates, and their location was confirmed using ultraviolet lighting. The parent herbicides and their metabolites were scraped from the silica gel plates and placed in 13 by 100 mm test tubes. The modified Duke et al. (1984)

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[10] Sorvall Omni-mixer, Sorvall Inc., Newton, CT 06470.

[11] Whatman Inc., Clifton, NJ 07011.

[12] Ambis Systems, Inc., 3939 Ruffin Road, San Diego, CA 92123.

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electrolyte leakage assay procedures established biological activity of the parent herbicides and the metabolites. Fluthiacet, two fluthiacet metabolites, flumiclorac, and one flumiclorac metabolite were biologically active (data not presented). Metabolism was calculated in the treated leaf by dividing the remaining biologically active ^{14}C by the total ^{14}C in the treated leaf. The experiment was a completely randomized design with four replications.

Statistical Analyses

All experiments were repeated over time, and data were analyzed using analysis of variance (ANOVA). Data for individual experiments were combined as analyses revealed no treatment by time interaction. Means were separated by Fisher's protected least significant difference test (LSD) at the 5% level.

RESULTS AND DISCUSSION

Herbicide Effect on the Porphyrin Pathway

Electrolyte Leakage. Several herbicide classes, including cyclic imides, diphenyl ethers, and oxadiazoles, initiate light-dependent chlorosis resulting from an accumulation of the photodynamic tetrapyrrole, protoporphyrin IX (Proto) (Duke et al. 1990). These herbicides also inhibit protoporphyrinogen oxidase (Protox), the last common enzyme in the heme and chlorophyll biosynthesis pathways (Duke et al. 1991). Protox is present in plant plastids and mitochondria and catalyzes the oxidation of protoporphyrinogen IX (Protogen) to protoporphyrin IX (Proto) (Jacobs et al. 1991). Reports suggest Protoxinhi

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inhibiting herbicides induce Protogen accumulation that diffuses into the cytoplasm and is oxidized to Proto by an unidentified oxidase in the plasma membrane (Jacobs et al. 1991). Once outside the normal porphyrin pathway, Proto induces the formation of membrane and chlorophyll-destroying singlet oxygen (Lydon and Duke 1988). Singlet oxygen is highly toxic to plants and results in a measurable increase in cellular conductivity. Herbicide initiated electrolyte efflux was assessed by monitoring the herbicide treated bathing medium conductivity (Duke et al. 1984). However, the bathing medium conductivity did not increase when Protox-inhibiting herbicides were applied in darkness (Wright et al. 1995). Similarly, preliminary experiments revealed fluthiacet and flumiclorac require light to initiate herbicidal activity (data not presented).

The herbicidal effects evident by electrolyte leakage from 1 μM fluthiacet and 1 μM flumiclorac on velvetleaf, redroot pigweed, corn, and soybean leaf disks were equivalent (Table 2). However, herbicidal effects on wild mustard leaf disks were greater with fluthiacet when compared with flumiclorac. One mM 4,6-dioxoheptanoic acid (DA) alone did not induce electrolyte leakage compared with an untreated control. Yet, adding DA to fluthiacet or flumiclorac reduced herbicidal activity compared with fluthiacet and flumiclorac applied without DA. Duke et al. (1991) reported that the addition of DA to Protox-inhibiting herbicides reduces their herbicidal activity by inhibiting an early enzyme in the prophyrin synthesis pathway, δ-aminolevulinic acid (ALA) dehydratase.

ALA is an early intermediate in the prophyrin synthesis pathway (Lydon and Duke 1988). Exogenous ALA applications may result in herbicidal effects by initiating the accumulation of photodynamic porphyrin compounds (Lydon and Duke 1988). Wright et al. (1995) reported treating cucumber (*Cucumis sativus* L.) leaf disks with 50 μM ALA increased

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increased the bathing medium conductivity. However, in our experiments, velvetleaf, redroot pigweed, wild mustard, corn, and soybean leaf disks were not affected by the addition of 50 μM ALA (Table 3). Conductivity in the velvetleaf, wild mustard, corn, and soybean assay tubes was equivalent between fluthiacet and flumiclorac. Applying 50 μM ALA to fluthiacet or flumiclorac increased herbicidal activity except for fluthiacet on redroot pigweed. All data suggest fluthiacet and flumiclorac exert their light-dependent herbicidal effects by inhibiting Protox.

Fluthiacet and Flumiclorac Selectivity

Species Sensitivity. The field use rate for fluthiacet is 4 to 5 g ha^{-1} (Anonymous 1995), whereas flumiclorac is used at rates of 30 to 60 g ha^{-1} (Kurtz and Pawlak 1993). Velvetleaf, redroot pigweed, wild mustard, corn, and soybean sensitivities to 2 g ha^{-1} fluthiacet or 15 g ha^{-1} flumiclorac were determined for greenhouse grown plants (Table 4). Velvetleaf was sensitive to both herbicides, as a postemergence herbicide application reduced velvetleaf dry weight by 96% (Table 4). Similarly, fluthiacet and flumiclorac reduced redroot pigweed dry weight by at least 90%. However, redroot pigweed was more sensitive to flumiclorac when compared with fluthiacet. Fluthiacet provided a 91% reduction in wild mustard dry weight, yet flumiclorac only reduced wild mustard dry weight by 53%. Corn and soybean were tolerant to fluthiacet and flumiclorac as dry weight reduction was less than 5%.

Herbicide Retention. Species susceptibility to a postemergence herbicide application is affected by herbicide retention (Gillespie 1994). Sprague et al. (1997) reported a fivefold increase in isoxaflutole (5-cyclopropyl isoxazol-4-yl-2-mesyl-4-trifluoromethylphenyl ketone) retention when metolachlor/benoxacor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-`(2-methoxy-1-methylethyl)acetamide/(4-dichloroacetyl)-3,1dihydro-3-methyl-2*H*-1,4-benzoxazine) was added which resulted in enhanced corn injury compared with isoxaflutole alone.

Fluthiacet and flumiclorac retention on leaves varied among test species with the greatest differences occurring between the crop and weed species (Table 5). Fluthiacet and flumiclorac retention by redroot pigweed was eightfold greater than soybean. Thus, for each square leaf area unit, eight times more herbicide was present on a redroot pigweed leaf than a soybean leaf. Velvetleaf and wild mustard retained less fluthiacet and flumiclorac than redroot pigweed; however, herbicide retention by these species was twice that of corn or soybean. Differences in redroot pigweed and soybean epicuticular wax structure could explain differences in herbicide retention of these species. Harr et al. (1991) reported 54 and 75° leaf contact angles for redroot pigweed and soybean, respectively, confirming differences in the epicuticular wax of these two species.

Herbicide Absorption. Fluthiacet and flumiclorac both provide excellent postemergence velvetleaf control (Table 4). However, fluthiacet absorption by velvetleaf foliage was greater than flumiclorac 12 HAT (Table 6). Although soybean is tolerant to both herbicides, foliar absorption of fluthiacet and flumiclorac was greater in soybean than velvetleaf. However, corn absorbed less fluthiacet than velvetleaf.

Fluthiacet absorption was greater by redroot pigweed, wild mustard, and corn when compared with absorption of flumiclorac 12 HAT. Increased fluthiacet absorption in wild mustard may explain greater sensitivity of wild mustard to fluthiacet than flumiclorac. However, redroot pigweed absorbed more fluthiacet than flumiclorac, yet redroot pigweed is more tolerant of fluthiacet than flumiclorac. Corn is equally sensitive to both herbicides; and fluthiacet and flumiclorac foliar absorption was similar in corn 2 HAT. Foliar absorption of fluthiacet and flumiclorac alone cannot account for differences in herbicide sensitivity or selectivity.

Herbicide Translocation. Protox-inhibiting herbicides are regarded as contact herbicides because of limited translocation (Scalla and Matringe 1994). Fluthiacet and flumiclorac movement within plants was evaluated by measuring ^{14}C translocation out of the ^{14}C treated leaf. Herbicide translocation was limited as less than 29% of the ^{14}C herbicide was translocated out of the treated leaves (Table 6). Relative herbicide translocation did not vary between species and herbicides 2 and 12 HAT. This was not surprising since herbicidal injury symptoms from fluthiacet or flumiclorac were present within 3 h after treatment (data not presented). Differences in species sensitivity to fluthiacet and flumiclorac are not explained by differential herbicide translocation.

Translocation of fluthiacet and flumiclorac 12 HAT was greater in wild mustard and corn compared with velvetleaf. However, translocation did not correlate with fluthiacet and flumiclorac selectivity. Wild mustard is tolerant to flumiclorac yet susceptible to fluthiacet, while corn is tolerant to both herbicides (Table 4). Fluthiacet and flumiclorac tolerant species translocated similar or greater amounts of herbicide compared with plants susceptible to these herbicides. Thus, herbicide translocation did not appear to contribute to fluthiacet or flumiclorac selectivity.

Herbicide Metabolism. Research evaluated differences in fluthiacet and flumiclorac metabolism to a nonbiologically active metabolite. Although both herbicides were metabolized, the structural characterization of these metabolites was beyond the scope of this study.

Velvetleaf, redroot pigweed, and corn metabolized more fluthiacet than flumiclorac 12 HAT to nonbiologically active metabolites (Table 6). However, redroot pigweed was the only species more sensitive to flumiclorac than fluthiacet. Fluthiacet metabolism to a nonbiologically active metabolite was greater in redroot pigweed, corn, and soybean 12 HAT when compared with velvetleaf and wild mustard (Table 6). Metabolism results support the species sensitivity experiment where redroot pigweed, corn, and soybean were more tolerant to fluthiacet than velvetleaf (Table 4). Likewise, there were more of the biologically active forms of flumiclorac present in the most sensitive species, velvetleaf and redroot pigweed. Flumiclorac metabolism to a nonactive form was greater in wild mustard, corn, and soybean than velvetleaf and redroot pigweed. Fluthiacet and flumiclorac tolerant species metabolize these herbicides more rapidly than sensitive species.

Fluthiacet and flumiclorac exert their light-dependent herbicidal effects by inhibiting Protox. However, the selectivity mechanisms plants use to protect against these herbicides varies by species. Table 7 identifies the factors that significantly contribute to species tolerance to these herbicides when compared with velvetleaf. Differential herbicide metabolism and differential foliar herbicide retention, absorption, and translocation contribute to fluthiacet and flumiclorac selectivity. However, the differences in foliar absorption and metabolism in wild mustard treated with fluthiacet compared with flumiclorac does not account for the dramatic differences in the whole plant sensitivity to these herbicides. Sherman et al. (1991) reported that mustard, which is tolerant to acifluorfen, produced limited Proto in response to acifluorfen despite having susceptible Protox. Jacobs et al. (1990) reported tolerant soybean root mitochondria are insensitive to acifluorfen, thus suggesting acifluorfen selectivity may be explained by differences in Protox sensitivity. However, further investigations by Sherman et al. (1991) found no correlation between Protox sensitivity and herbicidal effects from acifluorfen. Thus, species selectivity to Protox-inhibiting herbicides may be explained by less Proto accumulation, decreased absorption, increased translocation, rapid metabolism, and other mechanisms; but apparently, it is not due to differences in Protox sensitivity (Scalla and Matringe 1994).

Another explanation for tolerance to Protox-inhibiting herbicides is an enhanced capacity to detoxify singlet oxygen. Plants contain natural defense mechanisms that provide protection from damaging oxygen radicals. The reductant, ascorbate, is one such molecule. Sandmann and Böger (1990) reported fifteenfold greater ascorbate levels in Protox-inhibiting herbicide tolerant *Bumilleriopsis* microalgae when compared with susceptible *Scendesmus*. Similarly, tobacco (*Nicotiana tabacum* L.)) susceptibility to flumiclorac and acifluorfen was attributed to an enhanced antioxidant system in tolerant biotypes (Gullner et al. 1991). Antioxidant systems that can protect plants from Protox-inhibiting herbicides are one selectivity mechanism. However, their impact on Protox-inhibiting herbicide efficacy is unclear. Plant tolerance to Protox-inhibiting herbicides is a complex process, and factors not examined in these experiments may contribute to fluthiacet and flumiclorac selectivity. A complex interaction of factors including herbicide retention, absorption, translocation, and metabolism ultimately determine species sensitivity to a particular Protox-inhibiting herbicide.

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Table 1. Characterization of fluthiacet and flumiclorac metabolites.[a]

Herbicide	Metabolite	R_f	Biologically active[b]
Fluthiacet	Parent	0.75	Yes
	A	0.52	Yes
	B	0.31	Yes
	C	0.13	No
Flumiclorac	Parent	0.88	Yes
	A	0.44	Yes
	B	0.27	No
	C	0.13	No

[a] Quantified parent herbicide and metabolites from Thin Layer Chromatography (TLC) separation using 20 by 20 cm silica gel (60 F 254) TLC plates. Plates were developed in a 13 cm solvent front in toluene : ethyl acetate : acetic acid (5:7:1 v/v/v).
[b] Electrolyte leakage assay indicated biological activity equivalent to the parent herbicide.

Table 2. Effect of 4,6-dioxoheptanoic acid (DA) on electrolyte leakage 24 h after fluthiacet and flumiclorac treatment.[a]

Treatment	Rate	Species				
		Velvetleaf	Redroot pigweed	Wild mustard	Corn	Soybean
	μM	μmhos^{-1} cm^{-1} assay tube^{-1}				
Fluthiacet	1	194	144	291	73	255
Flumiclorac	1	181	139	208	75	213
DA	1000	3	28	2	4	11
Fluthiacet + DA	1000 + 1	56	9	89	33	166
Flumiclorac + DA	1000 + 1	82	30	74	36	155
LSD (0.05)		43				

[a] Means may be compared within or across columns within herbicides and within species.

Table 3. Effect of δ-aminolevulinic acid (ALA) on electrolyte leakage 24 h after fluthiacet and flumiclorac treatment.[a]

		Species				
Treatment	Rate	Velvetleaf	Redroot pigweed	Wild mustard	Corn	Soybean
	μM	—— μmhos^{-1} cm^{-1} assay tube^{-1} ——				
Fluthiacet	0.2	155	171	175	73	138
Flumiclorac	0.2	126	129	144	42	157
ALA	50	27	9	15	4	3
Fluthiacet + ALA	0.2 +50	206	182	226	127	201
Flumiclorac + ALA	0.2 + 50	210	196	240	94	229
LSD (0.05)		—— 41 ——				

[a] Means may be compared within or across columns within herbicides and within species.

Table 4. Species sensitivity to 2 g ha^{-1} fluthiacet and 15 g ha^{-1} flumiclorac in the greenhouse 14 d after treatment.[a]

	Herbicide	
Species	Fluthiacet	Flumiclorac
	—— % dry weight reduction ——	
Velvetleaf	96 a	96 a
Redroot pigweed	90 b	97 a
Wild mustard	91 b	53 c
Corn	5 d	2 d
Soybean	5 d	5 d

[a] Means may be compared within or across columns within herbicides and within species. Means followed by the same letter are not significantly different according to Fisher's Protected LSD (α= 0.05). All treatments included nonionic surfactant at 0.25% v/v.

Table 5. Fluthiacet and flumiclorac retention in five plant species.[a]

	Herbicide	
Species	Fluthiacet	Flumiclorac
	—— % of theoretical maximum retention ——	
Velvetleaf	45 c	42 c
Redroot pigweed	78 a	66 b
Wild mustard	37 c	42 c
Corn	17 d	17 d
Soybean	8 d	8 d

[a] Means may be compared within or across columns within herbicides and within species. Means followed by the same letter are not significantly different according to Fisher's Protected LSD (α= 0.05). All treatments included nonionic surfactant at 0.25% v/v.

Table 6. Fluthiacet and flumiclorac absorption, translocation, and metabolism in 5 plant species.[a]

	Harvest time			
	2 h		12 h	
Species	Fluthiacet	Flumiclorac	Fluthiacet	Flumiclorac
	Foliar absorption			
	% of applied ^{14}C			
Velvetleaf	64 c	44 d	81 c	56 f
Redroot pigweed	79 a	42 d	93 a	66 e
Wild mustard	79 a	68 bc	95 a	85 bc
Corn	50 d	43 d	73 d	60 f
Soybean	75 ab	70 abc	90 ab	87 b
	Translocation[b]			
	% of applied ^{14}C			
Velvetleaf	99 a	99 a	96 a	98 a
Redroot pigweed	96 ab	86 b	98 a	92 ab
Wild mustard	89 ab	90 ab	82 bc	84 b
Corn	76 c	74 c	73 c	71 c
Soybean	99 a	99 a	96 a	99 a
	Metabolism[c]			
	% of applied ^{14}C			
Velvetleaf	83 a	77 ab	49 bc	63 a
Redroot pigweed	68 b	70 b	35 de	54 ab
Wild mustard	80 ab	72 ab	39 cde	46 bcd
Corn	78 ab	46 c	36 de	30 e
Soybean	40 c	72 ab	15 f	40 cde

[a] Means may be compared within or across columns within factors and within harvest time. Means followed by the same letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$).

[b] Radioactive herbicide remaining in the treated leaf.

[c] Metabolism expressed as percentage remaining biologically active within the treated leaf.

Table 7. Factors affecting plant tolerance to fluthiacet and flumiclorac 12 h after treatment.[a]

			Herbicide			
Herbicide	Species	Tolerance[b]	Retention	Absorption	Translocation	Metabolism
Fluthiacet	velvetleaf	S	—	—	—	—
	redroot pigweed	S	—	—	—	X
	wild mustard	S	—	—	X	—
	corn	T	X	X	X	X
	soybean	T	X	—	—	X
Flumiclorac	velvetleaf	S	—	—	—	—
	redroot pigweed	S	—	—	—	—
	wild mustard	ST	—	—	X	X
	corn	T	X	—	X	X
	soybean	T	X	—	—	X

[a] X = significantly contributes, — = does not significantly contribute to species tolerance.
[b] S= sensitive, T= tolerant based on Table 4.

CHAPTER 2

Environmental Effects on Fluthiacet and Flumiclorac Efficacy and Soybean Tolerance

ABSTRACT

Laboratory and field experiments were designed to examine the effect temperature, light intensity, time to initial light exposure, relative humidity, and the presence of dew had on fluthiacet and flumiclorac efficacy. Increasing temperature from 10 to 40 C and light intensity from 0 to 1000 μmol m^{-2} s^{-1} increased fluthiacet and flumiclorac activity on redroot pigweed and common lambsquarters. Time to initial light exposure and relative humidity did not affect fluthiacet and flumiclorac activity on redroot pigweed and common lambsquarters. The presence of dew reduced herbicide activity on redroot pigweed and common lambsquarters. A field study was conducted to determine if fluthiacet or flumiclorac applications at 0600 h, 1400 h, or 2200 h influenced soybean tolerance and weed control. The greatest soybean injury occurred from fluthiacet or flumiclorac applications at 0600 h compared with 1400 or 2200 h. Common lambsquarters control was greatest when fluthiacet or flumiclorac was applied at 0600 h or 1400 h compared with 2200 h. However, redroot pigweed control was greatest when fluthiacet or flumiclorac was applied at 1400 h. Application time of day did not effect

velvetleaf control with either herbicide. Results suggest environmental conditions at application influence soybean tolerance and weed control with fluthiacet and flumiclorac.

Nomenclature: Fluthiacet, [[2-chloro-4-fluoro-5-[(tetrahydro-3-oxo-1*H*, 3*H*-[1,3,4]thiadiazolo[3,4-a]pyridazin-1-ylidene)amino]phenyl]thio]aceate; flumiclorac, pentyl[2-chloro-4-fluoro-5-(1,3,4,5,6,7-hexahydro-1,3-dioxo-2*H*-isoindol-2-yl)phenoxy]acetic acid; common lambsquarters, *Chenopodium album* L. #[1] CHEAL; redroot pigweed, *Amaranthus retroflexus* # AMARE; velvetleaf, *Abutilon theophrasti* Medik. # ABUTH; soybean *Glycine max* (L.) Merr. 'Conrad' # GLYMA.

Key Words: Application time of day, temperature, relative humidity, light intensity, dew, CHEAL, AMARE, ABUTH, GLYMA.

Abbreviations: COC, crop oil concentrate; DAT days after treatment; HAT, hours after treatment; NIS, nonionic surfactant; Protox, protoporphyrinogen oxidase; UAN, 28% urea ammonium nitrate; v/v, volume per volume.

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[1]Letters following this symbol are a WSSA-approved computer code from Composite List of Weed, Revised 1989. Available from WSSA.

INTRODUCTION

Environmental conditions at application such as temperature, light, relative humidity, rainfall, and soil moisture influence herbicide efficacy (Coupland 1983; Kudsk et al. 1990). Because environmental conditions vary within the day, application time may influence the herbicidal activity of cyclic imide herbicides such as fluthiacet and flumiclorac.

Several classes of photodynamic herbicides including cyclic imides, diphenyl ethers, and oxadiazoles block the enzymatic oxidation of protoporphyrinogen IX to protoporphyrin IX by protoporphyrinogen oxidase (Protox) (Duke et al. 1991). Protoporphyrin IX rapidly generates singlet oxygen in the presence of light and molecular oxygen, subsequently causing lipid peroxidation and immediate cellular death in sensitive plant species (Lee and Duke 1994).

Research investigating environmental effects on soybean tolerance and efficacy of photodynamic herbicides is limited. Common cocklebur (*Xanthium strumarium* L.) and velvetleaf control with bentazon (3-(1-methylethyl)-(1*H)*-2,1,3-benzothiadiazin-4(3*H)*-one 2,2-dioxide) were reduced when bentazon was applied early morning, late evening, or at night (Doran and Anderson 1976). Paraquat (1,1'-dimethyl-4,4'-bipyridinium ion) provided greater quackgrass (*Elyitrigia repens* L.) control when applied at 2000 h compared with an application at 1400 h (Putnam and Ries 1968). Yet, common lambsquarters and redroot pigweed control with paraquat and acifluorfen (5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoic acid) increased when applied at 0900 h or 1500 h compared with 0300 h or 2100 h (Zhou and Ahrens 1995). Hemp sesbania (*Sesbania* *exaltata* (Raf.) Cory) control with acifluorfen increased when applied at 2100 h compared with 0600 h or 1200 h (Lee and Oliver 1982).

Temperature and relative humidity influence the translocation and efficacy of diphenyl ether herbicides. Acifluorfen translocation in showy crotalaria (*Crotalaria spectabilis* Roth) increased fourfold when relative humidity increased from 40 to 100% (Wills and McWhorter 1981). Common cocklebur and common ragweed (*Ambrosia artemisiifolia* L.) control with acifluorfen was 10 to 30% greater when acifluorfen was applied at 85% relative humidity compared with 50% relative humidity (Ritter and Coble 1981). Similarly, increasing relative humidity from 50 to 85% enhanced acifluorfen, fomesafen (5-[2-chloro-4-(trifluoromethyl)phenoxy](methylsulfonyl)-2-nitrobenzamide), and lactofen ((±)-2-ethoxy-1-methyl-2-oxoethyl-5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoate) activity on prickly sida (*Sida spinosa* L.), pitted morningglory, (*Ipomoea lacunosa* L.), entireleaf morningglory (*Ipomoea hederacea* var. *integriuscula* L.), and common cocklebur (Wichert et al. 1992).

Inconsistent weed control with flumiclorac was reported in 1995 (K. A. Renner, personal communication). The effect environmental conditions have on soybean tolerance and weed control with fluthiacet or flumiclorac has not been documented. Therefore, the objectives of this research were to evaluate the effect temperature, light intensity, time to initial light exposure, relative humidity, the presence of dew, and the application time of day has on fluthiacet or flumiclorac efficacy and soybean tolerance.

MATERIALS AND METHODS

General methods for laboratory experiments. Experiments were conducted to determine the effect temperature, light intensity, time to initial light exposure, and relative humidity have on fluthiacet and flumiclorac efficacy. Uniform, fully expanded leaves from natural populations of field-grown common lambsquarters and redroot pigweed were harvested at the Michigan State University Research Farm in East Lansing, MI, in August 1998. Leaf sections of 1.5 by 1.5 cm were excised and placed in 20 by 100-mm petri dishes containing No. 2 Whatman filter paper[2] and 5 ml of distilled water. Distilled water was added throughout the experiment to maintain leaf turgor.

Herbicide application consisted of five, 1 μl droplets of solution applied to the adaxial leaf surface. Treatments included 4 g ha^{-1} fluthiacet, 30 g ha^{-1} flumiclorac, and an untreated control. Herbicide treatments were applied with 0.25% (v/v) nonionic surfactant[3] (NIS).

Fluthiacet and flumiclorac activity on common lambsquarters and redroot pigweed leaf sections were visually evaluated 72 h after treatment (HAT). Visual ratings were based on a scale from 0 (no effect) to 100% (complete dessication). Values represent leaf discoloration and necrosis.

Each experiment was a completely randomized design with six replications. Experiments were conducted twice, and the data presented are the means of the two experiments. Unless otherwise indicated, the following conditions were standardized:

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[2]Filter paper, Whatman #2. Whatman International Ltd., Maidstone, England.

[3]Activator-90, nonionic surfactant, a mixture of alkyl polyoxyethylene ether and fatty acids. Loveland Industries, Inc., P.O. Box 1289, Greeley, CO 80632.

temperature at 30 C, 24-h illumination at 40 μmol $m^{-2} s^{-1}$, and 6 leaf sections per treatment.

Temperature. Petri dishes containing hydrated leaf sections were placed in water baths calibrated to 10, 20, 30, or 40 C. Leaf sections were equilibrated to the water temperature for 45 min before herbicide application.

Light intensity. Light intensity was examined by comparing herbicidal activity on hydrated leaf sections exposed to 0, 4, 40, or 1,000 μmol $m^{-2} s^{-1}$ for 72 h.

Time to initial light exposure. Leaf sections were equilibrated for 1 h at 30 C in darkness before herbicide application. Leaf sections were removed from darkness at 0, 2, 4, 6, 8, or 12 HAT and exposed to 24-h illumination at 40 μmol $m^{-2} s^{-1}$.

Relative humidity. A continuous flow system consisting of a vapor generator and three 9.3 L glass chambers connected with 3 mm i.d. teflon tubing was designed. In-line microbial filters[4] filtered incoming air. Flow rate of 150 ml per min was regulated with glass microbore capillary tubes and a pressure regulator[5]. Humidity was established within the chambers by directing air flow through 1) sterilized water (90% relative humidity), 2) saturated calcium nitrate solution (50% relative humidity), or 3) by directly transferring air into the chamber (10% relative humidity). The glass chambers were equilibrated for 24 h before leaf sections were treated with herbicide. Treated leaf sections were placed in the chambers for 8 h and exposed to 4 μmol $m^{-2} s^{-1}$. Leaf sections were removed from the glass chambers and exposed to 40 μmol $m^{-2} s^{-1}$ for 64 h.

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[4]Microbial filter, Alltech Associates, Inc., Deerfield, IL 60015.

[5]Scientific pressure regulator, South Plainfield, NJ 07080.

Influence of dew on efficacy. Experiments were conducted at the Michigan State University Research Farm in East Lansing, MI, in 1998. Locally collected common lambsquarters and redroot pigweed seeds were planted in BACCTO[6] potting soil in 946-ml plastic pots. Initial environmental conditions were maintained within a greenhouse at 27 ± 5 C. Following emergence, seedlings were transferred to outdoor environmental conditions. Plants were thinned to 1 plant pot^{-1}, fertilized with 50 ml of a water-soluble fertilizer solution (400 ppm N, 400 ppm P_2O_5, and 400 ppm K_2O), and watered as needed. Plants were split into two groups the evening prior to herbicide application, dew or no dew. Dew designated plants were left uncovered while the no dew plants were loosely covered with burlap to inhibit natural dew formation. Plants were treated with fluthiacet or flumiclorac 30 min after burlap removal.

The experiment was a completely randomized design with four replications. Treatments included 4 g ha^{-1} fluthiacet, 30 g ha^{-1} flumiclorac, and an untreated control. All treatments were applied in combination with 0.25% (v/v) NIS.

Herbicides were applied on July 4, 1998 and July 6, 1998 with a carbon dioxide backpack sprayer traveling at 6.3 km h^{-1} and delivering 178 L ha^{-1} at 207 kPa of pressure. Treatments were applied with 8003 flat-fan nozzles[7] spaced 51 cm apart and 48 cm above the canopy. At application, common lambsquarters plants were 1 to 6 cm tall with two to ten leaves; and redroot pigweed plants were 1 to 10 cm tall with two to twelve leaves.

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[6]BACCTO professional planting mix, Michigan Peat Co., Houston, TX 77098.

[7]Teejet flat-fan tips, Spraying Systems Co., North Avenue and Schmale Road, Wheaton, IL 60188.

Common lambsquarters and redroot pigweed control was visually evaluated for phytotoxicity 7 and 14 d after treatment (DAT). Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 indicating plant death. Evaluations represented visual stunting, chlorosis, and necrosis.

Field experiment. Experiments were conducted at the Michigan State University Research Farm at East Lansing, MI, in 1996 and 1998 and at the Michigan State University Horticulture Research Station at Clarksville, MI, in 1997. The East Lansing soil was a Capac sandy clay loam (fine-loamy, mixed mesic Aeric Ochraqualfs) with 3.3 and 2.2% organic matter in 1996 and 1998, respectively. The Clarksville soil was a Lapeer sandy loam (coarse-loamy, mixed, mesic Mollic Haplaquepts) with 1.9% organic matter. The soil pH was 7.0, 6.8, and 7.1 in 1996, 1997, and 1998, respectively. The 1996 and 1998 sites were fall chisel plowed with secondary tillage consisting of two field cultivations at planting. The 1997 site was spring moldboard plowed, and secondary tillage consisted of two field cultivations at planting. 'Conrad' soybean was planted in 76-cm rows at 395,000 seed ha^{-1}. Plots were 3 m wide by 9.1 m in length.

The experimental design was a split plot with four replications. Main plots were herbicide. Subplots were time of application. Main plots included either 4 g ha^{-1} fluthiacet or 30 g ha^{-1} flumiclorac. Each herbicide treatment was applied within a 24 h time period at 0600 h, 1400 h, and 2200 h (Table 6). All treatments included either 0.25% (v/v) NIS plus 1.0% (v/v) 28% urea ammonium nitrate (UAN) or 0.5% (v/v) crop oil concentrate[8] (COC).

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[8]Herbimax, crop oil concentrate, 83% petroleum oil, 17% surfactant, Loveland Industries, Inc., P.O. Box 1289, Greeley, CO 80632.

Herbicides were applied June 13, 1996, June 24, 1997, and June 9, 1998, 26, 31, and 27 d after planting, with a compressed air tractor-mounted sprayer traveling at 6.3 km h^{-1} and delivering 178 L ha^{-1} at 207 kPa of pressure. Treatments were applied with 8003 flat-fan nozzles spaced 51 cm apart and 48 cm above the weed canopy. At application, soybean plants were 10 to 12 cm tall with two fully developed trifoliolates, common lambsquarters plants were 1 to 10 cm tall with 2 to 24 leaves, redroot pigweed plants were 1 to 10 cm tall with 2 to 12 leaves, and velvetleaf plants were 1 to 10 cm tall with 1 to 7 leaves.

Soybean injury was visually evaluated 3, 7, 14, and 21 DAT. Weed control was evaluated for each species 7, 14, and 21 DAT. Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 signifying plant death. Soybean injury and weed control evaluations represent visual stunting, chlorosis, and necrosis.

Statistical analyses. All experiments were repeated over time, and data were analyzed using analysis of variance (ANOVA). Data for individual experiments were combined as analyses revealed no treatment by time interaction. Means were separated by Fisher's protected least significant difference (LSD) at the 5% level.

RESULTS AND DISCUSSION

Laboratory experiments.

Temperature. Fluthiacet and flumiclorac activity on common lambsquarters increased four and sevenfold, respectively, when temperature increased from 10 to 40 C (Table 1). Similarly, when temperature increased from 10 to 40 C, activity of both herbicides increased threefold on redroot pigweed. However, fluthiacet and flumiclorac activity on redroot pigweed increased, while activity on common lambsquarters did not increase when temperature increased from 30 to 40 C.

Eckl and Gruler (1980) found species dependent phase changes in plant cuticles were associated with changes in temperature. The composition and structure of epicuticular wax affects herbicide efficacy (Flore and Bukovac 1978). Harr et al. (1991) reported nonpolar fractions of common lambsquarters and redroot pigweed cuticles were 30 and 42%, respectively, confirming natural differences exist in the epicuticular wax of these species. Differences in phase changes or the epicuticular wax structure of common lambsquarters and redroot pigweed cuticles may explain differences in herbicidal response of these weed species at 30 and 40 C.

Light intensity. Increasing light intensity from 4 to 1,000 μmol m^{-2} s^{-1} increased fluthiacet and flumiclorac activity on common lambsquarters and redroot pigweed 4 to 15 fold (Table 2). Light and molecular oxygen combine with protoporphyrin IX to generate singlet oxygen, which initiates lipid peroxidation and cellular death in Protox susceptible plant species (Lee and Duke 1994). Thus, increased herbicidal activity on common lambsquarters and redroot pigweed was observed with increasing light intensity.

Time to initial light exposure. Time to initial light exposure did not affect fluthiacet and flumiclorac activity on common lambsquarters or redroot pigweed 72 HAT (Table 3). Fluthiacet and flumiclorac activity is evident within 3 h after application if light is present at application (data not presented). Thus, the mechanism of fluthiacet or flumiclorac selectivity must occur rapidly in tolerant species. Ritter and Coble (1981) reported that soybean tolerance to acifluorfen was explained by less rapid herbicide penetration and translocation coupled with increased metabolism rates. Less rapid absorption and decreased translocation rates of fluthiacet and flumiclorac may account for differences in herbicidal response of common lambsquarters and redroot pigweed.

Relative humidity. Increased relative humidity can enhance herbicidal activity by prolonging the drying time and increasing cuticle hydration (Caseley 1989; Ritter and Coble 1981). Wichert et al. (1992) reported increased relative humidity enhanced Protox-inhibiting herbicide activity on prickly sida, pitted and entireleaf morningglory, and common cocklebur. In our research, increased relative humidity prolonged drying time (personal observation), but did not affect fluthiacet or flumiclorac activity on common lambsquarters and redroot pigweed 72 HAT (Table 4). The lack of response to relative humidity may result from factors such as temperature and light masking the subtle effects of relative humidity.

Influence of dew on efficacy. The presence of dew at application may increase or decrease herbicide performance depending upon the herbicide and species involved (Caseley 1989; Wanamarta and Penner 1989). The presence of dew at application reduced common lambsquarters and redroot pigweed control with fluthiacet or flumiclorac 14 DAT (Table 5).

Field experiment. Preliminary experiments revealed soybean tolerance and weed control with lactofen, oxasulfuron, and tank mixtures of lactofen or oxasulfuron with fluthiacet or flumiclorac were unaffected by application time of day (data not presented). However, application time of day affected soybean tolerance and weed control with fluthiacet or flumiclorac applied alone (Table 7).

Soybean injury was greatest 7 DAT for both herbicides applied at 0600 h (Table 7). Fluthiacet or flumiclorac applied at 0600 h and 1400 h provided greater common lambsquarters control compared with herbicides applied at 2200 h (Table 7). Either herbicide applied at 1400 h provided greater redroot pigweed control compared with applications at 0600 h or 2200 h. Velvetleaf control 14 DAT with fluthiacet or flumiclorac was unaffected by application time of day (Table 7).

Fluthiacet or flumiclorac applied at 1400 h provided the greatest broad-spectrum broadleaf weed control. At 1400 h, air temperature and light intensity in the field were greatest (Table 6). Interestingly, soybean injury did not increase with increasing temperature or light intensity. Therefore, soybean tolerance to fluthiacet and flumiclorac must be influenced by other factors. Common lambsquarters and redroot pigweed control decreased in the field when initial light exposure occurred 8 h after fluthiacet or flumiclorac applications. Laboratory experiments suggest reduced weed control with evening applications of fluthiacet or flumiclorac is not related to a delay in light exposure. However, laboratory experiments were conducted at 30 C, whereas the air temperature in the field was ≤26 C and decreased following herbicide application (Table 6). Thus, at low temperatures time to initial light exposure may influence fluthiacet or flumiclorac activity. Dew was only present at 0600 h in 1996 (Table 6), and weed control was not reduced compared with other years (data not presented).

Herbicide absorption is a complex process with no single controlling factor. Spray solution, plant foliage, and environmental conditions before, at, and following application determine herbicide response (Holen and Dexter 1993; Wanamarta and Penner 1989). Leaf movements have important implications on herbicide efficacy (Anderson and Koukkari 1979). Rhythmic leaf movements allow leaves to maximize the capture of light (Akey et al. 1990). Daily leaf oscillations in velvetleaf account for decreased velvetleaf control with bentazon by reducing spray interception when leaves are positioned vertically (Anderson and Koukkari 1978; Doran and Anderson 1979). However, Koukkari and Johnson (1979) reported the physical orientation of velvetleaf leaves did not affect bentazon retention, thus concluding plant susceptibility was due to diurnal changes in the plants physiological ability to detoxify the herbicide. Similarly, velvetleaf control with fluthiacet or flumiclorac did not decrease at 2200 h although the leaves had a vertical orientation. Weaver and Nylund (1963) reported increased carbohydrate concentrations at application were associated with the susceptibility of field pea to MCPA (2-methyl-4-chlorophenoxyacetic acid). These aspects and others ultimately combine to influence herbicide tolerance and efficacy in the field.

Laboratory results suggest a herbicide application at high temperature, high light intensity, and in the absence of dew would increase fluthiacet or flumiclorac activity on common lambsquarters and redroot pigweed. Field studies confirmed these observations for redroot pigweed as maximum control was obtained from an application of fluthiacet or flumiclorac at 1400 h. The greatest common lambsquarters control in the field was achieved with fluthiacet or flumiclorac applications at 0600 h or 1400 h. Equivalent common lambsquarters susceptibility to fluthiacet or flumiclorac applied in the field early morning and afternoon illustrates the complex nature of herbicide selectivity. A reduction in herbicide retention or absorption may not be relevant for velvetleaf control with fluthiacet or flumiclorac because of high velvetleaf sensitivity to these herbicides (Fausey and Renner 1998). Greater soybean tolerance to fluthiacet or flumiclorac at 1400 h or 2200 h applications compared with 0600 h applications could be due to more rapid herbicide drying, less herbicide uptake, or an increase in the detoxifying capabilities of soybean.

Beyers and Smeda (1997) reported reduced weed control with a late evening glufosinate (2-amino-4-(hydroxymethylphosphinyl)butanoic acid) application. The presence of dew, lower air temperature, or a lack of light may explain ineffective weed control with an evening glufosinate application. A further understanding of the direct and indirect effect environmental conditions at and following herbicide application is needed to identify the ideal application time of day for photodynamic herbicides.

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Table 1. Effect of temperature on common lambsquarters and redroot pigweed control with fluthiacet and flumiclorac 72 h after treatment.

Treatment[a]	Rate	Temperature	Common lambsquarters	Redroot pigweed
	g ha^{-1}	C	——— % control ———	
Fluthiacet	4	10	6	20
	4	20	14	36
	4	30	24	53
	4	40	28	63
Flumiclorac	30	10	4	23
	30	20	16	32
	30	30	29	41
	30	40	31	58
LSD (0.05)			7	10

[a]All treatments were applied with 0.25% nonionic surfactant (NIS).

Table 2. Effect of light intensity on common lambsquarters and redroot pigweed control with fluthiacet and flumiclorac 72 h after treatment.

Treatment[a]	Rate	Light intensity	Common lambsquarters	Redroot pigweed
	g ha^{-1}	μmol m^{-2} s^{-1}	——— % control ———	
Fluthiacet	4	0	3	4
	4	4	9	8
	4	40	23	43
	4	1000	38	56
Flumiclorac	30	0	4	1
	30	4	5	5
	30	40	20	49
	30	1000	46	75
LSD (0.05)			5	4

[a]All treatments were applied with 0.25% nonionic surfactant (NIS).

Table 3. Effect of time to initial light exposure on common lambsquarters and redroot pigweed control with fluthiacet and flumiclorac 72 h after treatment.

Treatment[a]	Rate	Time to initial light exposure	Common lambsquarters	Redroot pigweed
	g ha^{-1}	h	——— % control ———	
Fluthiacet	4	0	21	33
	4	2	21	33
	4	4	21	33
	4	6	19	32
	4	8	19	31
	4	12	19	32
Flumiclorac	30	0	24	42
	30	2	23	41
	30	4	24	43
	30	6	24	43
	30	8	23	41
	30	12	23	42
LSD (0.05)			3	4

[a]All treatments were applied with 0.25% nonionic surfactant (NIS).

Table 4. Effect of relative humidity on common lambsquarters and redroot pigweed control with fluthiacet and flumiclorac 72 h after treatment.

Treatment[a]	Rate	Relative humidity	Common lambsquarters	Redroot pigweed
	g ha^{-1}	%	—— % control ——	
Fluthiacet	4	10	38	45
	4	50	36	44
	4	90	38	45
Flumiclorac	30	10	40	48
	30	50	39	48
	30	90	36	50
LSD (0.05)			7	6

[a]All treatments were applied with 0.25% nonionic surfactant (NIS).

Table 5. Effect of dew on common lambsquarters and redroot pigweed control with fluthiacet and flumiclorac 14 d after treatment.

Treatment[a]	Rate	Leaf surface	Common lambsquarters	Redroot pigweed
	g ha^{-1}		——— % control ———	
Fluthiacet	4	dew	92	69
	4	no dew	97	87
Flumiclorac	30	dew	91	76
	30	no dew	96	95
LSD (0.05)			3	8

[a]All treatments were applied with 0.25% nonionic surfactant (NIS).

Table 6. Herbicide application conditions in 1996, 1997, and 1998 field experiments.

Date treated	Application time	Cloud cover	Air temperature	Relative humidity	Leaf surface moisture[a]
	h	%	C	%	
6/13/96	0600	90	19	95	1
	1400	30	29	62	5
	2200	100	26	88	4
6/24/97	0600	80	26	65	5
	1400	20	33	47	5
	2200	90	29	62	5
6/9/98	0600	95	14	70	5
	1400	30	21	26	5
	2200	100	16	55	5

[a] Visual 1 to 5 rating with 1 signifying wet and 5 dry.

Table 7. Effect of time of application on tolerance and efficacy of fluthiacet and flumiclorac applied at 0600, 1400, and 2000 h.[a]

Treatment[b]	Rate	Application time	Soybean	Common lambsquarters	Redroot pigweed	Velvetleaf
	$g\ ha^{-1}$	h	% injury[c]	——— % control[d] ———		
Fluthiacet	4	0600	14	74	51	98
	4	1400	11	73	74	99
	4	2200	12	61	52	98
Flumiclorac	30	0600	16	71	60	94
	30	1400	11	68	77	94
	30	2200	12	53	60	90
LSD (0.05)			2	7	7	6

[a]Data averaged over 1996, 1997, and 1998.
[b]All treatments included either 0.25% (v/v) nonionic surfactant (NIS) plus 1.0% (v/v) 28% urea ammonium nitrate (UAN) or 0.5% (v/v) crop oil concentrate (COC).
[c]Percent injury 7 d after treatment (DAT).
[d]Percent control 14 DAT.

CHAPTER 3

Adjuvant Effects on Fluthiacet and Flumiclorac Efficacy and Soybean Tolerance

ABSTRACT

Greenhouse and field studies evaluated adjuvant effects on weed control and soybean tolerance with fluthiacet or flumiclorac applied alone and in combination with imazethapyr and oxasulfuron. Adjuvants enhanced common lambsquarters, redroot pigweed, common ragweed, and velvetleaf control with fluthiacet by 53, 57, 29, and 29% and flumiclorac by 36, 62, 41, and 34%, respectively, in the greenhouse. In field studies, soybean injury and common lambsquarters, redroot pigweed, and common ragweed control were equivalent when fluthiacet or flumiclorac was applied with a crop oil concentrate[1] (0.5 or 1.0% v/v) or a nonionic surfactant[2] plus 28% urea ammonium nitrate (UAN) (0.25 + 1.0% v/v). In greenhouse studies, a tank mixture of fluthiacet and imazethapyr with a methylated seed oil[3] or an organosilicone[4] adjuvant enhanced common lambsquarters and velvetleaf control compared with a nonionic surfactant. Redroot pigweed control with fluthiacet plus imazethapyr; and common lambsquarters and velvetleaf control with flumiclorac plus imazethapyr increased by the addition of an organosilicone adjuvant compared with a nonionic surfactant. Redroot pigweed and

common ragweed control with tank mixtures of fluthiacet or flumiclorac plus oxasulfuron were enhanced by adding an organosilicone adjuvant compared with a nonionic surfactant. In field evaluations of fluthiacet or flumiclorac plus imazethapyr, adding a nonionic surfactant or an organosilicone adjuvant resulted in equivalent soybean injury and giant foxtail, common lambsquarters, and redroot pigweed control. The addition of an organosilicone adjuvant increased redroot pigweed control and soybean yield in tank mixtures of fluthiacet or flumiclorac plus oxasulfuron compared with a nonionic surfactant.

Nomenclature: Fluthiacet, [[2-chloro-4-fluoro-5-[(tetrahydro-3-oxo-1*H*, 3*H*-[1,3,4]thiadiazolo[3,4-a]pyridazin-1-ylidene)amino]phenyl]thio]acetate; flumiclorac, pentyl[2-chloro-4-fluoro-5-(1,3,4,5,6,7-hexahydro-1,3-dioxo-2*H*-isoindol-2-yl)phenoxy]acetic acid; imazethapyr, 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid; oxasulfuron, 2-[[[[(4,6-dimethyl-2-pyrimidinyl)-amino]carbonyl]amino]sulfonyl] benzoic acid, 3-oxetanyl ester; velvetleaf, *Abutilon theophrasti* Medik. #[1] ABUTH; redroot pigweed, *Amaranthus retroflexus* L. # AMARE; common ragweed, *Ambrosia artemisiifolia* L. # AMBEL; common lambsquarters, *Chenopodium album* L. # CHEAL; giant foxtail, *Setaria faberi* Herrm. # SETFA; soybean, *Glycine max* (L.) Merr. 'Conrad' # GLYMA.

Key Words: Herbicide additive, surfactant, ABUTH, AMARE, AMBEL, CHEAL, GLYMA.

Abbreviations: COC, crop oil concentrate; DAT, days after treatment; MSO, methylated

[1]Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available from WSSA, 810 East 10th Street, Lawrence, KA 66044-8897.

seed oil; NIS, nonionic surfactant; Protox, protoporphyrinogen oxidase; UAN, 28% urea ammonium nitrate; v/v, volume per volume.

INTRODUCTION

Predicting herbicide efficacy is challenging. Environmental conditions at application (Doran and Anderson 1976), herbicide rate (King and Oliver 1992), weed size (Kells et al. 1984), interactions with other herbicides (Hatzios and Penner 1985), and the addition of an adjuvant (Roggenbuck et al. 1990) influence herbicidal response. Adjuvants optimize herbicide penetration and efficacy under adverse environmental conditions (Sun et al. 1996) and provide more consistent control of marginally controlled species (Wills and McWhorter 1981). Enhanced herbicidal efficacy generally reflects increased herbicide absorption (Harrison and Wax 1986); however, increased herbicide absorption does not always correlate with increased efficacy (Starke et al. 1996).

The recently developed cyclic imide herbicides fluthiacet and flumiclorac control broadleaf weeds postemergence in corn (*Zea mays* L.) and soybean (Porpiglia et al. 1994; Kamoshita et al. 1993). The mode of action of cyclic imide, diphenyl ether, oxadiazole, and triazolinone herbicides is protoporphyrinogen oxidase (Protox) inhibition (Anonymous 1995; Duke et al. 1991; Mito et al. 1991). Protox inhibition leads to an uncontrolled nonenzymatic oxidation of protoporphyrinogen IX to protoporphyrin IX in sensitive plant species. Herbicidal activity of these herbicide classes is light-dependent and closely associated with the concentration of accumulated protoporphyrin IX (Duke et al. 1990).

Fluthiacet and flumiclorac provide exceptional postemergence velvetleaf control (Brown et al. 1991; Fausey and Renner 1998; Kapusta et al. 1995). Roeth and Schleufer (1994) reported that velvetleaf control with flumiclorac was not affected when flumiclorac was applied with a crop oil concentrate (COC) or a COC plus 28% urea ammonium nitrate (UAN). However, Dill et al. (1994) reported that a COC or an organosilicone spray additive provided more consistent weed control with fluthiacet than a nonionic spray additive.

Weed control programs must provide acceptable season-long weed control for each weed species present. This is commonly achieved by tank mixing herbicides. Understanding the potential interactions between herbicides used in tank mixtures is important when developing weed management systems (Young et al. 1996). Tank mixtures of fluthiacet or flumiclorac with imazethapyr or oxasulfuron provide more consistent broad-spectrum weed control compared with fluthiacet or flumiclorac alone (Dill et al. 1994; James et al. 1994; Krutz and Pawlak 1992). Potentially, tank mixtures of fluthiacet or flumiclorac with imazethapyr or oxasulfuron may enhance velvetleaf control and provide consistent broad-spectrum broadleaf weed control (Dill et al. 1994; James et al. 1994; Kurtz and Pawlak 1992). However, Nelson and Renner (1998) reported that adding fluthiacet to oxasulfuron reduced common ragweed control compared with oxasulfuron alone.

Research investigating adjuvant effects on fluthiacet or flumiclorac efficacy and soybean tolerance is limited. Conceivably, adjuvant selection may enhance or reduce efficacy and affect soybean tolerance in tank mixtures with fluthiacet or flumiclorac. Therefore, the objectives of this research were to determine the influence adjuvant selection has on efficacy and soybean tolerance with fluthiacet or flumiclorac applied alone and in tank mixtures with imazethapyr and oxasulfuron.

MATERIALS AND METHODS

General Methods for Greenhouse Experiments

Velvetleaf and common lambsquarters seed was collected at the Michigan State University Crop and Soil Sciences Research Farm in East Lansing, Michigan. Redroot pigweed and common ragweed seed was obtained from a commercial seed supplier[2]. Seeds were planted in BACCTO[3] potting soil in 946 ml plastic pots. Environmental conditions were maintained within a greenhouse at 27 ± 5 C. Plants were grown under a 16-h photoperiod of natural and supplemental high pressure sodium lighting with a photosynthetic photon flux density of 1000 μmol m^{-2} s^{-1}. Plants were thinned to 1 plant pot^{-1}, fertilized with 50 ml of a water-soluble fertilizer solution (400 ppm N, 400 ppm P_2O_5, and 400 ppm K_2O), and watered as needed. Herbicides were applied with a continuous belt-linked sprayer fitted with an 8001E flat-fan nozzle[4] traveling at 1.53 km h^{-1} and delivering 234 L ha^{-1} at 193 kPa of pressure.

Each experiment was a completely randomized design with four replications. Weed control was visually evaluated in each experiment 3, 7 and 14 d after treatment (DAT). Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 indicating plant death. Evaluations represented visual stunting, chlorosis, and necrosis. Dry weight reduction was determined in each experiment 14 DAT by harvesting the

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[2]Seed, V & J Seed Farms, P.O. Box 82, Woodstock, IL 60098.

[3]BACCTO professional planting mix, Michigan Peat Co., P.O. Box 98129, Houston, TX 77098.

[4]Teejet flat-fan nozzles, Spraying Systems Co., North Avenue and Schmale Road, Wheaton, IL 60532.

aboveground plant material. Percent dry weight reduction was calculated as 100[1 - (plant dry weight/untreated plant dry weight)].

Adjuvant Efficacy. Experiments were conducted to evaluate adjuvant effects on fluthiacet and flumiclorac efficacy. Commercial formulations of fluthiacet or flumiclorac were applied at 2 g ha^{-1} and 15 g ha^{-1}, respectively. Herbicides were applied with: no adjuvant; UAN (1.0% v/v); Activator 90[5] (0.25% v/v), Activator 90 plus UAN (0.25 + 1.0% v/v); Herbimax[6] (0.5,1.0, and 2.0% v/v); Herbimax plus UAN (0.5 + 1.0% v/v); Dash[7] (1.0% v/v); Scoil[8] (1.0% v/v); Scoil plus UAN (1.0 + 1.0% v/v); Sylgard 309[9] (0.25% v/v); and Sylgard 309 plus UAN (0.25 + 1.0% v/v).

Separate experiments were conducted for velvetleaf, common lambsquarters, redroot pigweed, and common ragweed. At application, velvetleaf plants were 10 to 11 cm tall with six leaves; common lambsquarters plants were 6 cm tall with six to eight leaves; redroot pigweed plants were 6 cm tall with four to six leaves; and common ragweed plants were 6 cm tall with six leaves. Herbicide injury was visually evaluated, and aboveground biomass was harvested 14 DAT, oven dried, and weighed.

Tank Mixtures with Fluthiacet and Flumiclorac. Experiments were conducted to

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[5]Activator-90, nonionic surfactant, a mixture of alkyl poloxyethlene ether and free fatty acids, Loveland Industries Inc., P.O. Box 1289, Greeley, CO 80632.

[6]Herbimax, 83% petroleum oil, 17% surfactant, Loveland Industries Inc., P.O. Box 1289, Greeley, CO 80632.

[7]Dash, 45% petroleum hydrocarbons, 5% naphthalene, 1.5% phosphoric acid, and 48.5% mixture of alkyl esters and anionic surfactant. BASF Corp., RTP, NC 27709.

[8]Scoil, methylated seed oil, AGSCO. Inc., P.O. Box 458 Grand Forks, ND 58206.

[9]Sylgard 309, organosilicone adjuvant, 2-(3-hydroxy-propyl)-heptamethyl-trisiloxane, ethoxylated acetate, Dow Corning Corp., Midland, MI 48686-0944.

evaluate adjuvant effect on weed control with tank mixtures of fluthiacet or flumiclorac with imazethapyr and oxasulfuron (Table 4). Treatments included 18 g ha^{-1} imazethapyr or 16 g ha^{-1} oxasulfuron applied in combination with 1 g ha^{-1} fluthiacet or 8 g ha^{-1} flumiclorac. All treatments were applied with Activator 90 plus UAN (0.25 + 0.1% v/v), Scoil plus UAN (1.0 + 1.0% v/v), and Sylgard 309 plus UAN (0.25 + 1.0% v/v). At application, velvetleaf plants were 12 cm tall with four to six leaves; common lambsquarters plants were 9 cm tall with ten to 12 leaves; redroot pigweed plants were 10 cm tall with eight to ten leaves; and common ragweed plants were 6 cm tall with eight to 10 leaves. Herbicide injury was visually evaluated, and aboveground biomass was harvested 14 DAT, oven dried, and weighed.

Field Experiments

Species Sensitivity. Experiments were conducted at the Michigan State University Research Farm in East Lansing, MI in 1996 and 1997. The soil was a Capac sandy clay loam (fine-loamy, mixed mesic Aeric Ochraqualfs) with 2.4% organic matter in 1996 and a sandy loam with 2.5% organic matter in 1997. The soil pH was 7.9 and 6.7 in 1996 and 1997, respectively. Sites were fall chisel plowed with secondary tillage consisting of two field cultivations at planting. 'Conrad' soybean was planted in 76-cm rows at 395,000 seed ha^{-1}. Plots were 3 m wide by 12.2 m in length in 1996 and 3 m wide by 9.1 m in length in 1997.

The experiment was a randomized complete block with four replications. Treatments included 4 g ha^{-1} fluthiacet or 30 g ha^{-1} flumiclorac applied with Herbimax (0.5 and 1.0% v/v) or Activator 90 plus UAN (0.25 + 1.0% v/v).

Herbicides were applied on June 10, 1996 and June 17, 1997, 24 and 26 d after planting (DAP), with a compressed air tractor-mounted sprayer traveling at 6.3 km h^{-1} and delivering 178 L ha^{-1} at 207 kPa of pressure. Treatments were applied with 8003 flat-fan nozzles[4] spaced 51 cm apart and 48 cm above the weed canopy. At application, soybean plants were 8 to 10 cm tall with one fully developed trifoliolate; common lambsquarters plants were 1 to 10 cm tall with two to 24 leaves; redroot pigweed plants were 1 to 8 cm tall and from cotyledon to eight leaves; and common ragweed plants were 1 to 7 cm tall and from cotyledon to eight leaves.

Soybean injury and weed control were visually evaluated 7, 14, and 28 DAT. Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 signifying plant death. Soybean injury and weed control evaluations represented visual stunting, chlorosis, and necrosis.

Tank Mixtures with Fluthiacet and Flumiclorac. Experiments were conducted at the Michigan State University Research Farm at East Lansing, MI in 1997 and 1998. The soil was a Capac sandy clay loam (fine-loamy, mixed mesic Aeric Ochraqualfs) with 2.8 and 4.2% organic matter in 1997 and 1998, respectively. The soil pH was 6.6 and 6.3 in 1997 and 1998, respectively. Sites were fall chisel plowed with secondary tillage consisting of two field cultivations at planting. Asgrow[10] '2701 RR' soybean was planted in 76-cm rows at 345,000 seed ha^{-1}. Plots were 3 m wide by 10.6 m in length.

The experiment was a randomized complete block with four replications. Treatments included 2240 g ha^{-1} metolachlor preemergence (PRE) followed by 4 g ha^{-1} fluthiacet or 30 g ha^{-1} flumiclorac postemergence (POST); and tank mixtures of 4 g ha^{-1} fluthiacet or

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[10]Soybean, Asgrow Seed Company, P.O. Box 7570, Des Moines, IA 50322.

30 g ha^{-1} flumiclorac with 70 g ha^{-1} imazethapyr or 65 g ha^{-1} oxasulfuron plus 60 g ha^{-1} quizalofop (POST). All POST herbicide treatments were applied with Activator 90 plus UAN (0.25 + 1.0% v/v) or Sylgard 309 plus UAN (0.25 + 1.0% v/v).

PRE herbicide applications were applied on May 13, 1997 and 1998. POST herbicide applications were applied on June 17, 1997, and June 8, 1998, 35 and 26 DAP. All herbicide treatments were applied with a compressed air tractor-mounted sprayer traveling at 6.3 km h^{-1} and delivering 178 L ha^{-1} at 207 kPa of pressure. Treatments were applied with 8003 flat-fan nozzles[4] spaced 51 cm apart and 48 cm above the weed canopy. At application, soybean plants were 10 to 14 cm tall with two fully developed trifoliolates; giant foxtail plants were 1 to 15 cm tall with one to four leaves; common lambsquarters plants were 1 to 10 cm tall with two to 22 leaves; and redroot pigweed plants were 1 to 8 cm tall and from cotyledon to ten leaves.

Soybean injury was visually evaluated 3, 7, and 14 DAT. Weed control was evaluated for each species 7, 14, 21, 35, and 56 DAT. Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 signifying plant death. Soybean injury and weed control evaluations represented visual stunting, chlorosis, and necrosis. The two middle rows from each plot were harvested with a Massey 10[11] small-plot combine. Soybean yield was adjusted to 13% moisture.

Statistical Analyses

All experiments were repeated over time, and data were analyzed using analysis of variance (ANOVA). Data for individual experiments were combined as analyses revealed no treatment by time interaction. Means were separated by Fisher's protected

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[11]Kincaid Equipment Manufacturing, P.O. Box 400, Haven, KS 47543.

least significant difference test (LSD) at the 5% level.

RESULTS AND DISCUSSION

Adjuvant Efficacy. Selected adjuvants increased velvetleaf, common lambsquarters, redroot pigweed, and common ragweed control by fluthiacet in the greenhouse, however, enhancement varied by species (Table 1). All adjuvants, except UAN alone, increased velvetleaf, common lambsquarters, redroot pigweed, and common ragweed control by fluthiacet compared with fluthiacet applied without an adjuvant. Velvetleaf control with fluthiacet was greatest when applied with Herbimax (0.5, 1.0, 2.0% v/v), Herbimax plus UAN, Dash, Scoil, or Scoil plus UAN. Maximum common lambsquarters control with fluthiacet was obtained with Scoil plus UAN, while common ragweed control with fluthiacet was greatest with Sylgard 309 plus UAN. Redroot pigweed control with fluthiacet was greatest with Dash, Scoil plus UAN, Sylgard 309, or Sylgard 309 plus UAN. Although other adjuvants provided maximum control of a single species, adding Scoil plus UAN to fluthiacet provided the most effective velvetleaf, common lambsquarters, and redroot pigweed control.

Velvetleaf, common lambsquarters, redroot pigweed, and common ragweed control with flumiclorac was enhanced in the greenhouse with all adjuvants but UAN alone (Table 2). Maximum velvetleaf control was obtained with flumiclorac plus Herbimax plus UAN or flumiclorac plus Sylgard 309 plus UAN. Adding Sylgard 309 plus UAN provided the greatest redroot pigweed control with flumiclorac. Maximum common lambsquarters control with flumiclorac was achieved by adding Activator 90 plus UAN, Herbimax (2.0% v/v), Dash, Scoil plus UAN, or Sylgard 309 plus UAN. Herbimax (2.0% v/v), Herbimax plus UAN, Scoil plus UAN, or Sylgard 309 plus UAN provided the greatest common ragweed control with flumiclorac. Adjuvants enhanced flumiclorac activity on a single species, however, Sylgard 309 plus UAN provided the most effective velvetleaf, common lambsquarters, redroot pigweed, and common ragweed control with flumiclorac.

Adding an adjuvant to fluthiacet or flumiclorac increased soybean injury and common lambsquarters, redroot pigweed, and common ragweed control in the field compared with these herbicides applied without an adjuvant (Table 3). Adding Herbimax (0.5 or 1.0% v/v) or Activator 90 plus UAN to fluthiacet or flumiclorac resulted in equivalent soybean tolerance and weed control in the field. This differed from greenhouse studies where common lambsquarters control with fluthiacet or flumiclorac increased when Activator 90 plus UAN was added compared with 0.5% (v/v) Herbimax. In a second field experiment, weed control with fluthiacet or flumiclorac did not increase by adding Sylgard 309 plus UAN or Activator 90 plus UAN when compared with Activator 90 plus UAN (Table 5). Field results were contrary to the greenhouse results where redroot pigweed control with these herbicides increased when applied with Sylgard 309 plus UAN compared with Activator 90 plus UAN. Differences in the greenhouse and field application rates of fluthiacet or flumiclorac may explain these conflicting results. Fluthiacet and flumiclorac were applied in the greenhouse at one-half the field application rate. Thus, weed control in the field may increase by adding Sylgard 309 plus UAN compared with Activator 90 plus UAN if fluthiacet or flumiclorac are applied at reduced rates. Alternatively, a change in cuticle development may explain the differences in efficacy between greenhouse and field grown plants. Regardless, field results indicated adjuvant selection did not affect soybean tolerance or weed control with 4 g ha^{-1} fluthiacet or 15 g ha^{-1} flumiclorac.

Tank Mixtures with Fluthiacet and Flumiclorac.

Greenhouse. Velvetleaf and common lambsquarters control with fluthiacet plus imazethapyr increased when Scoil plus UAN or Sylgard 309 plus UAN was added. Sylgard 309 plus UAN provided the greatest velvetleaf and common lambsquarters control with flumiclorac plus imazethapyr (Table 4). Redroot pigweed control with fluthiacet plus imazethapyr was greatest with Sylgard 309 plus UAN. Scoil plus UAN or Sylgard 309 plus UAN increased redroot pigweed control with fluthiacet plus oxasulfuron compared with Activator 90 plus UAN. Adding Sylgard 309 plus UAN to flumiclorac plus oxasulfuron maximized redroot pigweed control while common ragweed control was greatest with Sylgard 309 plus UAN (Table 4).

Field. Soybean exhibited leaf necrosis from tank mixtures with fluthiacet or flumiclorac, but this was not apparent 21 DAT (data not presented). Kapusta et al. (1986) and Wichert and Talbert (1993) reported that leaf necrosis from Protox-inhibiting herbicides does not affect soybean yield. In contrast to our greenhouse results, common lambsquarters and redroot pigweed control in the field with tank mixtures of fluthiacet or flumiclorac plus imazethapyr and Activator 90 plus UAN equaled that of Sylgard 309 plus UAN (Table 5). Adjuvant selection did not affect soybean injury, weed control, and soybean yield with tank mixtures of fluthiacet or flumiclorac with imazethapyr in the field.

Adding Sylgard 309 plus UAN to fluthiacet plus oxasulfuron plus quizalofop increased common lambsquarters and redroot pigweed control which was reflected as a 14% increase in soybean yield when compared with adding Activator 90 plus UAN. Similarly, redroot pigweed control and soybean yield with flumiclorac plus oxasulfuron plus quizalofop increased by 12 and 16%, respectively, by adding Sylgard 309 plus UAN compared with Activator 90 plus UAN.

Field results suggest adjuvant selection does affect the efficacy of fluthiacet or flumiclorac tank mixtures in the field. Thus, careful consideration must be given when choosing an adjuvant for fluthiacet and flumiclorac tank mixtures. Cantwell et al. (1989) and Wesley and Shaw (1992) reported that tank mixtures with Protox-inhibiting herbicides may increase or decrease weed control. Nelson and Renner (1998) observed decreased common ragweed control with a tank mixture of fluthiacet plus oxasulfuron compared with oxasulfuron alone. An alternate adjuvant choice may eliminate antagonism between fluthiacet and oxasulfuron when applied in a tank mixture.

Fluthiacet and flumiclorac activity on velvetleaf, common lambsquarters, redroot pigweed, and common ragweed was enhanced by selected adjuvants. However, a single application of fluthiacet or flumiclorac provided insufficient broad-spectrum broadleaf weed control in the field (Fausey and Renner 1998). James et al. (1994) and Kurtz and Pawlak (1993) reported enhanced broadleaf weed control by adding fluthiacet or flumiclorac to several postemergence broadleaf herbicides. With the appropriate adjuvant, tank mixtures of imazethapyr or oxasulfuron plus quizalofop with fluthiacet or flumiclorac may provide season-long broad-spectrum weed control in the field.

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Table 1. Adjuvant effect on fluthiacet efficacy in the greenhouse 14 d after treatment.[a]

Adjuvant	Rate	ABUTH	CHEAL	AMARE	AMBEL
	% v/v	——— % control ———			
No adjuvant	—	69	18	16	12
UAN[b]	1.0	93	14	48	19
Activator 90	0.25	52	34	37	19
Activator 90 + UAN	0.25 + 1.0	83	41	48	20
Herbimax	0.5	91	28	46	19
Herbimax	1.0	95	36	46	24
Herbimax	2.0	97	44	57	24
Herbimax + UAN	0.5 + 1.0	97	25	45	24
Dash	1.0	96	56	64	29
Scoil	1.0	96	53	45	24
Scoil + UAN	1.0 + 1.0	98	71	63	30
Sylgard 309	0.25	76	35	68	19
Sylgard 309 + UAN	0.25 + 1.0	90	45	73	41
Untreated control	—	0	0	0	0
LSD (0.05)		7	5	11	4

[a]All treatments received 2 g ha^{-1} fluthiacet.
[b]UAN, 28% urea ammonium nitrate.

Table 2. Adjuvant effect on flumiclorac efficacy in the greenhouse 14 d after treatment.[a]

Adjuvant	Rate	ABUTH	CHEAL	AMARE	AMBEL
	% v/v	—	— % control	—	
No adjuvant	—	51	20	28	25
UAN[b]	1.0	54	21	37	28
Activator 90	0.25	66	48	49	36
Activator 90 + UAN	0.25 + 1.0	73	54	57	52
Herbimax	0.5	66	30	63	44
Herbimax	1.0	66	48	74	53
Herbimax	2.0	62	54	61	61
Herbimax + UAN	0.5 + 1.0	85	43	66	63
Dash	1.0	71	51	73	58
Scoil	1.0	68	48	54	46
Scoil + UAN	1.0 + 1.0	63	54	71	64
Sylgard 309	0.25	59	49	71	51
Sylgard 309 + UAN	0.25 + 1.0	78	56	90	66
Untreated control	—	0	0	0	0
LSD (0.05)		7	5	14	7

[a]All treatments received 15 g ha^{-1} flumiclorac.
[b]UAN, 28% urea ammonium nitrate.

Table 3. Adjuvant effect on fluthiacet or flumiclorac soybean tolerance and efficacy in the field.[a]

Herbicide[b]	Adjuvant[c]	Rate	GLYMA	CHEAL	AMARE	AMBEL
		% v/v	% injury	———	% control	———
Fluthiacet	no adjuvant	—	5	24	57	65
	Herbimax	0.5	14	98	76	97
	Herbimax	1.0	15	91	77	92
	Activator 90 + UAN	0.25 + 1.0	16	95	80	92
Flumiclorac	no adjuvant	—	7	52	74	78
	Herbimax	0.5	13	90	97	98
	Herbimax	1.0	15	99	99	99
	Activator 90 + UAN	0.25 + 1.0	15	89	99	98
LSD (0.05)			2	19	17	12

[a] Soybean injury 7 d after treatment (DAT) and weed control 14 DAT.
[b] Treatments applied with either 4 g ha^{-1} fluthiacet or 30 g ha^{-1} flumiclorac.
[c] UAN, 28% urea ammonium nitrate.

Table 4. Broadleaf weed control in the greenhouse with fluthiacet and flumiclorac tank mixtures 14 d after treatment.

Treatment	Rate	Adjuvant[a]	ABUTH	CHEAL	AMARE	AMBEL
	g ha^{-1}		% control			
Imazethapyr + fluthiacet	18 + 1	Activator 90	87	25	81	56
Imazethapyr + fluthiacet	18 + 1	Scoil	97	43	77	63
Imazethapyr + fluthiacet	18 + 1	Sylgard 309	96	48	92	54
Imazethapyr + flumiclorac	18 + 8	Activator 90	68	44	85	66
Imazethapyr + flumiclorac	18 + 8	Scoil	69	33	87	57
Imazethapyr + flumiclorac	18 + 8	Sylgard 309	91	53	92	58
Oxasulfuron + fluthiacet	16 + 1	Activator 90	91	48	67	57
Oxasulfuron + fluthiacet	16 + 1	Scoil	98	56	80	54
Oxasulfuron + fluthiacet	16 + 1	Sylgard 309	96	55	88	68
Oxasulfuron + flumiclorac	16 + 8	Activator 90	83	53	68	46
Oxasulfuron + flumiclorac	16 + 8	Scoil	83	54	71	57
Oxasulfuron + flumiclorac	16 + 8	Sylgard 309	90	60	93	59
LSD (0.05)			8	9	10	10

[a]Activator 90 and Sylgard 309 treatments were applied at 0.25% v/v. Scoil treatments were applied at 1.0% v/v. All treatments included 28% urea ammonium nitrate (UAN) at 1.0% v/v.

Table 5. Weed control and soybean yield in the field with fluthiacet and flumiclorac alone and in tank mixtures.[a]

		Application		Injury	Control			Yield
Treatment	Adjuvant[b]	Timing	Rate	GLYMA	SETFA	CHEAL	AMARE	GLYMA
			g ha^{-1}	%				kg ha^{-1}
Metolachlor / fluthiacet	Activator 90	PRE/POST	2240 + 5	10	85	81	69	3344
Metolachlor / fluthiacet	Sylgard 309	PRE/POST	2240 + 5	9	89	77	72	3413
Metolachlor / flumiclorac	Activator 90	PRE/POST	2240 + 45	12	87	83	87	3486
Metolachlor / flumiclorac	Sylgard 309	PRE/POST	2240 + 45	12	87	87	83	3409
Imazethapyr + fluthiacet	Activator 90	POST	70 + 4	12	78	80	98	3821
Imazethapyr + fluthiacet	Sylgard 309	POST	70 + 4	14	71	85	97	3824
Imazethapyr + flumiclorac	Activator 90	POST	70 + 30	14	70	83	99	3772
Imazethapyr + flumiclorac	Sylgard 309	POST	70 + 30	15	71	90	100	3752
Oxasulfuron + fluthiacet + quizalofop	Activator 90	POST	65 + 4 + 60	14	70	76	68	2897
Oxasulfuron + fluthiacet + quizalofop	Sylgard 309	POST	65 + 4 + 60	13	77	85	77	3396
Oxasulfuron + flumiclorac + quizalofop	Activator 90	POST	65 + 30 + 60	12	68	80	60	2630
Oxasulfuron + flumiclorac + quizalofop	Sylgard 309	POST	65 + 30 + 60	13	77	77	72	3125
LSD (0.05)				3	11	8	8	373

[a]Data averaged over 1997 and 1998. Soybean injury 7 d after postemergence treatment (DAT) and weed control 28 DAT.
[b]Activator 90 and Sylgard 309 were applied at 0.25% v/v. All treatments included 28% urea ammonium nitrate (UAN) at 1.0% v/v.

CHAPTER 4

Broadleaf Weed Control in Corn (*Zea mays*) and Soybean (*Glycine max*) with Fluthiacet and Flumiclorac Alone and in Tank Mixtures

ABSTRACT

Greenhouse and field studies evaluated broadleaf weed control with fluthiacet and flumiclorac applied alone and in tank mixtures. Velvetleaf, common lambsquarters, redroot pigweed, common ragweed, common cocklebur, eastern black nightshade, and wild mustard growth in the greenhouse were reduced by 50% from 0.1, 2.9, 0.9, 1.1, 0.8, 0.4, and 1.2 g ha^{-1} of fluthiacet and 0.7, 3.0, 2.4, 3.3, 3.0, 3.4, and 74.1 g ha^{-1} of flumiclorac, respectively. Fluthiacet or flumiclorac tank mixtures with atrazine, bentazon, bromoxynil, dicamba, halosulfuron, imazethapyr, lactofen, primisulfuron plus prosulfuron, or 2,4-D increased velvetleaf, common lambsquarters, redroot pigweed, or common ragweed control in the greenhouse 14 d after treatment (DAT) when compared with the control provided by the tank mix partner alone. Redroot pigweed control increased when flumiclorac was tank mixed with oxasulfuron compared with oxasulfuron alone. However, adding fluthiacet to oxasulfuron did not increase velvetleaf, common lambsquarters, redroot pigweed, or common ragweed control in the greenhouse. In field studies, tank mixtures of fluthiacet or flumiclorac plus atrazine, dicamba, and 2,4-D

increased velvetleaf control compared with control by atrazine, dicamba, and 2,4-D alone. Fluthiacet or flumiclorac tank mixtures with primisulfuron plus prosulfuron increased common lambsquarters control compared with primisulfuron plus prosulfuron alone. Fluthiacet or flumiclorac tank mixtures with bentazon, lactofen, or oxasulfuron increased weed control in the field 14 DAT; however, season-long control of redroot pigweed, common ragweed, and eastern black nightshade with bentazon tank mixtures; common ragweed and eastern black nightshade with oxasulfuron tank mixtures; and common lambsquarters with lactofen tank mixtures was less than 80%. Tank mixing flumiclorac with imazethapyr provided season-long common lambsquarters, redroot pigweed, common ragweed, and eastern black nightshade control.

Nomenclature: Atrazine, 6-chloro-*N*-ethyl-*N*'-(1-methylethyl)-1,3,5-triazine-2,4-diamine; bentazon, 3-(1-methylethyl)-(1*H*)-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide; bromoxynil, 3,5-dibromo-4-hydroxybenzonitrile; 2,4-D, (2,4-dichlorophenoxy)acetic acid; dicamba, 3,6-dichloro-2-methoxybenzoic acid; fluthiacet, methyl[[2-chloro-4-fluoro-5-[(tetrahydro-3-oxo-1*H*, 3*H*-[1,3,4]thiadiazolo[3,4-a]pyridazin-1-ylidene)amino]phenyl]thio]acetate; flumiclorac, pentyl[2-chloro-4-fluoro-5-(1,3,4,5,6,7-hexahydro-1,3-dioxo-2*H*-isoindol-2-yl)phenoxy]acetic acid; halosulfuron, methyl 5-[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonylaminosulfonyl]-3-chloro-1-methyl-1-*H*-pyrazole-4-carboxylate; imazethapyr, 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid; lactofen, (±)-2-ethoxy-1-methyl-2-oxoethyl 5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoate; oxasulfuron, 2-[[[[(4,6-dimethyl-2-pyrimidinyl)-amino]carbonyl]amino]sulfonyl] benzoic acid, 3-oxetanyl ester; primisulfuron, 2-[[[[[4,6-bis(difluoromethoxy)-2-

pyrimidinyl]amino]carbonyl]amino]sulfonyl]benzoic acid; prosulfuron, 1-(4-methoxy-6-methyl-triazin-2-yl)-3-[2-(3,3,3-trifluoropropyl)-phenylsulfonyl]-urea; common cocklebur, *Xanthium strumarium* L. # XANST; common lambsquarters, *Chenopodium album* L. # CHEAL; common ragweed, *Ambrosia artemisiifolia* L. # AMBEL; eastern black nightshade, *Solanum ptycanthum* Dun. # SOLPT; Pennsylvania smartweed, *Polygonum pensylvanicum* L. # POLPY; redroot pigweed, *Amaranthus retroflexus* L. # AMARE; velvetleaf, *Abutilon theophrasti* Medik. #[1] ABUTH; wild mustard, *Brassica kaber* (D.C.) L.C. Wheeler # SINAR; corn, *Zea mays* L. 'Pioneer 3751', 'Dekalb 404SR', and 'Dekalb 493 SR' # ZEAMA; soybean, *Glycine max* (L.) Merr. 'Conrad' # GLYMA.

Key Words: Antagonism, herbicide interaction, Protox, ABUTH, AMARE, AMBEL, CHEAL, POLPY, SINAR, SOLPT, XANST, GLYMA, ZEAMA.

Abbreviations: COC, crop oil concentrate; DAP, days after planting; DAT, days after treatment; NIS, nonionic surfactant; Protox, protoporphyrinogen oxidase; UAN, 28% urea ammonium nitrate; v/v, volume per volume.

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[1]Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available from WSSA, 810 East 10th Street, Lawrence, KA 66044-8897.

INTRODUCTION

Several commercial and experimental herbicides including cyclic imides, diphenyl ethers, oxadiazoles, and triazolinones inhibit protoporphyrinogen oxidase (Protox), the enzyme that converts protoporphyrinogen IX to protoporphyrin IX (Anonymous 1995; Duke et al. 1991; Mito et al. 1991). Protox inhibition, although detectable in sensitive plant species 30 minutes after herbicide exposure, requires light to initiate herbicidal activity (Duke et al. 1990; Lehnen et al. 1990).

Fluthiacet and flumiclorac are cyclic imide herbicides used in corn and soybean to control broadleaf weeds postemergence (Porpiglia et al. 1994; Kamoshita et al. 1993). Fluthiacet and flumiclorac provided greater than 96% season-long velvetleaf control (Brown et al. 1991; Fausey and Renner 1998; Kapusta et al. 1995). However, season-long common cocklebur control with fluthiacet was 83% (Kapusta et al. 1995), and Pennsylvania smartweed control with flumiclorac was 60% (Brown et al. 1991). Tank mixtures with fluthiacet or flumiclorac provided more consistent broad-spectrum weed control when compared with fluthiacet or flumiclorac alone (Dill et al. 1994; James et al. 1994; Kurtz and Pawlak 1992). Fluthiacet or flumiclorac tank mixtures with acifluorfen (5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoic acid), atrazine, bentazon, chlorimuron (2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl] benzoic acid), dicamba, imazethapyr, nicosulfuron (2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-*N,N*-dimethyl-3-pyridinecarboxamide), primisulfuron, prosulfuron, or 2,4-D may enhance velvetleaf control and provide more consistent broadleaf weed control compared with these herbicides applied alone (Dill et al. 1994; James et al. 1994; Kurtz and Pawlak 1992).

Understanding interactions between herbicides used in tank mixtures is important for the development of effective weed control programs. Giant foxtail (*Setaria faberi* Herrm.) control with sethoxydim (2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) was not affected by adding fluthiacet or flumiclorac (James et al. 1994; Young et al. 1996); yet, shattercane (*Sorghum bicolor* (L.) Moench) control was reduced (Young et al. 1996). Large crabgrass (*Digitaria sanguinalis* (L.) Scop.) control with sethoxydim was not affected by the addition of fluthiacet, however, control was reduced when flumiclorac was added. Fluthiacet or flumiclorac tank mixtures with glyphosate (*N*-(phosphonomethyl)glycine) increased velvetleaf and common ragweed control compared with glyphosate alone (Lich et al. 1997). In contrast, tank mixing fluthiacet with oxasulfuron decreased common ragweed control compared with oxasulfuron alone (Nelson and Renner 1998).

Potential benefits of fluthiacet and flumiclorac include low use rates, short-half lives, resistance management, and the ability to broaden the spectrum of other herbicides (Anonymous 1995). Research investigating corn and soybean tolerance and weed control with fluthiacet or flumiclorac is limited. Tank mixtures including fluthiacet or flumiclorac may increase broadleaf weed control, however, affects on crop tolerance have not been reported. Therefore, the objective of this research was to evaluate corn and soybean tolerance and broadleaf weed control with fluthiacet and flumiclorac applied alone and in tank mixtures.

MATERIALS AND METHODS

General Methods for Greenhouse Experiments

Velvetleaf, common lambsquarters, common cocklebur, and eastern black nightshade seed were collected at the Michigan State University Research Farm in East Lansing. Redroot pigweed and common ragweed seed was obtained from a commercial seed supplier[2]. The corn variety 'Pioneer 3751'[3] and soybean variety 'Conrad' were evaluated.

Seeds were planted in BACCTO[4] potting soil in 946 ml plastic pots. Environmental conditions were maintained within a greenhouse at 27 ± 5 C. Plants were grown under a 16-h photoperiod of natural and supplemental high pressure sodium lighting with a photosynthetic photon flux density of 1000 μmol m^{-2} s^{-1}. Plants were thinned to 1 plant pot^{-1}, fertilized with 50 ml of a water-soluble fertilizer solution (400 ppm N, 400 ppm P_2O_5, and 400 ppm K_2O), and watered as needed. Herbicides were applied with a continuous belt-linked sprayer fitted with an 8001E flat-fan nozzle[5] traveling at 1.53 km h^{-1} and delivering 234 L ha^{-1} at 193 kPa of pressure.

Each experiment was a completely randomized design with four replications. Crop tolerance and weed control were visually evaluated in each experiment 3, 7 and 14 d after treatment (DAT). Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 indicating plant death. Evaluations represented visual stunting,

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[2]Seed, V & J Seed Farms, P.O. Box 82, Woodstock, IL 60098.

[3]Corn, Pioneer Hi-Bred International, Inc., Des Moines, IA 50301.

[4]BACCTO professional planting mix, Michigan Peat Co., P.O. Box 98129, Houston, TX 77098.

[5]Teejet flat-fan nozzles, Spraying Systems Co., North Avenue and Schmale Road, Wheaton, IL 60532.

chlorosis, and necrosis. Dry weight reduction was determined in each experiment 14 DAT by harvesting the aboveground plant material. Percent dry weight reduction was calculated as 100[1 - (plant dry weight/untreated plant dry weight)].

Species Sensitivity. Experiments compared weed sensitivity to fluthiacet and flumiclorac. Commercial formulations of each herbicide were applied at various rates. Herbicides were applied with 0.25% (v/v) nonionic surfactant[6] (NIS) and 1.0% (v/v) 28% urea ammonium nitrate (UAN). At application, velvetleaf plants were 5 cm tall with two leaves, 7.5 cm tall with four leaves, and 11 cm tall with six to seven leaves; common lambsquarters plants were 6 cm tall with six to eight leaves; redroot pigweed plants were 6 cm tall with four to six leaves; common ragweed plants were 6 cm tall with six to eight leaves; common cocklebur plants were 9 cm tall with four to five leaves; eastern black nightshade plants were 5 cm tall with five to seven leaves; and wild mustard plants were 6 cm tall with five to six leaves. Herbicide injury was visually evaluated, and aboveground biomass was harvested 14 DAT, oven dried, and weighed.

Separate experiments were conducted for each weed species. Data were fit to the log logistic model as described by Seefeldt et al. (1995). Nonlinear regression was conducted with SAS[7], and GR_{50} values were calculated for both plant dry weight reduction and the percent of the field use rate required to reduce plant growth by 50% (Table 1). Dry weight reduction represents the g ha^{-1} required to reduce plant growth by 50%, whereas percent of the field use rate represents the percent of either 4 g ha^{-1} fluthiacet or 30 g ha^{-1}

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[6]Activator-90, nonionic surfactant, a mixture of alkyl polyoxyethylene ether and fatty acids, Loveland Industries Inc., P.O. Box 1289, Greeley, CO 80632.

[7]SAS Institute Inc., SAS Circle, Box 8000, Cary, NC 27512-8000.

flumiclorac required to reduce plant growth by 50%.

Tank Mixtures with Fluthiacet and Flumiclorac. Experiments evaluated corn tolerance and weed control with tank mixtures including fluthiacet or flumiclorac. Treatments included an untreated control, 210 g ha^{-1} atrazine, 70 g ha^{-1} bromoxynil, 70 g ha^{-1} dicamba, 9 g ha^{-1} halosulfuron, 10 g ha^{-1} primisulfuron plus prosulfuron (6:4), and 140 g ha^{-1} 2,4-D amine applied alone and in a tank mixture with 1 g ha^{-1} fluthiacet or 8 g ha^{-1} flumiclorac. All atrazine treatments were applied with 1.0% (v/v) crop oil concentrate[8] (COC); and bromoxynil, dicamba, halosulfuron, primisulfuron plus prosulfuron, and 2,4-D treatments included 0.25% (v/v) NIS[6]. Corn plants were 16 cm tall with four leaves; velvetleaf plants were 11 cm tall with four to five leaves; common lambsquarters plants were 9 cm tall with 10 to 12 leaves; redroot pigweed plants were 10 cm tall with eight to ten leaves; and common ragweed plants were 10 cm tall with eight to 12 leaves. Herbicide injury was visually evaluated, and aboveground biomass was harvested 14 DAT, oven dried, and weighed.

Experiments evaluated soybean tolerance and weed control in the greenhouse with fluthiacet or flumiclorac tank mixtures. Treatments included an untreated control, 210 g ha^{-1} bentazon, 18 g ha^{-1} imazethapyr, 26 g ha^{-1} lactofen, and 16 g ha^{-1} oxasulfuron applied alone and in a tank mixture with 1 g ha^{-1} fluthiacet or 8 g ha^{-1} flumiclorac. All bentazon treatments were applied with 1.0% (v/v) COC[8]; imazethapyr and oxasulfuron treatments included 0.25% (v/v) NIS[6] plus 1.0% (v/v) UAN; and lactofen treatments included 0.5% COC[8]. At application, soybean plants were 10 cm tall with two trifoliolates, and weed

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[8]Herbimax, 83% petroleum oil, 17% surfactant, Loveland Industries Inc., P.O. Box 1289, Greeley, CO 80632.

sizes were as previously described. Herbicide injury was visually evaluated, and aboveground biomass was harvested 14 DAT, oven dried, and weighed.

Field Experiments

Corn. Experiments were conducted at the Michigan State University Research Farm in East Lansing, MI in 1996 and 1997. The soil was a Capac sandy clay loam (fine-loamy, mixed mesic Aeric Ochraqualfs) with 3.1 and 3.2% organic matter in 1996 and 1997, respectively. The soil pH was 6.5 and 7.2 in 1996 and 1997, respectively. Sites were fall moldboard plowed with secondary tillage consisting of two field cultivations at planting. 'DK 404 SR'[9] corn was planted in 76-cm rows at 62,000 seed ha^{-1} in 1996, and 'DK 493 SR'[9] corn was planted in 76-cm rows at 56,000 seed ha^{-1} in 1997. Plots were 3 m wide by 9.1 m in length.

The experiment was a randomized complete block with three replications. Treatments included 840 g ha^{-1} atrazine, 280 g ha^{-1} bromoxynil, 208 g ha^{-1} dicamba, 35 g ha^{-1} halosulfuron, 40 g ha^{-1} primisulfuron plus prosulfuron (6:4), and 560 g ha^{-1} 2,4-D amine applied alone and in a tank mixture with 4 g ha^{-1} fluthiacet or 30 g ha^{-1} flumiclorac. A weed-free control and an untreated control were included. All atrazine treatments included 1.0% (v/v) COC[8]; and bromoxynil, dicamba, halosulfuron, primisulfuron plus prosulfuron, and 2,4-D treatments included 0.25% (v/v) NIS[6]. Sethoxydim was applied broadcast for annual grass control June 3, 1996 and June 9, 1997.

Herbicides were applied on June 14, 1996 and June 13, 1997, 28 and 30 d after planting (DAP), with a compressed air tractor-mounted sprayer traveling at 5.7 km h^{-1} and

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[9]Corn, DEKALB Genetics Corporation, 3100 Sycamore Road Dekalb, IL 60115.

delivering 187 L ha^{-1} at 207 kPa of pressure. Treatments were applied with 8003 flat-fan nozzles spaced 51 cm apart and 48 cm above the weed canopy. At application, corn plants were 13 to 20 cm tall with five to six leaves; Pennsylvania smartweed plants were 1 to 3 cm tall and from cotyledon to three leaves; velvetleaf plants were 1 to 10 cm tall and from cotyledon to five leaves; common lambsquarters plants were 1 to 7 cm tall with two to ten leaves; and redroot pigweed plants were 1 to 8 cm tall and from cotyledon to eight leaves.

Corn injury was visually evaluated 3, 7, and 14 DAT. Weed control was evaluated for each species 7, 14, 21, 35, and 56 DAT. Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 signifying plant death. Corn injury and weed control evaluations represented visual stunting, chlorosis, and necrosis. The two middle rows from each plot were harvested with a Massey 10[10] small-plot combine. Corn yield was adjusted to 15.5% moisture.

Soybean. Experiments were conducted at the Michigan State University Research Farm in East Lansing, MI in 1996 and 1997. The soil was a Capac sandy clay loam (fine-loamy, mixed mesic Aeric Oehroqualfs) with 2.4% organic matter in 1996 and a sandy loam with 2.5% organic matter in 1997. The soil pH was 7.9 and 6.7 in 1996 and 1997, respectively. The 1996 and 1997 sites were fall chisel plowed with secondary tillage consisting of two field cultivations at planting. 'Conrad' soybean was planted in 76-cm rows at 395,000 seed ha^{-1}. Plots were 3 m wide by 12.2 m in length in 1996, and 3 m wide by 9.1 m in length in 1997.

The experiment was a randomized complete block with four replications. Treatments

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[10]Kincaid Equipment Manufacturing, P.O. Box 400, Haven, KS 47543.

included 840 g ha^{-1} bentazon, 105 g ha^{-1} lactofen, 70 g ha^{-1} imazethapyr, 65 g ha^{-1} oxasulfuron applied alone and in a tank mixture with 4 g ha^{-1} fluthiacet or 30 g ha^{-1} flumiclorac, a weed-free control, and an untreated control. All bentazon treatments were applied in combination with 1.0% (v/v) COC[8]; imazethapyr and oxasulfuron treatments included 0.25% (v/v) NIS[6] plus 1.0% (v/v) UAN; and lactofen treatments included 0.5% (v/v) COC[8].

Herbicides were applied on June 10, 1996 and June 17, 1997, 24 and 26 DAP, with a compressed air tractor-mounted sprayer traveling at 6.3 km h^{-1} and delivering 178 L ha^{-1} at 207 kPa of pressure. Treatments were applied with 8003 flat-fan nozzles spaced 51 cm apart and 48 cm above the weed canopy. At application, soybean plants were 8 to 10 cm tall with one fully developed trifoliolate; eastern black nightshade plants were 1 to 4 cm tall and from cotyledon to five leaves; common lambsquarters plants were 1 to 10 cm tall with two to 24 leaves; redroot pigweed plants were 1 to 8 cm tall and from cotyledon to eight leaves; and common ragweed plants were 1 to 7 cm tall and from cotyledon to eight leaves.

Soybean injury was visually evaluated 3, 7, and 14 DAT. Weed control was evaluated for each species 7, 14, 21, 35, and 56 DAT. Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 signifying plant death. Soybean injury and weed control evaluations represented visual stunting, chlorosis, and necrosis. The two middle rows from each plot were harvested with a Massey 10[10] small-plot combine. Soybean yield was adjusted to 13% moisture.

Statistical Analyses

All experiments were repeated over time, and data were analyzed using analysis of variance (ANOVA). Data for individual experiments were combined as analyses revealed no treatment by time interaction. Means were separated by Fisher's protected least significant difference test (LSD) at the 5% level.

RESULTS AND DISCUSSION

Greenhouse Experiments

Species Sensitivity. Species sensitivities to fluthiacet or flumiclorac were calculated as GR_{50} values based on a percent dry weight reduction and converted to the percent of the field use rate (Table 1). The field use rate for fluthiacet is 4 to 5 g ha^{-1} (Anonymous 1995), whereas flumiclorac is used at rates of 30 to 60 g ha^{-1} (Kurtz and Pawlak 1993). Calculated values for the percent of the field use rate of fluthiacet or flumiclorac required to reduce plant growth by 50% are based on application rates used in our field research; 4 and 30 g ha^{-1}, respectively.

Velvetleaf was sensitive to both herbicides. GR_{50} values were below 10% of the field use rate for either herbicide (Table 1). Two, four, and six to seven-leaf velvetleaf were more sensitive to fluthiacet when compared with flumiclorac. GR_{50} values calculated on the percent of the field use rate required to reduce the growth of four and six to seven leaf velvetleaf by 50% revealed greater sensitivity to fluthiacet compared with flumiclorac. However, GR_{50} values calculated on the percent of the field use rate revealed two leaf velvetleaf were more sensitive to flumiclorac than fluthiacet.

The quantity of active ingredient required to reduce common lambsquarters dry weight by 50% did not differ between fluthiacet and flumiclorac (Table 1). However, based on the percent of the field rate required for a 50% reduction in growth, common lambsquarters had greater tolerance to fluthiacet compared with flumiclorac.

GR_{50} values calculated on redroot pigweed, common ragweed, and common cocklebur dry weight reduction indicated these species were more sensitive to fluthiacet than flumiclorac. When the GR_{50} values were converted to a percent of the field use rate, values revealed redroot pigweed, common ragweed, and common cocklebur were more sensitive to flumiclorac than fluthiacet. These data support Kapusta et al. (1995) and Brown et al. (1991) that common ragweed is more sensitive to flumiclorac when compared with fluthiacet.

Eastern black nightshade and wild mustard required less active ingredient and a lower percent of the field use rate of fluthiacet to reduce growth by 50% when compared with flumiclorac. GR_{50} values for eastern black nightshade were below 12% of the field use rate for either herbicide, while GR_{50} values for wild mustard were 30% of the field use rate for fluthiacet and 245% for flumiclorac. Thus, our results suggest broadleaf weed sensitivity to fluthiacet and flumiclorac varies by species.

Tank Mixtures with Fluthiacet and Flumiclorac. Adding fluthiacet or flumiclorac to atrazine, dicamba, 2,4-D, bromoxynil, halosulfuron, or primisulfuron plus prosulfuron increased corn injury 3 DAT compared with these herbicides applied alone (Table 2). Tank mixtures with flumiclorac resulted in greater corn injury compared with fluthiacet tank mixtures.

Cantwell et al. (1989) and Wesley and Shaw (1992) reported that tank mixtures with Protox-inhibiting herbicides may increase or decrease weed control. Fluthiacet or flumiclorac tank mixtures with atrazine or dicamba increased velvetleaf and common lambsquarters control 14 DAT compared with atrazine or dicamba alone (Table 2). Redroot pigweed and common ragweed control increased when flumiclorac, but not when fluthiacet was tank mixed with atrazine or dicamba. Fluthiacet or flumiclorac tank mixtures with 2,4-D increased velvetleaf, redroot pigweed, and common ragweed control compared with 2,4-D alone. Velvetleaf, common lambsquarters, and redroot pigweed control with bromoxynil increased by adding fluthiacet or flumiclorac. Common lambsquarters control increased, but common ragweed control decreased with fluthiacet or flumiclorac plus halosulfuron compared with halosulfuron alone. Redroot pigweed control with primisulfuron plus prosulfuron increased by adding fluthiacet or flumiclorac. Fluthiacet or flumiclorac tank mixtures with halosulfuron or primisulfuron plus prosulfuron did not reduce velvetleaf control as previously reported (Hart 1997). With the exception of halosulfuron, the addition of fluthiacet or flumiclorac did not decrease broadleaf weed control in these greenhouse studies.

Adding fluthiacet or flumiclorac to bentazon, imazethapyr, lactofen, or oxasulfuron increased soybean injury 3 DAT compared with bentazon, imazethapyr, lactofen, or oxasulfuron alone (Table 3). Fluthiacet or flumiclorac tank mixtures with bentazon increased velvetleaf, common lambsquarters, and redroot pigweed control compared with bentazon alone 14 DAT. Common lambsquarters, redroot pigweed, and common ragweed control with imazethapyr increased by adding flumiclorac. However, adding fluthiacet to imazethapyr only increased common lambsquarters control. Adding fluthiacet or flumiclorac to lactofen increased velvetleaf, common lambsquarters, and common ragweed control. However, redroot pigweed control with lactofen increased only when flumiclorac was added. Fluthiacet or flumiclorac tank mixtures with oxasulfuron decreased common ragweed control compared with oxasulfuron alone. Similarly, Nelson and Renner (1998) observed decreased common ragweed control in a tank mixture of oxasulfuron plus fluthiacet. Greenhouse results confirm reports that tank mixtures with Protox-inhibiting herbicides, such as fluthiacet and flumiclorac, can increase or decrease weed control.

Field Experiments

Corn. Adding fluthiacet or flumiclorac to atrazine, dicamba, 2,4-D, bromoxynil, halosulfuron, or primisulfuron plus prosulfuron increased corn injury 7 DAT compared with these herbicides alone (Table 4). Corn injury was greater from flumiclorac tank mixtures with atrazine, bromoxynil, halosulfuron, and 2,4-D compared with fluthiacet tank mixtures. These results support our greenhouse observations that suggested corn injury increased more by the addition of flumiclorac to these herbicides.

Fluthiacet or flumiclorac tank mixtures with atrazine, dicamba, or 2,4-D increased velvetleaf control 56 DAT compared with the control provided by atrazine, dicamba, or 2,4-D alone. However, Pennsylvania smartweed control was less than 50% 35 DAT when 2,4-D was tank mixed with fluthiacet or flumiclorac. Broadleaf weed control in the greenhouse and in the field was not reduced when fluthiacet or flumiclorac was tank mixed with atrazine, dicamba, or 2,4-D. However, corn yield did not increase with increased weed control. Schmenk and Kells (1998) reported reduced velvetleaf competition in corn following an atrazine application. Thus, applying atrazine, dicamba, or 2,4-D may reduce velvetleaf competitiveness in corn to a level where increased velvetleaf control from fluthiacet or flumiclorac tank mixtures would not increase corn yield.

In contrast to our greenhouse studies, velvetleaf, common lambsquarters, and redroot pigweed control with bromoxynil in the field were not affected by the addition of fluthiacet or flumiclorac. Fluthiacet or flumiclorac tank mixtures with the fast-acting contact herbicide lactofen displayed similar inconsistences.

Tank mixtures of fluthiacet or flumiclorac with halosulfuron increased early season common lambsquarters control (data not presented), but by 56 DAT, common lambsquarters control was less than 75%. In contrast to our greenhouse studies, broadleaf weed control did not decrease in the field when fluthiacet or flumiclorac were tank mixed with halosulfuron. Fluthiacet or flumiclorac tank mixtures with primisulfuron plus prosulfuron increased common lambsquarters control 56 DAT compared with primisulfuron plus prosulfuron alone.

Soybean. Fluthiacet or flumiclorac added to bentazon, imazethapyr, lactofen, or oxasulfuron increased soybean injury 7 DAT compared with these herbicides alone (Table 5). In the greenhouse, soybean injury was similar from tank mixtures of fluthiacet or flumiclorac with bentazon, imazethapyr, lactofen, and oxasulfuron. However, soybean injury in the field was greater from flumiclorac tank mixtures with bentazon or oxasulfuron compared with fluthiacet plus bentazon or oxasulfuron.

Tank mixtures of fluthiacet or flumiclorac with bentazon increased velvetleaf, common lambsquarters, and redroot pigweed control in the greenhouse (Table 3). Similarly, broadleaf weed control in the field with bentazon plus fluthiacet or flumiclorac was greater than 90% for all species 14 DAT (data not presented). However, late emerging redroot pigweed, common ragweed, and eastern black nightshade reduced season-long control to less than 80% with these tank mixtures (Table 5).

In the field, common lambsquarters control with lactofen increased by adding fluthiacet or flumiclorac compared with lactofen alone, but was less than 60% 56 DAT (Table 5). The addition of fluthiacet to lactofen reduced common ragweed control in the field but increased control in the greenhouse compared with lactofen alone. Fluthiacet or flumiclorac tank mixtures with lactofen did not provide season-long broadleaf weed control in the field. Data suggests fluthiacet or flumiclorac tank mixtures with fast-acting contact herbicides, such as lactofen or bromoxynil, may provide fewer benefits than tank mixtures with other herbicides.

Despite reports of acifluorfen or bentazon antagonism with imazethapyr (Cantwell et al. 1989), weed control in the greenhouse and in the field was not reduced by fluthiacet or flumiclorac tank mixtures with imazethapyr. Tank mixtures of imazethapyr with fluthiacet or flumiclorac increased common ragweed control and soybean yield in the field compared with imazethapyr alone. Common lambsquarters control with fluthiacet or flumiclorac plus imazethapyr was 90 and 92% 56 DAT, respectively. Similarly, common lambsquarters control with 2 or 3 g ha^{-1} thifensulfuron (3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]-2- thiophenecarboxylic acid) plus 70 g ha^{-1} imazethapyr was 85 and 93% 28 DAT, respectively (Simpson and Stoller 1995).

Tank mixtures of fluthiacet or flumiclorac with oxasulfuron increased redroot pigweed and common ragweed control in the field yet reduced common ragweed control in the greenhouse compared with oxasulfuron alone. Fluthiacet or flumiclorac tank mixtures with oxasulfuron increased eastern black nightshade control compared with oxasulfuron alone, yet control was less than 60% 35 DAT.

Fluthiacet and flumiclorac display activity on various broadleaf weeds. A single application of these herbicides provided exceptional velvetleaf control but insufficient broad-spectrum broadleaf weed control in the field (Fausey and Renner 1998). Likewise, no other postemergence herbicide applied alone provided season-long control of all broadleaf species evaluated. However, tank mixtures of atrazine, dicamba, imazethapyr, and primisulfuron plus prosulfuron with fluthiacet or flumiclorac provided season-long broadleaf weed control of all the species evaluated. These results confirm reports by James et al. (1994) and Kurtz and Pawlak (1993) that adding fluthiacet or flumiclorac to atrazine, bentazon, dicamba, imazethapyr, or 2,4-D improved broadleaf weed control.

Corn and soybean exhibited minor leaf necrosis from tank mixtures with fluthiacet or flumiclorac but outgrew the injury by 21 DAT (data not presented). Kapusta et al. (1986) and Wichert and Talbert (1993) reported that leaf necrosis does not affect soybean yield, yet the effect Protox-inhibiting herbicides have on corn yield remains unclear. Corn yield did not increase when weed control increased with fluthiacet or flumiclorac tank mixtures plus atrazine or dicamba. However, soybean yield increased when fluthiacet or flumiclorac was tank mixed with imazethapyr or oxasulfuron compared with imazethapyr or oxasulfuron alone.

Tank mixtures including fluthiacet or flumiclorac have several advantages. Increased weed control with fluthiacet or flumiclorac tank mixtures would decrease future weed infestations by reducing weed seed return to the soil seed bank. Tank mixtures including fluthiacet or flumiclorac also provide additional strategies for managing weed resistance. Research investigating fluthiacet or flumiclorac tank mixtures in herbicide resistant corn and soybean would be beneficial for weed control programs in these genetically modified crops.

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Table 1. Weed species sensitivities to fluthiacet and flumiclorac in the greenhouse.[a]

		GR_{50}[b]			
	Growth	Dry weight basis		Field rate[c]	
Species	stage	Fluthiacet	Flumiclorac	Fluthiacet	Flumiclorac
	True leaves	—— g ha^{-1} ——		—— % ——	
Velvetleaf	2	0.1 a	0.7 b	3 b	2 a
	4	0.3 a	2.5 b	6 a	8 b
	6-7	0.2 a	1.5 b	4 a	5 b
Common lambsquarters	6-8	2.9 a	3.0 a	70 b	10 a
Redroot pigweed	4-6	0.9 a	2.4 b	22 b	8 a
Common ragweed	6-8	1.1 a	3.3 b	27 b	11 a
Common cocklebur	4-5	0.8 a	3.0 b	19 b	10 a
Eastern black nightshade	5-7	0.4 a	3.4 b	10 a	11 a
Wild mustard	5-6	1.2 a	74.1 b	30 a	245 b

[a]All treatments included 0.25% (v/v) nonionic surfactant (NIS) and 1.0% (v/v) 28% urea ammonium nitrate (UAN). Significance between herbicides is only to be compared across rows. Values followed by a common letter are not significantly different at the 5% level.
[b]Dry weight reduction represents the g ha^{-1} required to reduce plant growth by 50%, whereas percent of the field use rate represents the percent of either 4 g ha^{-1} fluthiacet or 30 g ha^{-1} flumiclorac required to reduce plant growth by 50%.
[c]Calculated based on a field use rate of 4 g ha^{-1} fluthiacet and 30 g ha^{-1} flumiclorac.

Table 2. Corn injury 3 d after treatment (DAT) and broadleaf weed control 14 DAT in the greenhouse with fluthiacet or flumiclorac tank mixtures.[a]

Herbicide	Rate	ZEAMA	ABUTH	CHEAL	AMARE	AMBEL
	g ha^{-1}	% injury	———	% control	———	
Atrazine	210	0	19	31	72	59
Atrazine + fluthiacet	210 +1	5	59	45	78	63
Atrazine + flumiclorac	210 +8	10	74	53	93	71
Dicamba	70	0	30	57	60	61
Dicamba + fluthiacet	70 + 1	3	50	67	65	62
Dicamba + flumiclorac	70 + 8	6	68	77	81	74
2, 4-D	140	5	39	77	32	53
2,4-D + fluthiacet	140 +1	8	61	77	62	60
2,4-D + flumiclorac	140 +8	11	60	78	85	74
Bromoxynil	70	1	43	32	15	67
Bromoxynil + fluthiacet	70 + 1	6	63	48	49	65
Bromoxynil + flumiclorac	70 + 8	12	63	57	85	66
Halosulfuron	9	0	71	0	58	75
Halosulfuron + fluthiacet	9 + 1	3	67	21	63	66
Halosulfuron + flumiclorac	9 + 8	6	54	26	70	53
Primisulfuron + prosulfuron	10	0	72	51	64	76
Primisulfuron + prosulfuron + fluthiacet	10 + 1	4	68	48	75	73
Primisulfuron + prosulfuron + flumiclorac	10 + 8	7	67	52	81	75
Untreated control	—	0	0	0	0	0
LSD (0.05)		2	6	5	8	6

[a]All atrazine treatments included 1.0% crop oil concentrate (COC); bromoxynil, dicamba, halosulfuron, primisulfuron plus prosulfuron, and 2, 4-D treatments included 0.25% (v/v) nonionic surfactant (NIS).

Table 3. Soybean injury 3 d after treatment (DAT) and broadleaf weed control 14 DAT in the greenhouse with fluthiacet or flumiclorac tank mixtures.[a]

Herbicide	Rate	GLYMA	ABUTH	CHEAL	AMARE	AMBEL
	g ha^{-1}	%	% control			
Bentazon	210	1	65	33	35	46
Bentazon + fluthiacet	210 + 1	12	96	40	58	49
Bentazon + flumiclorac	210 + 8	12	95	47	80	53
Imazethapyr	18	10	66	28	78	46
Imazethapyr + fluthiacet	18 + 1	12	68	36	80	53
Imazethapyr +	18 + 8	12	67	40	93	64
Lactofen	26	15	43	20	87	79
Lactofen + fluthiacet	26 + 1	19	67	39	87	89
Lactofen + flumiclorac	26 + 8	20	81	57	97	92
Oxasulfuron	16	7	85	51	66	55
Oxasulfuron + fluthiacet	16 + 1	10	87	44	60	46
Oxasulfuron + flumiclorac	16 + 8	12	81	47	76	42
Untreated control	—	0	0	0	0	0
LSD (0.05)		2	6	6	9	8

[a]All bentazon treatments included 1.0% crop oil concentrate (COC); imazethapyr and oxasulfuron treatments included 0.25% (v/v) nonionic surfactant (NIS) plus 1.0% (v/v) 28% urea ammonium nitrate (UAN); and lactofen treatments included 0.5% (v/v) COC.

Table 4. Corn injury, broadleaf weed control, and corn yield in the field with fluthiacet or flumiclorac tank mixtures.[a]

		7 DAT[b]	35 DAT	56 DAT			
Herbicide[c]	Rate	ZEAMA	POLPE	ABUTH	CHEAL	AMARE	ZEAMA
	g ha^{-1}	% injury	% control				kg ha^{-1}
Atrazine	840	0	99	41	97	97	10137
Atrazine + fluthiacet	840 + 4	11	99	96	97	97	10172
Atrazine + flumiclorac	840 + 30	19	98	96	97	96	10786
Dicamba	280	1	90	72	95	85	10257
Dicamba + fluthiacet	280 + 4	9	88	87	96	85	10425
Dicamba + flumiclorac	280 + 30	12	81	88	94	86	10048
2,4-D	560	22	35	60	90	82	9619
2,4-D + fluthiacet	560 + 4	27	47	82	94	87	9654
2,4-D + flumiclorac	560 + 30	31	48	82	94	88	9641
Bromoxynil	280	15	98	79	88	79	9782
Bromoxynil + fluthiacet	280 + 4	23	98	79	89	79	10056
Bromoxynil + flumiclorac	280 + 30	28	98	76	89	78	10222
Halosulfuron	35	3	74	87	7	78	9755
Halosulfuron + fluthiacet	35 + 4	8	67	95	72	96	9964
Halosulfuron + flumiclorac	35 + 30	13	81	93	58	95	10087
Primisulfuron + prosulfuron	40	3	96	92	82	92	9927

Table 4. Continued

Primisulfuron + prosulfuron + fluthiacet	40 + 4	10	99	97	91	97	9805
Primisulfuron + prosulfuron + flumiclorac	40 + 30	14	97	95	91	96	9964
Weed-free control	—	0	100	100	100	100	10164
Untreated control	—	0	0	0	0	0	7103
LSD (0.05)		4	14	9	5	7	744

[a] Data averaged over 1996 and 1997.

[b] Days after treatment (DAT).

[c] All atrazine treatments included 1.0% crop oil concentrate (COC); bromoxynil, dicamba, halosulfuron, primisulfuron plus prosulfuron, and 2,4-D treatments included 0.25% (v/v) nonionic surfactant (NIS).

Table 5. Soybean injury, broadleaf weed control, and soybean yield in the field with fluthiacet or flumiclorac tank mixtures.[a]

		7 DAT[b]	35 DAT	56 DAT			
Herbicide[c]	Rate	GLYMA	SOLPT	CHEAL	AMARE	AMBEL	GLYMA
	g ha^{-1}	% injury	——— % control ———				kg ha^{-1}
Bentazon	840	4	34	89	34	58	2445
Bentazon + fluthiacet	840 + 4	22	69	88	66	62	2718
Bentazon + flumiclorac	840 + 30	25	78	87	71	66	2592
Imazethapyr	70	12	99	86	93	52	2574
Imazethapyr + fluthiacet	70 + 4	17	97	90	97	75	3102
Imazethapyr + flumiclorac	70 + 30	18	99	92	97	86	3322
Lactofen	105	28	90	4	95	91	2503
Lactofen + fluthiacet	105 + 4	32	92	50	89	81	2998
Lactofen + flumiclorac	105 + 30	31	88	53	86	81	2750
Oxasulfuron	65	7	21	88	74	60	2783
Oxasulfuron + fluthiacet	65 + 4	16	50	93	85	71	3269
Oxasulfuron + flumiclorac	65 + 30	19	57	92	92	86	3579
Weed-free control	—	0	100	100	100	100	3453
Untreated control	—	0	0	0	0	0	843
LSD (0.05)		2	11	8	6	9	361

[a] Data averaged over 1996 and 1997.

[b] Days after treatment (DAT).

[c] All bentazon treatments included 1.0% crop oil concentrate (COC); imazethapyr and oxasulfuron treatments included 0.25% (v/v) nonionic (NIS) surfactant plus 1.0% (v/v) 28% urea ammonium nitrate (UAN); and lactofen treatments included 0.5% (v/v)COC.

CHAPTER 5

Incorporating Fluthiacet and Flumiclorac into Annual Weed Control Programs for Corn (*Zea mays*) and Soybean (*Glycine max*)

ABSTRACT

Greenhouse and field studies evaluated annual weed control programs for corn and soybean that included fluthiacet and flumiclorac. Fluthiacet or flumiclorac added to imazethapyr, quizalofop, sethoxydim, or clethodim did not affect giant foxtail and barnyardgrass control. Fluthiacet or flumiclorac added to fluazifop increased giant foxtail control compared with fluazifop alone. However, barnyardgrass control with fluazifop decreased in the greenhouse when flumiclorac was added. Velvetleaf control with fluthiacet and flumiclorac was greatest 7 DAT when applied to 5 cm tall plants in the field. However, season-long velvetleaf control with both herbicides was greatest when applied to 45 or 60 cm tall plants. In field studies, fluthiacet or flumiclorac applied POST following metolachlor or metolachlor plus atrazine PRE increased velvetleaf control compared to only a PRE application of metolachlor plus atrazine. Similarly, fluthiacet or flumiclorac added to 2,4-D applied POST following metolachlor applied PRE increased velvetleaf control compared to metolachlor followed by 2,4-D alone. Velvetleaf control also increased when fluthiacet or flumiclorac were tank mixed with nicosulfuron plus

atrazine, or nicosulfuron plus dicamba applied POST. In soybean, metolachlor plus metribuzin plus clomazone applied PRE, metolachlor applied PRE followed by fluthiacet or flumiclorac applied POST, metolachlor plus metribuzin applied PRE followed by fluthiacet or flumiclorac applied POST, imazethapyr plus fluthiacet or flumiclorac applied POST, glyphosate alone, and tank mixtures of glyphosate with fluthiacet or flumiclorac applied LATE POST controlled giant foxtail, common lambsquarters, redroot pigweed, and velvetleaf in 1997. However, only metolachlor plus metribuzin applied PRE followed by fluthiacet or flumiclorac applied POST and imazethapyr plus fluthiacet or flumiclorac applied POST controlled these weeds in 1998.

Nomenclature: Atrazine, 6-chloro-*N*-ethyl-*N*'-(1-methylethyl)-1,3,5-triazine-2,4-diamine; bromoxynil, 3,5-dibromo-4-hydroxybenzonitrile; 2,4-D, (2,4-dichlorophenoxy)acetic acid; clethodim, (*E,E*)-(±)-2-[1-[[(3-chloro-2-propenyl)oxy]imino]butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one; clomazone, 2-[(2-chlorophenyl)methyl]4,4-dimethyl-3-isoxazolidinone; dicamba, 3,6-dichloro-2-methoxybenzoic acid; fluazifop, (±)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoic acid; fluthiacet, methyl[[2-chloro-4-fluoro-5-[(tetrahydro-3-oxo-1*H*, 3*H*-[1,3,4]thiadiazolo[3,4-a]pyridazin-1-ylidene)amino]phenyl]thio]acetate; flumiclorac, pentyl[2-chloro-4-fluoro-5-(1,3,4,5,6,7-hexahydro-1,3-dioxo-2*H*-isoindol-2-yl)phenoxy]acetic acid; glyphosate (*N*-(phosphonomethyl)glycine); imazethapyr, 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid; metolachlor, 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide; metribuzin, 4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one; nicosulfuron (2-[[[[(4,6-

dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]-*N,N*-dimethyl-3-pyridinecarboxamide); oxasulfuron, 2-[[[[(4,6-dimethyl-2-pyrimidinyl)-amino]carbonyl]amino]sulfonyl] benzoic acid, 3-oxetanyl ester; quizalofop (±)-2-[4-[(6-chloro-2-quinoxalinyl)oxy]phenoxy]propanoic acid; sethoxydim, 2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one; 2,4-D, (2,4-dichlorophenoxy)acetic acid; common lambsquarters, *Chenopodium album* L. # CHEAL; redroot pigweed, *Amaranthus retroflexus* L. # AMARE; barnyardgrass, Echinochloa *Crus-galli* L. Beauv. ECHCG; giant foxtail, *Setaria faberi* Herrm. # SETFA; velvetleaf, *Abutilon theophrasti* Medik. #[1] ABUTH; wild mustard, *Brassica kaber* (D.C.) L.C. Wheeler # SINAR; corn, *Zea mays* L. # ZEAMA; soybean, *Glycine max* (L.) Merr. # GLYMA.

Key Words: Antagonism, herbicide interaction, Protox, ABUTH, AMARE, CHEAL, SETFA, GLYMA, ZEAMA.

Abbreviations: COC, crop oil concentrate; DAP, days after planting; DAT, days after treatment; LATE POST, late postemergence; NIS, nonionic surfactant; POST, postemergence; Protox, protoporphyrinogen oxidase; PRE, preemergence; UAN, 28% urea ammonium nitrate.

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[1]Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available from WSSA, 810 East 10th Street, Lawrence, KA 66044-8897.

INTRODUCTION

Fluthiacet and flumiclorac are cyclic imide herbicides that effectively control velvetleaf, one of the most troublesome broadleaf weeds in corn and soybean (Porpiglia et al. 1994; Kamoshita et al. 1993). These selective herbicides control weeds by inhibiting the protoporphyrinogen oxidase (Protox) enzyme in susceptible plants (Duke et al. 1990; Duke et al. 1991; Mito et al. 1991).

Fluthiacet and flumiclorac provided greater than 96% season-long velvetleaf control (Brown et al. 1991; Kapusta et al. 1995). However, season-long common cocklebur control with fluthiacet was 83% (Kapusta et al. 1995), and Pennsylvania smartweed control with flumiclorac was 60% (Brown et al. 1991).

Broad-spectrum weed control is commonly achieved by tank mixing herbicides. Tank mixtures including fluthiacet or flumiclorac may enhance velvetleaf control and provide more consistent broadleaf weed control compared with the tank mix partner alone (Dill et al. 1994; James et al. 1994; Kurtz and Pawlak 1992). Understanding herbicide performance in tank mixtures is important when creating weed management programs (Young et al. 1996). Giant foxtail control with sethoxydim (2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) was not affected by the addition of fluthiacet or flumiclorac (James et al. 1994; Young et al. 1996); however, shattercane (*Sorghum bicolor* (L.) Moench) control was reduced (Young et al. 1996). Similarly, large crabgrass (*Digitaria sanguinalis* (L.) Scop.) control with sethoxydim was not affected by the addition of fluthiacet, however, control was reduced by adding flumiclorac. Fluthiacet or flumiclorac tank mixtures with glyphosate (*N*-(phosphonomethyl)glycine) increased velvetleaf and common ragweed control compared with glyphosate alone (Lich et al. 1997). However, adding fluthiacet to oxasulfuron reduced common ragweed control compared with oxasulfuron alone (Nelson and Renner 1998).

Potential benefits of fluthiacet and flumiclorac include low use rates, short-half lives, resistance management, and the ability to broaden the spectrum of other herbicides (Anonymous 1995). Research investigating broad-spectrum weed control programs in corn and soybean with fluthiacet or flumiclorac is limited. Field research has not determined the most effective time to apply fluthiacet or flumiclorac in corn or soybean or their performance with other postemergence herbicides. Therefore, the objective of this research was to evaluate broad-spectrum weed control programs in corn and soybean that include fluthiacet and flumiclorac.

MATERIALS AND METHODS

Greenhouse Experiments

Annual Grass Control with Fluthiacet and Flumiclorac Tank Mixtures. Giant foxtail and barnyardgrass seed was obtained from a commercial seed supplier[2]. Seeds were planted in BACCTO[3] potting soil in 946 ml plastic pots. Environmental conditions were maintained within a greenhouse at 27 ± 5 C. Plants were grown under a 16-h photoperiod of natural and supplemental high pressure sodium lighting with a photosynthetic photon

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[2]Seed, V & J Seed Farms, P.O. Box 82, Woodstock, IL 60098.

[3]BACCTO professional planting mix, Michigan Peat Co., P.O. Box 98129, Houston, TX 77098.

flux density of 1000 μmol m^{-2} s^{-1}. Plants were thinned to 1 plant pot^{-1}, fertilized with 50 ml of a water-soluble fertilizer solution (400 ppm N, 400 ppm P_2O_5, and 400 ppm K_2O), and watered as needed. Herbicides were applied with a continuous belt-linked sprayer fitted with an 8001E flat-fan nozzle[4] traveling at 1.53 km h^{-1} and delivering 234 L ha^{-1} at 193 kPa of pressure.

The experiment was a completely randomized design with four replications. Giant foxtail and barnyardgrass were visually evaluated in each experiment 3, 7 and 14 d after treatment (DAT). Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 indicating plant death. Evaluations represented visual stunting, chlorosis, and necrosis.

Experiments evaluated giant foxtail and barnyardgrass control with tank mixtures including fluthiacet and flumiclorac. Treatments included an untreated control, 18 g ha^{-1} imazethapyr, 12 g ha^{-1} quizalofop, 52 g ha^{-1} sethoxydim, 35 g ha^{-1} clethodim, and 52 g ha^{-1} fluazifop applied alone and in a tank mixture with 1 g ha^{-1} fluthiacet or 8 g ha^{-1} flumiclorac. All treatments were applied with crop oil concentrate[5] (COC) (1.0% v/v). Giant foxtail plants were 10 cm tall with three to four leaves, and barnyardgrass plants were 10 cm tall with two to three leaves at application. Giant foxtail and barnyardgrass were visually evaluated for phytotoxicity 7 and 14 DAT. Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 signifying plant death. Evaluations represented visual stunting, chlorosis, and necrosis.

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[4]Teejet flat-fan nozzles, Spraying Systems Co., North Avenue and Schmale Road, Wheaton, IL 60532.

[5]Herbimax, 83% petroleum oil, 17% surfactant, Loveland Industries Inc., P.O. Box 1289, Greeley, CO 80632.

Field Experiments

Annual Grass Control with Fluthiacet and Flumiclorac Tank Mixtures. Research was conducted at the Michigan State University Research Farm in East Lansing, MI in 1997. The soil was a Capac sandy clay loam (fine-loamy, mixed mesic Aeric Ochraqualfs) with 2.8% organic matter and a pH of 6.6. The site was fall moldboard plowed with secondary tillage consisting of two field cultivations at planting. 'Conrad' soybean was planted in 76-cm rows at 345,000 seed ha^{-1}. Plots were 3 m wide by 10.6 m in length.

The experiment was a randomized complete block with four replications. Treatments included an untreated control, 140 g ha^{-1} clethodim, and 210 g ha^{-1} fluazifop applied alone and in a tank mixture with 5 g ha^{-1} fluthiacet or 45 g ha^{-1} flumiclorac. All treatments included COC[5] (1.0% v/v).

Herbicides were applied on June 17, 1997, 35 d after planting (DAP), with a compressed air tractor-mounted sprayer traveling at 6.3 km h^{-1} and delivering 178 L ha^{-1} at 207 kPa of pressure. Treatments were applied with 8003 flat-fan nozzles spaced 51 cm apart and 48 cm above the weed canopy. At application, soybean plants were 8 to 10 cm tall with one fully developed trifoliolate; and giant foxtail and barnyardgrass plants were 1 to 12 cm tall with one to five leaves.

Giant foxtail and barnyardgrass control was evaluated 7, 14, and 28 DAT. Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 signifying plant death. Evaluations represented visual stunting, chlorosis, and necrosis.

Velvetleaf Control. Experiments were conducted at the Michigan State University Research Farm in East Lansing, MI in 1996 and 1997. The soil was a Capac sandy loam (fine-loamy, mixed mesic Aeric Ochraqualfs) with 2.5 and 2.4% organic matter in 1996 and 1997, respectively. The soil pH was 6.5 in 1996 and 1997. Sites were spring chisel plowed with secondary tillage consisting of two field cultivations at planting. Dekalb[6] '404 SR' corn was planted in 76-cm rows at 62,000 seed ha^{-1}. Plots were 3 m wide by 9.1 m in length.

The experiment was a randomized complete block with four replications. Treatments included 4 and 5 g ha^{-1} fluthiacet or 30 and 45 g ha^{-1} flumiclorac applied with COC[5] 0.5% (v/v). Herbicides were applied on June 12, July 2, and July 9, 1996 and June 10, June 27, and July 1, 1997 with a compressed air tractor-mounted sprayer traveling at 6.3 km h^{-1} and delivering 178 L ha^{-1} at 207 kPa of pressure. Treatments were applied with 8003 flat-fan nozzles spaced 51 cm apart and 48 cm above the weed canopy. At application, velvetleaf plants were 2 cm tall and from cotyledon to two-leaf stage; 45 cm tall with eight to 10 leaves; and 60 cm tall with ten to 12 leaves.

Corn injury was visually evaluated 3, 7, and 14 DAT. Velvetleaf control was evaluated 7 and 14 DAT, and 21 d after the third application timing. Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 signifying plant death. Corn injury and velvetleaf control evaluations represented visual stunting, chlorosis, and necrosis.

Annual Weed Control in Corn. Experiments were conducted at the Michigan State University Research Farm at East Lansing, MI and at the Michigan State Horticultural Research Station at Clarksville, MI in 1998. The East Lansing soil was a Capac sandy clay loam (fine-loamy, mixed mesic Aeric Ochraqualfs) with 2.5% organic matter and a pH of 6.5. The Clarksville soil was a Lapeer sandy loam (coarse-loamy, mixed mesic

[6]Corn, DEKALB Genetics Corporation, 3100 Sycamore Road Dekalb, IL 60115.

Mollic Haplaquepts) with 1.9% organic matter and a pH of 6.8. Sites were spring moldboard plowed with secondary tillage consisting of two field cultivations at planting. Dekalb[6] '493 RR' corn was planted in 76-cm rows at 62,000 seed ha^{-1}. Plots were 3 m wide by 10.6 m in length.

The experiment was a randomized complete block with four replications. Treatments included a weed-free and an untreated control. All POST atrazine treatments included COC[5] (1.0% v/v). All 2,4-D, dicamba, and bromoxynil treatments included Activator 90[7] (NIS) (0.25% v/v). Fluthiacet, flumiclorac, and glyphosate treatments included NIS[7] plus UAN (0.25 + 1.0% v/v).

PRE herbicide applications were applied on May 26, 1998 at East Lansing and May 19, 1998 at Clarksville. POST herbicide applications were applied at East Lansing and Clarksville on June 26, 1998 and June 18, 1998, 31 and 30 DAP, respectively. LATE POST applications were applied at East Lansing and Clarksville on June 29, 1998 and June 23, 1998, respectively. All herbicide treatments were applied with a compressed air tractor-mounted sprayer traveling at 6.3 km h^{-1} and delivering 178 L ha^{-1} at 207 kPa of pressure. Treatments were applied with 8003 flat-fan nozzles spaced 51 cm apart and 48 cm above the weed canopy. At the time of POST applications corn plants were 25 to 30 cm tall with five collars; giant foxtail plants were 1 to 15 cm tall with one to four leaves; common lambsquarters plants were 1 to 10 cm tall with two to 18 leaves; redroot pigweed plants were 1 to 8 cm tall and from cotyledon to ten leaves; and velvetleaf plants were 1 to 10 cm tall and from cotyledon to six leaves. At the time of LATE POST

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[7]Activator 90, nonionic surfactant, a mixture of alkyl polyoxyethylene ether and fatty acids, Loveland Industries, Inc., P.O. Box 1289, Greeley, CO 80632.

application corn plants were 30 to 38 cm tall with six collars; giant foxtail plants were 1 to 22 cm tall with one to six leaves; common lambsquarters plants were 1 to 15 cm tall with two to 30 leaves; redroot pigweed plants were 1 to 18 cm tall with two to 12 leaves; and velvetleaf plants were 1 to 18 cm tall with two to eight leaves.

Corn injury was visually evaluated 7 and 14 DAT. Weed control was evaluated for each species 14, 28, and 56 DAT. Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 signifying plant death. Corn injury and weed control evaluations represented visual stunting, chlorosis, and necrosis. The two middle rows from each plot were harvested with a Massey 10[8] small-plot combine. Corn yield was adjusted to 15.5% moisture.

Annual Weed Control in Soybean. Experiments were conducted at the Michigan State University Research Farm at East Lansing, MI in 1997 and 1998. The soil was a Capac sandy clay loam (fine-loamy, mixed mesic Aeric Ochraqualfs) with 2.8 and 4.2% organic matter in 1997 and 1998, respectively. The soil pH was 6.6 and 6.3 in 1997 and 1998, respectively. Sites were fall chisel plowed with secondary tillage consisting of two field cultivations at planting. Asgrow[9] '2701 RR' soybean was planted in 76-cm rows at 345,000 seed ha^{-1}. Plots were 3 m wide by 10.6 m in length.

The experiment was a randomized complete block with four replications. Treatments included a weed-free and an untreated control. All fluthiacet, flumiclorac, imazethapyr, oxasulfuron, and glyphosate treatments were applied with NIS[7] plus UAN (0.25 + 1.0% v/v). All clethodim treatments included COC[5] (1.0% v/v).

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[8]Kincaid Equipment Manufacturing, P.O. Box 400, Haven, KS 47543.

[9]Soybean, Asgrow Seed Company, P.O. Box 7570, Des Moines, IA 50322.

PRE herbicide applications were applied on May 13, 1997 and 1998. POST herbicide applications were applied on June 17, 1997 and June 8, 1998, 35 and 26 DAP, and LATE POST applications were applied on June 22, 1997 and June 14, 1998. All herbicide treatments were applied with a compressed air tractor-mounted sprayer traveling at 6.3 km h^{-1} and delivering 178 L ha^{-1} at 207 kPa of pressure. Treatments were applied with 8003 flat-fan nozzles spaced 51 cm apart and 48 cm above the weed canopy. At the time of POST applcations soybean plants were 10 to 14 cm tall with two fully developed trifoliolates; giant foxtail plants were 1 to 15 cm tall and from one to four leaves; common lambsquarters plants were 1 to 10 cm tall with two to 22 leaves; redroot pigweed plants were 1 to 8 cm tall and from cotyledon to ten leaves; and velvetleaf plants were 1 to 10 cm tall and from cotyledon to five leaves. At the time of LATE POST applications soybean plants were 15 to 20 cm tall with two to three trifoliolates; giant foxtail plants were 1 to 20 cm tall and from one to six leaves; common lambsquarters plants were 1 to 15 cm tall with four to 26 leaves; redroot pigweed plants were 1 to 10 cm tall with two to 12 leaves; and velvetleaf plants were 1 to 13 cm tall and from cotyledon to seven leaves.

Soybean injury was visually evaluated 7 and 14 DAT. Weed control was evaluated for each species 14, 28, and 56 DAT. Visual ratings were based on a scale from 0 to 100%, with 0 indicating no effect and 100 signifying plant death. Soybean injury and weed control evaluations represented visual stunting, chlorosis, and necrosis. The two middle rows from each plot were harvested with a Massey 10^8 small-plot combine. Soybean yield was adjusted to 13% moisture.

Statistical Analyses

All experiments were repeated over time, and data were analyzed using analysis of variance (ANOVA). When data for individual experiments revealed no treatment by time interaction experiments were combined. Means were separated by Fisher's protected least significant difference test (LSD) at the 5% level.

RESULTS AND DISCUSSION

Annual Grass Control with Fluthiacet and Flumiclorac Tank Mixtures. Fluthiacet tank mixed with imazethapyr, quizalofop, sethoxydim, clethodim, and fluazifop did not reduce giant foxtail or barnyardgrass control with these herbicides in the greenhouse (Table 1). Similarly, when flumiclorac was added to imazethapyr, quizalofop, sethoxydim, or clethodim giant foxtail and barnyardgrass control was not reduced (Table 1). Giant foxtail control with flumiclorac plus fluazifop increased by 4%, yet barnyardgrass control decreased by 32% in the greenhouse when compared with fluazifop alone. Similarly, Young et al. (1996) reported giant foxtail and large crabgrass control with sethoxydim was not affected by the addition of fluthiacet; however, large crabgrass control with sethoxydim was reduced by the addition of flumiclorac. Adding fluthiacet or flumiclorac to clethodim or fluazifop did not reduce giant foxtail or barnyardgrass control in the field when compared with clethodim or fluazifop alone (Table 2). Differing results between the greenhouse and field may be explained by flumiclorac and fluazifop application rates; both were applied in the greenhouse at one-fourth the application rate used in the field. Thus, increased herbicide rates in the field may have overcome any antagonism between flumiclorac and fluazifop. Regardless, our results suggest that fluthiacet and flumiclorac do not antagonize giant foxtail or barnyardgrass control by imazethapyr, quizalofop, sethoxydim, or clethodim.

Weed Control Programs.

Velvetleaf Control. Velvetleaf control was equivalent between 4 and 5 g ha^{-1} fluthiacet and 30 and 45 g ha^{-1} flumiclorac in the field at all three application timings, thus the data for each herbicide is combined over application rates. Fluthiacet and flumiclorac provided greater than 80% control of 60 cm-tall velvetleaf plants (Table 3). Velvetleaf control with fluthiacet and flumiclorac was greatest 7 DAT when applied to 5-cm tall plants in the field. However, season-long velvetleaf control with both herbicides was greatest when applied to 45 or 60 cm tall plants. Because fluthiacet and flumiclorac have no soil activity, delaying herbicide application allowed more velvetleaf to emerge prior to herbicide application. Similarly, Tharp and Kells (1997) reported that delaying glyphosate or glufosinate (2-amino-4-(hydroxymethylphosphinyl)butanoic acid) applications, which also have no soil activity, enhanced season-long weed control.

Annual Weed Control in Corn. Corn exhibited leaf necrosis from tank mixtures including fluthiacet or flumiclorac (Table 4), but injury was no longer evident by 21 DAT (data not presented). Giant foxtail, common lambsquarters, and redroot pigweed were controlled by all of the herbicide programs evaluated. A POST application of fluthiacet or flumiclorac following metolachlor or metolachlor plus atrazine applied PRE increased velvetleaf control 56 DAT compared with metolachlor plus atrazine applied PRE (Table 4). Adding fluthiacet or flumiclorac to 2,4-D applied POST following metolachlor applied PRE increased velvetleaf control compared with metolachlor followed by 2,4-D alone. Velvetleaf control also increased when fluthiacet or flumiclorac were added to nicosulfuron plus atrazine, or nicosulfuron plus dicamba applied POST.

Corn yield in the metolachlor applied PRE followed by fluthiacet plus atrazine applied POST treatment was greater than yield in the metolachlor plus atrazine applied PRE followed by fluthiacet applied POST. Corn yield with metolachlor applied PRE followed by 2,4-D applied POST, nicosulfuron plus bromoxynil applied POST, and glyphosate alone and tank mixtures of glyphosate with fluthiacet or flumiclorac applied LATE POST had lower yields when compared with the weed-free control. The yield reduction in the metolachlor applied PRE followed by 2,4-D applied POST and the nicosulfuron plus bromoxynil applied POST treatments resulted from a lack of velvetleaf control. However, corn yield did not increase with increased velvetleaf control from tank mixtures of fluthiacet or flumiclorac with nicosulfuron plus atrazine or dicamba. Schmenk and Kells (1998) reported reduced velvetleaf competitiveness in corn following an atrazine application. Thus, applying atrazine or dicamba may reduce velvetleaf competitiveness to a level where increased velvetleaf control from tank mixtures including fluthiacet or flumiclorac would not increase corn yield. Because reduced corn yield cannot be attributed to a lack of weed control in the glyphosate and glyphosate tank mixture treatments, yield loss may be attributed to weed competition. All glyphosate treatments were applied LATE POST, three to five days after POST herbicide treatments. Our data suggests weed competition during this time period reduced corn yield.

Annual Weed Control in Soybean. Soybean exhibited leaf necrosis from tank mixtures with fluthiacet or flumiclorac, but injury was not evident by 21 DAT (data not presented).

Kapusta et al. (1986) and Wichert and Talbert (1993) reported that leaf necrosis from Protox-inhibiting herbicides did not reduce soybean yield.

In 1997, metolachlor plus metribuzin plus clomazone applied PRE, metolachlor applied PRE followed by fluthiacet or flumiclorac applied POST, metolachlor plus metribuzin applied PRE followed by fluthiacet or flumiclorac applied POST, imazethapyr plus fluthiacet or flumiclorac applied POST, or glyphosate, and glyphosate tank mixtures with fluthiacet or flumiclorac applied LATE POST provided season-long, common lambsquarters, redroot pigweed, and velvetleaf control (Table 5). However, only metolachlor plus metribuzin applied PRE followed by fluthiacet or flumiclorac applied POST, or imazethapyr plus fluthiacet or flumiclorac applied POST controlled these weeds in 1998 (Table 6).

Precipitation affects herbicide performance (Wanamarta and Penner 1989). The first rainfall greater than 2.5 cm occurred 5 and 18 d after PRE application in 1997 and 1998, respectively. The total PRE herbicide program of metolachlor plus metribuzin plus clomazone provided adequate season-long weed control in 1997, but the lack of rainfall for two weeks after herbicide application resulted in insufficient weed control in 1998. Alternatively, the total POST treatments of fluthiacet or flumiclorac plus imazethapyr resulted in season-long weed control both years. Overall, PRE applications followed by POST applications and total POST herbicide programs provided more consistent weed control when compared with total PRE herbicide programs.

Previous research showed tank mixtures of fluthiacet or flumiclorac plus imazethapyr or oxasulfuron increased broadleaf weed control compared with imazethapyr or oxasulfuron alone (Fausey and Renner 1998). However, acceptable broad-spectrum weed control was only achieved by fluthiacet or flumiclorac tank mixtures with imazethapyr. Fluthiacet or flumiclorac tank mixtures with oxasulfuron and quizalofop provided less than 80% giant foxtail control in 1997 and less than 60% redroot pigweed control in 1998, and soybean yield was reduced compared with the weed-free control in 1997 and 1998.

Glyphosate and glyphosate tank mixtures with fluthiacet or flumiclorac provided season-long weed control with soybean yields equal to the weed-free control in 1997. However, the addition of fluthiacet to glyphosate reduced redroot pigweed control compared with glyphosate alone. Weed control with glyphosate alone and in tank mixtures including fluthiacet or flumiclorac provided excellent weed control 14 DAT in 1998 (data not presented). However, dry conditions followed by rainfall after herbicide application resulted in late emerging weeds. These weeds reduced soybean yield in the glyphosate treatments when compared with the weed-free control.

Field results suggest herbicide selection and time of application are critical to assure maximum crop yield. Cantwell et al. (1989) and Wesley and Shaw (1992) reported that tank mixtures with Protox-inhibiting herbicides may increase or decrease weed control. Thus, careful consideration must be given when choosing a tank mix partner for fluthiacet or flumiclorac. These herbicides control velvetleaf and have activity on common lambsquarters and redroot pigweed. However, a single fluthiacet or flumiclorac application in the field provided sufficient broad-spectrum weed control when applied following a PRE application of metolachlor plus atrazine in corn or a PRE application of metolachlor plus metribuzin in soybean. Likewise, a PRE application of metolachlor followed by atrazine or 2,4-D tank mixed with fluthiacet or flumiclorac provided season-long broadleaf weed control in corn. James et al. (1994) and Kurtz and Pawlak (1993) reported that adding fluthiacet or flumiclorac to several postemergence herbicides enhanced broadleaf weed control. Fluthiacet or flumiclorac tank mixtures with nicosulfuron plus atrazine or nicosulfuron plus dicamba in corn and imazethapyr in soybean provided season-long broadleaf weed control.

Weed control programs that include fluthiacet or flumiclorac have several benefits over current commercial standards. These herbicides provide unprecedented postemergence velvetleaf control and have the flexibility to be used in corn and soybean. Tank mixtures including these herbicides also provide an additional mode of action for managing weed resistance. Further research should investigate crop tolerance and weed control programs with fluthiacet and flumiclorac in herbicide resistant corn and soybean.

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Table 1. Giant foxtail and barnyardgrass control with fluthiacet or flumiclorac tank mixtures in the greenhouse 14 d after treatment.[a]

Herbicide	Rate	Giant foxtail	Barnyardgrass
	g ha^{-1}	% control	
Imazethapyr	18	19	18
Imazethapyr + fluthiacet	18 + 1	23	20
Imazethapyr + flumiclorac	18 + 8	32	44
Quizalofop	12	98	98
Quizalofop + fluthiacet	12 + 1	98	97
Quizalofop + flumiclorac	12 + 8	97	98
Sethoxydim	52	81	89
Sethoxydim + fluthiacet	52 + 1	84	93
Sethoxydim + flumiclorac	52 + 8	86	94
Clethodim	35	86	98
Clethodim + fluthiacet	35 + 1	86	98
Clethodim + flumiclorac	35 + 8	86	97
Fluazifop	52	80	95
Fluazifop + fluthiacet	52 + 1	83	95
Fluazifop + flumiclorac	52 + 8	84	63
Untreated control	—	0	0
LSD (0.05)		2	3

[a] All treatments received 1.0% (v/v) crop oil concentrate (COC).

Table 2. Giant foxtail and barnyardgrass control with fluthiacet or flumiclorac tank mixtures in the field 28 d after treatment.[a]

Herbicide	Rate	Giant foxtail	Barnyardgrass
	g ha^{-1}	——— % control ———	
Clethodim	140	100	100
Clethodim + fluthiacet	140 + 5	100	98
Clethodim + flumiclorac	140 + 45	100	100
Fluazifop	210	100	99
Fluazifop + fluthiacet	210 + 5	99	100
Fluazifop + flumiclorac	210 + 45	99	99
Untreated control	—	0	0
LSD (0.05)		2	3

[a] All treatments included 1.0% (v/v) crop oil concentrate (COC).

Table 3. Corn injury and velvetleaf control with fluthiacet and flumiclorac in the field.[a]

Herbicide	Plant height	Corn[b]	Velvetleaf[c]	Velvetleaf[d]
Fluthiacet[e]	cm	% injury	—— % control	——
	5	4	96	64
Flumiclorac[f]	45	8	97	95
	60	10	92	94
	5	9	96	65
	45	15	89	84
	60	14	83	82
LSD (0.05)		3	3	10

[a] All treatments included 0.5 % (v/v) crop oil concentrate (COC).
[b] Corn injury 7 d after treatment (DAT).
[c] Velvetleaf control 7 DAT.
[b] Velvetleaf control 21 d after application timing three.
[e] Fluthiacet data averaged over 4 and 5 g ha^{-1}.
[d] Flumiclorac data averaged over 30 and 45 g ha^{-1}.

Table 4. Corn injury, weed control and corn yield with fluthiacet and flumiclorac alone and in tank mixtures.[a]

	Application		Injury	Control				Yield
Treatment[b]	Timing	Rate	ZEAMA	SETFA	CHEAL	AMARE	ABUTH	ZEAMA
		g ha^{-1}	%					kg ha^{-1}
Metolachlor[c] + atrazine	PRE	1400 + 1120	0	94	99	100	44	9202
Metolachlor + atrazine / fluthiacet	PRE /POST	1400 + 1120 + 5	1	95	100	100	100	8607
Metolachlor + atrazine / flumiclorac	PRE /POST	1400 + 1120 + 45	3	97	99	100	99	8948
Metolachlor / atrazine + fluthiacet	PRE /POST	1400 + 840 + 4	4	93	99	99	99	9384
Metolachlor / atrazine + flumiclorac	PRE /POST	1400 + 840 + 30	6	97	99	100	99	9413
Metolachlor / 2,4-D	PRE/POST	1400 + 560	0	89	98	100	92	8940
Metolachlor / 2,4-D + fluthiacet	PRE/POST	1400 + 560 + 4	4	85	99	99	99	9003
Metolachlor / 2,4-D + flumiclorac	PRE /POST	1400 + 560 + 30	9	89	99	100	98	9072
Nicosulfuron + atrazine	POST	35 + 840	0	89	96	100	82	8999
Nicosulfuron + atrazine + fluthiacet	POST	35 + 840 + 4	4	87	97	100	99	8855
Nicosulfuron + atrazine + flumiclorac	POST	35 + 840 + 30	8	91	98	100	97	8777

Table 4. Continued

Nicosulfuron + dicamba	POST	35 + 280	0	95	99	99	93	9150
Nicosulfuron + dicamba + fluthiacet	POST	35 + 280 + 4	2	94	100	100	99	9205
Nicosulfuron + dicamba + flumiclorac	POST	35 + 280 + 30	4	93	99	100	99	8922
Nicosulfuron + bromoxynil	POST	35 + 280	8	93	97	99	79	8570
Glyphosate	L. POST	850	0	100	96	100	100	8837
Glyphosate + fluthiacet	L. POST	850 + 4	2	100	94	100	100	8403
Glyphosate + flumiclorac	L. POST	850 + 30	7	99	94	99	99	8647
Weed-free control	——	——	0	100	100	100	100	9677
Untreated control	——	——	0	0	0	0	0	6622
LSD (0.05)			2	5	4	2	4	730

[a] Corn injury 7 d after POST treatment (DAT) and weed control 56 DAT.

[b] All POST atrazine treatments included 1.0% (v/v) crop oil concentrate (COC). All 2,4-D, dicamba, and bromoxynil treatments included 0.25% (v/v) nonionic surfactant (NIS). Fluthiacet, flumiclorac, and glyphosate treatments included 0.25% (v/v) NIS plus 1.0% (v/v) 28% urea ammonium nitrate (UAN).

[c] All metolachlor treatment used the resolved isomer

Table 5. Soybean injury, weed control and soybean yield in 1997 with fluthiacet and flumiclorac alone and in tank mixtures.[a]

	Application		Injury	Control				Yield
Treatment[b]	Timing	Rate	GLYMA	SETFA	CHEAL	AMARE	ABUTH	GLYMA
		g ha^{-1}	%					kg ha^{-1}
Metolachlor + metribuzin	PRE	2240 + 425	0	77	76	93	61	2991
Metolachlor + metribuzin + clomazone	PRE	2240 + 425 + 280	0	88	89	91	94	3454
Metolachlor / fluthiacet / clethodim	PRE/POST /L. POST	2240 + 5 + 140	11	91	94	82	94	3009
Metolachlor / flumiclorac / clethodim	PRE/POST /L. POST	2240 + 45 + 140	14	91	92	98	87	3116
Metolachlor + metribuzin / fluthiacet / clethodim	PRE /POST/L. POST	2240 + 425 + 5 + 140	9	86	97	99	96	3026
Metolachlor + metribuzin / flumiclorac / clethodim	PRE /POST/L. POST	2240 + 425 + 45 + 140	12	85	99	100	98	3073
Oxasulfuron + fluthiacet + quizalofop	POST	65 + 4 + 60	19	66	78	93	100	2498
Oxasulfuron + flumiclorac + quizalofop	POST	65 + 30 + 60	19	59	83	88	99	2364
Imazethapyr + fluthiacet / clethodim	POST /L. POST	70 + 4 + 140	13	100	80	100	100	3302
Imazethapyr + flumiclorac / clethodim	POST /L. POST	70 + 30 + 140	12	100	81	100	100	3200

Table 5. Continued

Glyphosate	L. POST	850	0	93	94	93	94	3261
Glyphosate + fluthiacet	L. POST	850 + 4	9	96	98	83	99	3329
Glyphosate + flumiclorac	L. POST	850 + 30	11	94	97	90	99	3266
Weed-free control	—	—	0	100	100	100	100	3448
Untreated control	—	—	0	0	0	0	0	1396
LSD (0.05)			4	15	10	4	8	530

[a] Soybean injury 7 d after POST treatment (DAT) and weed control 56 DAT.
[b] All fluthiacet, flumiclorac, imazethapyr, oxasulfuron, and glyphosate treatments included 0.25% (v/v) nonionic surfactant (NIS) plus 1.0% (v/v) 28% urea ammonium nitrate (UAN). All clethodim treatments included 1.0% (v/v) crop oil concentrate (COC).

Table 6. Soybean injury, weed control and soybean yield in 1998 with fluthiacet and flumiclorac alone and in tank mixtures.[a]

	Application		Injury	Control				Yield
Treatment[b]	Timing	Rate	GLYMA	SETFA	CHEAL	AMARE	ABUTH	GLYMA
		g ha^{-1}	%					kg ha^{-1}
Metolachlor + metribuzin	PRE	2240 + 425	0	26	50	34	6	1612
Metolachlor + metribuzin + clomazone	PRE	2240 + 425 + 280	0	58	66	28	56	2542
Metolachlor / fluthiacet / clethodim	PRE/POST /L. POST	2240 + 5 + 140	9	100	86	75	69	3678
Metolachlor / flumiclorac / clethodim	PRE/POST /L. POST	2240 + 45 + 140	11	100	93	89	73	3856
Metolachlor + metribuzin / fluthiacet / clethodim	PRE /POST/L. POST	2240 + 425 + 5 + 140	10	100	93	89	99	4355
Metolachlor + metribuzin / flumiclorac / clethodim	PRE /POST/L. POST	2240 + 425 + 45 + 140	11	100	100	96	99	4448
Oxasulfuron + fluthiacet + quizalofop	POST	65 + 4 + 60	8	80	100	51	91	3296
Oxasulfuron + flumiclorac + quizalofop	POST	65 + 30 + 60	5	90	96	18	71	2918
Imazethapyr + fluthiacet / clethodim	POST /L. POST	70 + 4 + 140	11	100	100	100	100	4341
Imazethapyr + flumiclorac / clethodim	POST /L. POST	70 + 30 + 140	15	100	100	99	99	4568

Table 6. Continued

Glyphosate	L. POST	850	0	96	95	65	100	4027
Glyphosate + fluthiacet	L. POST	850 + 4	4	91	93	68	100	4103
Glyphosate + flumiclorac	L. POST	850 + 30	7	88	92	66	99	4111
Weed-free control	—	—	0	100	100	100	100	4743
Untreated control	—	—	0	0	0	0	0	1346
LSD (0.05)			3	11	9	17	12	617

[a] Soybean injury 7 d after POST treatment (DAT) and weed control 56 DAT.
[b] All fluthiacet, flumiclorac, imazethapyr, oxasulfuron, and glyphosate treatments included 0.25% (v/v) nonionic surfactant (NIS) plus 1.0% (v/v) 28% urea ammonium nitrate (UAN). All clethodim treatments included 1.0% (v/v) crop oil concentrate (COC).