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Master degree in Crop and Soil Sciences

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**INTERACTION OF GLYPHOSATE WITH POSTEMERGENCE
SOYBEAN HERBICIDES**

By

Julie Marie Lich

A THESIS

**Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

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ABSTRACT

INTERACTION OF GLYPHOSATE WITH POSTEMERGENCE SOYBEAN HERBICIDES

By

Julie Marie Lich

The response of giant foxtail and five broadleaf weeds to glyphosate and glyphosate tank mixtures was evaluated. In the greenhouse, combining bentazon but not thifensulfuron with glyphosate, increased common lambsquarters control compared to glyphosate alone. Adding bentazon, flumiclorac, chlorimuron or imazethapyr to glyphosate at 105 g ae ha⁻¹ increased common ragweed control. Tank mixing flumiclorac, 3 g ai ha⁻¹ of chlorimuron, 2 g ai ha⁻¹ of thifensulfuron, or 35 g ai ha⁻¹ of imazethapyr with 420 g ha⁻¹ of glyphosate increased velvetleaf control. Tank mixing 12 g ha⁻¹ of chlorimuron or 141 g ha⁻¹ of imazethapyr with glyphosate at 420 g ha⁻¹ enhanced ivyleaf morningglory control. In the field, adding bentazon to glyphosate increased velvetleaf and lambsquarters control in 1 of 2 years compared to glyphosate alone. Adding imazethapyr to glyphosate increased control of giant foxtail and redroot pigweed but not lambsquarters or velvetleaf. Tank mixing CGA-277476 or AC 299263 with glyphosate enhanced the control of pigweed but not velvetleaf or lambsquarters.

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REVIEW OF LITERATURE

Glyphosate

Glyphosate (*N*[phosphonomethyl]glycine) is a non-selective, foliar applied herbicide used for control of many annual and perennial weeds. Glyphosate has been widely used for weed control prior to crop emergence, spot treatment of perennial weeds, aquatic weed control, and control of select woody species.

The rate of absorption and translocation of glyphosate varies among species and is dependent upon the environmental conditions, glyphosate concentration, and surfactant concentration (24). Numerous studies have indicated that glyphosate is translocated via the phloem to areas of high meristematic activity (24, 35, 52, 99, 112, 125). Additional studies with tall morningglory (*Ipomoea purpurea* (L.) Roth) and quackgrass (*Elytrigia repens* L.) determined that glyphosate also moves in plant tissue through apoplastic transport (35, 52).

Wyrill and Burnside (125) investigated glyphosate absorption, translocation, and metabolism in hemp dogbane (*Apocynum cannabinum* L.) and common milkweed (*Asclepias syriaca* L.) in an attempt to explain the differential susceptibility of these two species to glyphosate. The authors determined that a greater amount of glyphosate was absorbed by the more susceptible species common milkweed than by hemp dogbane. The variation in the level of herbicide absorption between these two species was attributed to differences in leaf

characteristics such as the amount of epicuticular wax, the size of the cuticle, and the presence or absence of trichomes or stomata. Richard and Slife (82) determined that detached leaves and isolated cells of hemp dogbane exhibit similar patterns of glyphosate absorption. Their findings suggest that the cell membrane is the main barrier to glyphosate absorption by hemp dogbane.

Several studies have evaluated the effect of relative humidity and temperature on glyphosate absorption and translocation. In general, absorption and translocation of glyphosate increased with increasing relative humidity and temperature (62, 63, 112). Absorption and translocation of glyphosate was reduced with increasing moisture stress (2, 55, 62). Studies have indicated that the application of glyphosate in small, concentrated, droplets increases phytotoxicity to some annual species (5, 32, 64). Boerboom and Wyse (17) investigated the response of Canada thistle (*Cirsium arvense* (L.) Scop.) to concentrated solutions of glyphosate. The authors found that increasing the glyphosate concentration in a 2 ul droplet from 9 to 108 ug ul⁻¹ reduced ¹⁴C-glyphosate absorption and translocation, resulting in reduced control of Canada thistle. The addition of surfactant increases the phytotoxicity of dilute droplets of glyphosate in some cases (5, 32, 63). Richard and Slife (82) reported that detached hemp dogbane leaves absorbed 1.2% of the total ¹⁴C-glyphosate applied after 30 minutes. The addition of an adjuvant increased the amount of ¹⁴C-glyphosate absorbed in 30 minutes to 4.5%. Conversely, studies conducted by Wyrill and Burnside (125) indicated that the diffusion of glyphosate across the cuticle was not affected by the addition of surfactant, wax removal, or subcuticular

cell damage. The amount of ^{14}C -glyphosate absorbed by soybeans 72 hours after treatment increased from 25 to 45% with the addition of surfactant at 0.5% w/w (62). Shaner (93) investigated the effect of glyphosate on transpiration of Red kidney bean (*Phaseolus vulgaris* L.). Glyphosate applied alone at 5 mM decreased transpiration to less than 80% of the control after 6 hours. Glyphosate at 5 mM applied in combination with surfactant at 0.5% w/v decreased transpiration to less than 70% of the control within 4 hours. After 24 hours the reduction in transpiration was equivalent from both treatments.

Glyphosate exhibits herbicidal activity by inhibiting aromatic amino acid biosynthesis. An early study on the mode of action of glyphosate indicated that the growth inhibition of duckweed (*Lemna gibba* L.) by glyphosate could be reversed by the addition of the aromatic amino acids phenylalanine, tyrosine, and tryptophan (49). Additional studies with *Escherichia coli*, carrot (*Daucus carota* L.) cell cultures, and soybean cell cultures also reported a reversal of glyphosate inhibition with the addition of phenylalanine and tyrosine (44). Later studies with *Corydalis sempervirens* and *Aerobacter aerogenes* reported the accumulation of high levels of shikimic acid following glyphosate treatment (6, 101). This research indicated that the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) is the site of glyphosate inhibition (101). The EPSPS enzyme catalyzes the reaction of shikimate-3-phosphate with phosphoenolpyruvate (PEP) to form enolpyruvylshikimate-3-phosphate and an inorganic phosphate. Glyphosate is a competitive inhibitor of EPSPS with respect to PEP (18). Shieh et al. (94) provided evidence that glyphosate also affects carbon allocation. It was

hypothesized that glyphosate may slightly inhibit the enzyme ribulose biphosphate carboxylase, consequently altering carbon assimilation in the plant.

Glyphosate is relatively nonmobile and rapidly inactivated in the soil. The initial inactivation of glyphosate is due to rapid adsorption to soil particles (85, 97, 99). Sprankle and Penner (98) determined that phosphate competed with ^{14}C -glyphosate for adsorption sites indicating that glyphosate is bound to soil by the phosphonic acid moiety. The primary means of glyphosate metabolism is through microbial degradation in the soil. ^{14}C -glyphosate is rapidly degraded to $^{14}\text{C}\text{-CO}_2$ under aerobic and anaerobic conditions in a variety of soil types (85, 98). The major metabolite of aerobic and anaerobic glyphosate biodegradation is aminomethylphosphonic acid. Other metabolites of glyphosate degradation detected at very low levels include: *N*-methylaminomethylphosphonic acid, glycine, *N,N*-dimethylaminomethylphosphonic acid, hydroxymethylphosphonic acid, and two unknown metabolites (85).

Various studies on the metabolism of glyphosate in plants have provided conflicting results. Zandstra and Nishimoto (126) found no evidence of glyphosate metabolism in purple nutsedge (*Cyperus rotundus* L.) 16 days after treatment with ^{14}C -glyphosate. In contrast, Sprankle et al. (96) detected small amounts of aminomethylphosphonic acid, glycine, and sacrosine as possible metabolites of ^{14}C -glyphosate metabolism in *Convolvulus arvensis*.

The rapid inactivation and degradation of glyphosate in the soil has led to the use of tank mixtures of glyphosate plus a selective herbicide with soil residual in reduced tillage programs. Tank mixtures can result in synergistic or

antagonistic interactions. Reduced weed control was observed when glyphosate was applied in combination with atrazine (6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine) or simazine (6-chloro-*N,N'*-diethyl-1,3,5-triazine-2,4-diamine) (10, 89). In a greenhouse study the addition of dicamba (3,6-dichloro-2-methoxybenzoic acid), 2,4-D ester ((2,4-dichlorophenoxy)acetic acid) or bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) to glyphosate antagonized the phytotoxicity of glyphosate to wild oats (*Avena fatua* L.), barley (*Hordeum vulgare* L.), and wheat (*Triticum aestivum* L.). Increasing the rate of the selective herbicide resulted in increased antagonism. Antagonism was reduced or eliminated when the proportion of glyphosate in the tank mixture was increased (75). Selleck and Baird (89) reported reduced control of quackgrass when glyphosate was tank mixed with linuron (*N'*-(3,4-dichlorophenyl)-*N*-methoxy-*N*-methylurea) or metribuzin (4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one). In a recent study by Hydrick and Shaw (48) control of entireleaf morningglory (*Ipomoea hederacea* (L.) Jacq. var. *integriuscula* Gray) was reduced when glyphosate was applied in combination with imazaquin (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-quinolinecarboxylic acid) or metribuzin plus chlorimuron. The antagonism of the activity of glyphosate by some selective herbicides appears to result from a physical or chemical interaction between the two herbicides (10, 75). Appleby and Somabhi (10) reported an antagonism of the activity of glyphosate when glyphosate was combined with the inert ingredients of the simazine wettable powder formulation. Research conducted by O'Sullivan and O'Donovan (75) suggested that a physical

or chemical interaction in the spray tank was also responsible for the observed reduction in the activity of glyphosate when glyphosate was tank mixed with bromoxynil, dicamba or 2,4-D.

Antagonism is not the only interaction that has been observed when glyphosate is combined with another herbicide. Wells and Appleby (111) investigated the interaction between glyphosate and lactofen (($\pm$)2-ethoxy-1-methyl-2-oxoethyl 5-[2-chloro-4-(trifluoromethyl)phenoxy]-2-nitrobenzoate) by measuring shikimate accumulation in the shoots of treated plants. Reduced rates of lactofen in combination with glyphosate resulted in increased levels of shikimate when compared to the level of shikimate detected when glyphosate was applied alone. Wells and Appleby (111) suggested that lactofen disrupts the plasma membrane, facilitating the cellular uptake of glyphosate.

The presence of ions in the spray carrier has been shown to alter the phytotoxicity of glyphosate (22, 73, 100, 120). Iron, zinc, calcium, magnesium, sodium, and potassium cations antagonized the phytotoxicity of glyphosate to wheat (73). However, salts of sodium and potassium increased the phytotoxicity of glyphosate to purple nutsedge (120). Research has indicated that decreasing the carrier volume can overcome the cation antagonism of glyphosate (22, 100). The addition of diammonium sulfate was also shown to overcome the antagonism of the phytotoxicity of glyphosate by certain cations (72). Nuclear magnetic resonance indicated that calcium associates with the carboxyl and phosphonate groups on the glyphosate molecule. The ammonium cation from diammonium sulfate was shown to compete with calcium for these sites, suggesting that the

antagonism of glyphosate by calcium is chemically based (107).

Bentazon

Bentazon (3-(1-methylethyl)-(1*H*)-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide) is a selective herbicide used postemergence in a variety of crops for control of broadleaf weeds. Bentazon effectively controls problem broadleaf weeds and perennials such as velvetleaf (*Abutilon theophrasti* Medik.), common cocklebur (*Xanthium strumarium* L.), yellow nutsedge (*Cyperus esculentus* L.), and Canada thistle.

The absorption of bentazon by plant cells is pH dependent. Uncharged bentazon converts to a bentazon anion in the presence of an acidic pH. Bentazon moves across plant membranes via simple diffusion and accumulates inside the cell due to ion-trapping of the bentazon anion (102). Various soybean genotypes absorbed 13.9 to 27.2% of the ¹⁴C-bentazon applied by 24 hours after treatment (30). Sterling et al. (102) reported that maximum concentrations of bentazon in suspension-cultured velvetleaf cells were reached between 1 and 3 hours after exposure to bentazon.

The amount of bentazon translocated by a plant is affected by the environment and leaf maturity. Wills (121) reported greater translocation of ¹⁴C-bentazon in common cocklebur when the soil was wet and the temperature and relative humidity were high. Greater movement of ¹⁴C-bentazon was also observed when ¹⁴C-bentazon was applied to the most mature common cocklebur leaf or to the youngest fully expanded leaf in soybeans. The movement of ¹⁴C-

bentazon was mainly acropetal in both species (121). The amount of ^{14}C -bentazon translocated out of the treated leaves of several soybean genotypes ranged from 7 to 13% by 24 hours after application (30).

Bentazon acts by inhibiting photosynthesis (66, 79, 106). Bentazon was shown to inhibit the Hill reaction and photosynthetic CO_2 fixation in susceptible species (66). Further research identified the site of inhibition of photosynthetic electron transport as the reducing side of photosystem II, between primary electron acceptor Q and plastoquinone (106).

Metabolism is the mechanism by which some species exhibit tolerance to bentazon (30, 59). A study conducted with the bentazon tolerant species hot pepper (*Capsicum chinense* L. 'Bohemian Chili') and the susceptible species sweet pepper (*Capsicum annuum* L. 'Keystone Resistant Giant') determined that bentazon inhibited the Hill reaction of both species equally. Researchers concluded that the selectivity of bentazon is not due to resistance at the chloroplast level (11). Another study investigating tolerant and susceptible soybean genotypes found minor differences between genotypes in bentazon absorption and translocation. These differences did not correlate with tolerance. Susceptible genotypes metabolized only 10 to 15% of the bentazon absorbed as opposed to tolerant genotypes which metabolized 80 to 90% (30). Rapid metabolism was also associated with the tolerance of navy bean (*Phaseolus vulgaris* L.) to bentazon (59). The major products of bentazon metabolism produced in tolerant soybean genotypes were glycosyl conjugates of 6- and 8-hydroxybentazon. Susceptible genotypes did not produce these two metabolites (30).

Chlorimuron and Thifensulfuron

Chlorimuron (2-[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]methyl]benzoic acid) and thifensulfuron (3-[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylic acid) are two members of the sulfonylurea class of herbicides. Chlorimuron is a selective herbicide that can be applied preemergence or postemergence in a variety of crops. Thifensulfuron is a selective herbicide applied postemergence in cereals and soybeans. The sulfonylureas are characterized by their ability to control various weeds at low use rates.

Uptake and translocation of the sulfonylurea herbicides occurs through an acid-trapping mechanism (19). Several studies have indicated that the quantity of foliar applied, radiolabeled chlorimuron and thifensulfuron absorbed by a plant varies greatly among species (19, 20, 69, 113). Wilcut et al. (113) determined the rate of ^{14}C -chlorimuron absorption by the leaves of soybean, peanut (*Arachis hypogaea* L.), and several weed species. Three hours after application the absorption of ^{14}C -chlorimuron by soybean leaves exceeded 75%. In contrast, the total absorption of ^{14}C -chlorimuron by Florida beggarweed (*Desmodium tortuosum* (SW.)) was only 40% by 72 hours after treatment. Brown et al. (20) reported that the absorption of ^{14}C -thifensulfuron also varied among species. Soybean and redroot pigweed (*Amaranthus retroflexus* L.) absorbed 20% of the ^{14}C -thifensulfuron applied by 24 hours after treatment whereas velvetleaf absorbed less than 10% of the radiolabeled chemical during the same period of time. The

addition of a surfactant plus 28% urea ammonium nitrate (UAN) has been shown to increase the absorption of foliar applied chlorimuron and thifensulfuron by velvetleaf (40, 41). Velvetleaf absorbed less than 0.5% of the total ^{14}C -chlorimuron applied without additives by 12 hours after treatment. The addition of surfactant plus 28% UAN to ^{14}C -chlorimuron increased velvetleaf absorption during that time period to 13% (41). Similarly, the addition of surfactant plus 28% UAN to ^{14}C -thifensulfuron increased velvetleaf absorption of the radiolabeled compound by 14% (40). Reddy and Bendixen (81) reported that movement of foliar applied ^{14}C -chlorimuron was acropetal and basipetal in yellow and purple nutsedge. Al-khatib et al. (3) investigated the effect of thifensulfuron concentration on phytotoxicity, absorption, and translocation of thifensulfuron in pea (*Pisum sativum* L.). The absorption of ^{14}C -thifensulfuron by pea was greater from small, concentrated droplets than from large, dilute droplets. Translocation of the absorbed ^{14}C -thifensulfuron decreased 36% as herbicide concentration increased from 18 to 146 mg L⁻¹ (3). The level of uptake of root applied radiolabeled chlorimuron is low. Yellow and purple nutsedge absorbed 2.2 and 3.8% respectively of the total radioactivity applied after 48 hours (81). Moseley et al. (69) investigated ^{14}C -chlorimuron root absorption by two morningglory species and three soybean cultivars. The soybean cultivars absorbed 6% of the root-applied chlorimuron after 72 hours of exposure. The morningglory species absorbed only 1% of the root-applied chlorimuron during the same period of exposure (69).

LaRossa and Schloss (56) investigated the mode of action of the

sulfonylurea herbicide sulfometuron methyl (*N*-[(4,6-dimethylpyrimidin-2-yl)-aminocarbonyl]-2-methoxycarbonylbenzenesulfonamide) in *Salmonella typhimurium*. Growth of *Salmonella typhimurium* was inhibited by sulfometuron methyl. The addition of the branched-chain amino acid isoleucine reversed the inhibition of growth. The enzyme acetolactate synthase (ALS) was identified as the site of sulfometuron methyl inhibition (56, 80).

Metabolism has been identified as the basis for soybean tolerance to chlorimuron and thifensulfuron (20, 21, 69). Soybean seedlings metabolized ¹⁴C-chlorimuron more rapidly than common cocklebur and redroot pigweed. The half-life of ¹⁴C-chlorimuron in soybeans was 1 to 3 hours compared to a half-life greater than 30 hours in common cocklebur and redroot pigweed (21). A study with different soybean cultivars found that Essex soybeans metabolized chlorimuron more efficiently than the less tolerant Vance cultivar (69). The primary metabolite of chlorimuron in soybean seedlings was a homoglutathione conjugate (21). Soybean seedlings were also found to metabolize thifensulfuron more quickly than sensitive weed species such as velvetleaf, common lambsquarters (*Chenopodium album* L.) and redroot pigweed (20). In soybean thifensulfuron undergoes rapid deesterification to thifensulfuron acid, which is not active against the ALS enzyme (20).

Flumiclorac

Flumiclorac (pentyl 2-chloro-4-fluoro-5-(3,4,5,6-tetrahydrophthalimido)phenoxyacetate) is a *N*-phenyl tetrahydrophthalimide

herbicide (51). Flumiclorac is a fast-acting, contact herbicide for postemergence weed control in soybeans and field corn. Velvetleaf is extremely sensitive to this herbicide (9, 51).

Flumiclorac is readily absorbed by susceptible plants. There is little or no translocation of the herbicide to the roots (124). The herbicidal activity of flumiclorac produces visible symptoms within one day under bright sunlight. Symptoms include bleaching, necrosis, desiccation, and wilting (9, 51).

Similar to other *N*-phenyl tetrahydrophthalimide herbicides, flumiclorac appears to inhibit the enzyme protoporphyrinogen oxidase (Protox). Protox is part of the porphyrin pathway involved in the synthesis of chlorophylls and heme. Inhibition of Protox results in unregulated autoxidation of protoporphyrinogen IX to protoporphyrin IX (Proto). Proto reacts with light and molecular oxygen to produce singlet oxygen. The presence of singlet oxygen in the plant cell results in membrane lipid peroxidation and the eventual disintegration of the cell (37).

Flumiclorac is relatively immobile in the soil due to rapid microbial breakdown and strong adsorption to clay and organic matter (124). Photodecomposition or metabolism of flumiclorac produces CO₂ as a significant degradation product. Studies have indicated that the half-life of this compound in soil ranges from 1 to 6 days (9).

Rate of herbicide metabolism appears to be the basis for crop selectivity to flumiclorac. Research has indicated that tolerant species such as corn and soybeans degrade flumiclorac-pentyl more rapidly than a susceptible species such as velvetleaf (9, 124).

Imazethapyr

Imazethapyr (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid) is a member of the imidazolinone family of herbicides. Imazethapyr is a selective herbicide applied preplant incorporated, preemergence, and postemergence for control of various weed species in imidazolinone resistant corn, soybeans, and other leguminous crops.

Imazethapyr is absorbed by the roots and shoots of a plant (28, 92). Cole et al. (28) determined that the amount of ^{14}C - imazethapyr absorbed varies by species. After 3 hours soybeans absorbed 80% of the herbicide applied whereas redroot pigweed, Florida beggarweed and peanut absorbed only 55% of the applied herbicide during the same time period. After 24 hours all species studied had absorbed 92% of the ^{14}C -imazethapyr applied with the exception of Florida beggarweed which absorbed a total of 77% (28). VanEllis and Shaner (109) investigated the mechanism of cellular absorption of three imidazolinone herbicides. Their results indicated that the uptake of these herbicides can best be explained by ion-trapping.

Movement of imazethapyr away from a treated leaf is both acropetal and basipetal. When applied postemergence to plant foliage the majority of the absorbed herbicide remains in the treated leaf (28). Wilcut et al. (114) determined that translocation of ^{14}C - imazaquin was symplastic and apoplastic in soybean, peanut, Florida beggarweed, common cocklebur and sicklepod (*Cassia obtusifolia* L.). After 72 hours an average of 90% of root absorbed ^{14}C -

imazethapyr was translocated to the shoot in soybean, sicklepod, Florida beggarweed and redroot pigweed (28). Shaner and Robson (91) reported that a small percentage of root-applied ^{14}C -imazaquin was retranslocated back from the shoot of common cocklebur to the roots 3 days after application.

The site of action of the imidazolinone herbicides has been identified as the inhibition of the enzyme acetolactate synthase (ALS) (8, 70, 92). ALS catalyzes the first reaction in the biosynthesis of isoleucine, leucine and valine. The ALS enzyme is located in the plastid of plant cells (65). Supplying valine, leucine and isoleucine did not completely reverse the inhibitory effects of imazapyr (90). Shaner and Reider (90) theorized that the inhibition of the ALS enzyme results in the buildup of a toxic intermediate (α -ketobutyrate), which causes plant death.

Plant tolerance to imazethapyr is based on metabolism. The half-life of imazethapyr in redroot pigweed, a susceptible species, was 32.1 days. The half-life of imazethapyr in peanut and soybean, which are both tolerant species, was 6.5 and 6.6 days respectively (28). Metabolic profiles of extractable residues from soybean plants suggest that oxidative hydroxylation at the α -carbon of the ethyl substituent on the pyridine ring is the primary mechanism for initial metabolic conversion of the imazethapyr. The resulting α -hydroxyethyl imazethapyr then reacts with a glucose molecule to form a glucose conjugate as the primary metabolite (57).

Velvetleaf

Velvetleaf is a large, competitive annual weed that inhabits waste areas, cultivated fields and fence rows in North America and Europe (68). In 1987 nine of fourteen north central states ranked velvetleaf as the most troublesome weed in soybeans (84). Velvetleaf is a member of the Malvaceae family which also includes cotton.

Studies have determined that velvetleaf seed will remain viable in the soil for up to 50 years (110). Although germination inhibitors are present in velvetleaf seeds, seed dormancy is due to an impermeable seed coat (54). In addition, the presence of antimicrobial substances in velvetleaf seed may contribute to its longevity in the soil by preventing microbial attack (53). Velvetleaf seed has the ability to germinate throughout the warm growing season. An Illinois study reported large flushes of velvetleaf emergence from early April through early May, followed by smaller flushes in May and June. Precipitation preceded flushes of emergence after May 1st, whereas early flushes were attributed to soil warming (105). A greenhouse study found greatest velvetleaf emergence from a planting depth of 1.9 cm (25). The optimal temperature range for germination of permeable seeds was determined to be 24 to 30°C (47).

Velvetleaf flowers are yellow to yellow-orange and arranged singly or in small clusters from the leaf axils (68). A flower is usually self-fertilized the day it opens. Seeds mature 17 to 22 days after pollination and are located in a black capsule (123). A study conducted in Mississippi reported a peak seed pod production of 137 pods per plant. Over the entire season, velvetleaf produced a

high of 17,000 seeds per plant (25).

Velvetleaf is an effective competitor because it grows well when partially shaded and can grow taller than the corn canopy (68). Cotton yield was reduced by a velvetleaf density of 4 plants per 12 m of row (25). In soybeans, yield was reduced 27% by 1 velvetleaf per 30 cm of row competing full season (74). A competition study conducted in Kansas found that the main soybean growth parameter affected by velvetleaf competition was the number of soybean pods per plant (38). Allelopathy has also been investigated as a mechanism by which velvetleaf interferes with a crop. Residues of velvetleaf were found to inhibit corn and soybean growth. Aqueous extracts from field collected velvetleaf leaves inhibited the growth of soybean seedlings. Inhibited plants contained less chlorophyll and gave evidence of water stress (16).

Ivyleaf Morningglory

Ivyleaf morningglory (*Ipomoea hederacea* (L.) Jacq.) is an annual weed of economic importance primarily in parts of the midwestern and southern United States. Members of the genus *Ipomoea* are characterized as herbaceous, viney, climbing plants with conspicuous flowers (39).

The seed of ivyleaf morningglory has a hard seed coat which is developed after one winter in the soil (104). Seed hardness is the mechanism which preserves this seed in the soil resulting in its slow depletion from the seed bank. Morningglories require warm temperatures and abrasion of the seed coat for germination (39). Acid-scarification of morningglory seeds has been used to

increase germination (33). Crowley and Buchanan (33) observed maximum germination of ivyleaf morningglory seeds at 20°C. In the same study ivyleaf morningglory was determined to be the most tolerant to osmotic stress when compared with pitted (*Ipomoea lacunosa* L.), tall and cypressvine (*Ipomoea quamoclit* L.) morningglory. Morningglory seed have the ability to germinate throughout the growing season. A study conducted in Illinois on germination and emergence of ivyleaf morningglory reported flushes of emergence from April through August (104). Precipitation exceeding 1.5 cm preceded each flush of emergence (104).

Annual morningglories normally reproduce sexually. Commonly pollination of the morningglories is accomplished by insects, however, the reproductive structures of the ivyleaf morningglory flower are situated in a manner that facilitates self-pollination. Prior to the flower opening the stigma is located beneath the anthers. As the flower opens the style elongates and brushes past the anthers resulting in pollination (39). A study on seed production of seven *Ipomoea* species ranked ivyleaf morningglory as one of the two lowest in terms of quantity of seed produced per plant. Ivyleaf morningglory produced an average of 6000 seeds per plant whereas pitted and wild tall morningglory produced 10,000 and 26,000 seeds per plant respectively (34).

An important aspect in the review of ivyleaf morningglory is its ability to compete with the crop. Research conducted in Delaware reported a detectable soybean yield loss from a density of one ivyleaf morningglory per 61 cm of row. This study noted increased lodging and difficulty at harvest as other detrimental

effects of the presence of ivyleaf morningglory (122). Other research has indicated that a greater crop yield reduction occurs when warm, early season temperatures favor rapid weed growth. This study determined that ivyleaf morningglory does not effectively compete with soybeans for light or soil moisture, however, reductions in the soybean leaf area index resulted from a density of one ivyleaf morningglory per 30 cm of row (31).

Common Ragweed

Common ragweed (*Ambrosia artemisiifolia* L.) is a summer annual, short day plant that inhabits disturbed sites and is native to North America. Common ragweed is distinguished by its deeply lobed leaves and its abundant pollen that is responsible for hay fever discomforts. The inability of common ragweed to flower unless daylength has shortened to its requirement appears to preclude its establishment north of latitude 50°, or in subtropical or equatorial regions (4).

Seeds of common ragweed are in a state of primary dormancy when they mature in the autumn. Seeds in primary dormancy germinate in the spring in light or darkness after a period of chilling (86, 115, 116). Germination is reported to be greater in light than in darkness (116). This study on common ragweed seed dormancy reported an increase in endogenous gibberellin and auxin during stratification. The level of inhibitors in common ragweed seeds decreased during stratification. This information led the researchers to hypothesize that an inhibitor-promoter complex may control seed dormancy. Gibberellin and auxin were proposed to be the promoters in this complex (116). Stoller and Wax (105)

reported peak germination of common ragweed from early April through early May. Seeds of common ragweed that do not germinate in the spring enter a state of secondary dormancy. A study by Baskin and Baskin (12) indicated that secondary dormancy occurs in response to temperature regimes in late spring. Fall field application of the growth regulators kinetin, ethephon and gibberellin prevented the induction of secondary dormancy (86).

The reproductive phase of common ragweed development is initiated by shortened day length. Common ragweed is a monoecious plant with male flowers borne in clusters at the tips of branches and female flowers borne in clusters at the leaf axils (108). Ackerly and Jasienski (1) found a positive correlation between maleness and both plant height and biomass. Vegetative plant growth declines as inflorescences develop. Total seed production per plant is related to plant fresh weight at the time of maturity. A study conducted in Ithaca, New York reported total seed production of 32,000 seeds per plant from common ragweed that emerged in the middle of May (36). Coble et al. (26) investigated the influence of common ragweed interference on soybean yield. Yield was not reduced if soybeans were maintained free of common ragweed for at least 4 weeks after crop emergence. If common ragweed populations were allowed to emerge and grow with the crop, weed removal by 6 weeks after crop emergence was necessary to prevent soybean yield loss. A significant loss in yield was reported from a common ragweed density of 4 weeds per 10 m of row competing full season. In a separate study, Shurtleff and Coble (95) determined that soybean height was not affected by common ragweed competition, however, soybean leaf

area was reduced by weed interference. A 12% reduction in soybean yield was observed from a common ragweed density of 16 plants per 10 m of row.

Common Lambsquarters

Common lambsquarters is a widespread summer annual weed that grows well in a variety of climates and soils. The Chenopodiaceae (Goosefoot) family of which common lambsquarters is a member is characterized by plants with leaves shaped like goose feet. Common lambsquarters is also distinguished by the white, mealy cast to its leaves and stem (67, 118).

Common lambsquarters seeds can be divided into four categories based on physical characteristics: brown-smooth, brown-reticulate, black-smooth, and black-reticulate (117). Studies indicated that brown seeds germinate immediately upon release and do not exhibit dormancy. Black seeds are the dominant type produced and exhibit a dormancy that can be broken by chilling or the application of nitrates (117, 119). Germination of black seeds is also promoted by exposure to light (46). Seed polymorphism accounts for the two peaks observed in common lambsquarters germination. The first peak of seed germination occurs in the autumn after seed release and is followed by a second, larger flush of germination the following spring (13, 117, 119). Although maximum emergence of common lambsquarters occurs in April or May, black seeds will continue to germinate at low levels throughout the growing season (83).

Plants are designated as C_3 or C_4 based on the metabolic pathway by which CO_2 is fixed. A C_3 plant such as common lambsquarters exhibits optimal growth

at lower temperatures than those required by a C_4 plant as long as the relative humidity is sufficiently high (23). The use of the C_3 carbon dioxide fixation pathway provides common lambsquarters with a competitive advantage over a C_4 plant under conditions of low temperature and high relative humidity (78).

Common lambsquarters flowers in response to a shift in day length from long to short (42). The flowers are perfect and wind-pollinated. Mulligan and Findlay (71) found common lambsquarters to be self-compatible and reproduce both by self- and cross-pollination. Stevens (103) reported an approximate seed production of 72,450 seeds per average sized common lambsquarters plant. Seeds of common lambsquarters can remain viable in the soil for at least 20 years (58).

Several studies have investigated the effect of common lambsquarters interference on crop yield. Shurtleff and Coble (95) reported a 15% reduction in soybean yield from a weed density of 16 plants per 10 m of row. Soybean leaf area was the only measured growth parameter affected by common lambsquarters competition. Common lambsquarters interference did not affect soybean height or shoot dry weight in this study. Schweizer (87) investigated the effect of common lambsquarters competition on sugarbeet (*Beta vulgaris*) root yield and recoverable sucrose yields. A density of 24 common lambsquarters per 30 m of row reduced root yield and recoverable sucrose yield by 48 and 46% respectively. Sugarbeet root yield losses were detected from as few as 4 to 6 common lambsquarters per 30 m of row.

Herbicide Resistance in Crops

Virtually all crops are tolerant to certain herbicides. Current technology in plant breeding, tissue culture, and genetic engineering has led to the development of crops resistant to herbicides to which they are not normally tolerant. Herbicide resistant crops could offer several advantages to producers including broad spectrum weed control, increased herbicide options, and a reduced risk of crop injury (61). Four methods have been used to develop herbicide resistant crops: conventional breeding, mutation breeding, cell selection, and genetic engineering to produce transgenic plants.

Classical breeding techniques were utilized in the development of canola (*Brassica napus* L.) resistant to the triazines. A triazine resistant birdsrape mustard (*Brassica campestris* L.) biotype provided the genetic information needed to generate the triazine resistant canola cultivars. Research indicated that triazine tolerance in birdsrape mustard is cytoplasmically inherited and due to an altered receptor protein in photosystem II. Triazine resistant birdsrape mustard was backcrossed with canola to transfer the herbicide resistance trait to susceptible canola cultivars (15). Research has indicated that triazine resistant cultivars yield 20-30% less than susceptible cultivars (14). This yield reduction appears to be associated with a reduced rate of photosynthesis reported in triazine resistant weed biotypes (50).

Soybeans with enhanced tolerance to the sulfonylurea herbicides chlorimuron and thifensulfuron were developed using mutation breeding. In this process soybean seeds were treated with the chemical mutagen ethyl methane

sulfonate. Treated seeds were screened for tolerance to chlorsulfuron and resistant individuals isolated. Sulfonylurea resistance in tolerant individuals is controlled by a single, dominant nuclear encoded gene that alters the herbicide binding site on the ALS enzyme (88).

The process of cell selection utilizes crop plant cells grown in tissue culture. Cultured cells are placed in a media containing a certain concentration of a herbicide. Researchers attempt to identify a rare, mutant cell which can tolerate the herbicide and grow in its presence. Herbicide resistant mutant cells may then be exposed to increasing herbicide concentrations to select for greater levels of herbicide resistance. The most difficult aspect of cell selection is the regeneration of a whole plant from isolated herbicide resistant cells. The inability to regenerate certain crop plants from cell culture is a limitation of this technology. Two types of herbicide resistant corn have been developed through cell selection (7, 60). Five mutant maize plants resistant to the acetyl-coenzyme A carboxylase (ACCase)- inhibiting herbicides haloxyfop (2-[4-[[3-chloro-5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoic acid) and sethoxydim (2-[1-ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) were regenerated from tissue culture. Plant resistance was linked to the level of ACCase activity in the mutant corn plant (60). Marshall et al. (60) suggested that mutants had new alleles of the maize ACCase gene. It has been proposed that the altered ACCase enzymes are less sensitive to inhibition by the ACCase-inhibiting herbicides. Inheritance of the allele for herbicide resistance was determined to be as a partially dominant, nuclear mutation.

Corn resistant to the imidazolinone herbicides was also developed using cell selection. Eight imidazolinone resistant corn lines were initially isolated. Four resistant corn cell lines were successfully regenerated and produced resistant progeny. The XA17 line demonstrated cross resistance to the sulfonylurea herbicide chlorsulfuron. Herbicide resistance was attributed to a single, semidominant gene that encoded for an altered ALS enzyme. The alteration in the ALS enzyme appears to impair herbicide binding (7).

Current techniques in genetic engineering allow genes to be transferred from a foreign organism into crop plant cells. This technology has been used to introduce genes for herbicide resistance into susceptible crop plants. One method of transferring genes into crop plant cells is the use of a vector system. An *Agrobacterium rhizogenes* vector system was used to transfer a gene (aroA) for glyphosate resistance into tobacco cells. The aroA gene was isolated from a mutant, glyphosate tolerant *Salmonella typhimurium*. AroA encodes for an EPSP synthase enzyme that is several times less sensitive to glyphosate than the wild-type enzyme. Transgenic tobacco plants exhibited enhanced tolerance to glyphosate (29). Another method of transferring genes into crop plants is microprojectile high velocity bombardment (particle gun transformation). The particle gun method has been used to transfer a gene that confers glufosinate (2-amino-4-(hydroxymethylphosphinyl)butanoic acid) resistance into corn plants. Researchers identified a 35s-bar gene that encodes the enzyme phosphinothricin acetyltransferase (PAT). PAT catalyzes the acetylation of glufosinate at its free amino group, impairing glufosinate's ability to inhibit glutamine synthetase. The

insertion of this gene into corn cells had led to the development of corn lines that are resistant to high rates of glufosinate (43).

Particle gun transformation was also utilized in the development of a soybean line (40-3-2) resistant to glyphosate. A glyphosate tolerant EPSP synthase was isolated from a glyphosate-degrading strain of *Agrobacterium* designated CP4 (76). Prior to the discovery of the CP4 gene, researchers attempted to develop glyphosate resistant plants by altering the EPSP synthase gene by site-directed mutagenesis. A glycine to alanine substitution in an *Escherichia coli* EPSP synthase gene resulted in an enzyme highly tolerant to glyphosate but with a reduced catalytic efficiency (77). The CP4 EPSP synthase enzyme is highly tolerant to glyphosate and tightly binds the substrate PEP. Progeny of soybeans transformed with the CP4 gene are resistant to postemergence applications of glyphosate at 1.68 kg ha⁻¹ (76).

Herbicide Interactions

Tank mixing two or more herbicides is a common practice in many weed control systems. Herbicide combinations may increase the spectrum of weeds controlled and decrease production costs by reducing the number of trips across the field (45). The weed control observed from herbicide combinations can be labeled synergistic, antagonistic or additive in comparison to the weed control provided by each herbicide applied alone (27, 45). An antagonistic response has been described as one in which the observed response to a herbicide combination is less than that predicted by an appropriate reference model. Synergism is the

cooperative action of two herbicides where the observed response to the herbicide combination is greater than the predicted response. Herbicide combinations demonstrate an additive effect if the observed response is equal to that predicted by an appropriate reference model (45).

In order to appropriately analyze the response observed from a herbicide combination a suitable reference model must be selected. The additive dose model (ADM) equates the predicted response to a herbicide combination to the sum of the responses of each herbicide applied separately. The ADM is a suitable reference model if the herbicides in the combination act in the same manner. In the multiplicative survival model (MSM) the predicted response to a herbicide combination is expressed as a proportion of the product of the responses observed from each herbicide when applied alone. MSM is a suitable reference model for herbicide combinations in which the herbicides in the combination exhibit herbicidal activity in a different manner (45).

The most widely used MSM reference model for calculating predicted (expected) responses for herbicide combinations was described by Colby. Colby's method describes the response of weeds to herbicides as growth as a percent of the control. The expected level of response from a herbicide combination was calculated using the following equation:

$$E_1 = X_1 Y_1 / 100$$

where E_1 represents the expected growth as percent of control and X_1 and Y_1 represent the growth as a percent of control levels induced by the herbicides A and B, respectively.

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Response of Glyphosate Resistant Soybean (*Glycine max*), Common Lambsquarters (*Chenopodium album*), Common Ragweed (*Ambrosia artemisiifolia*), Velvetleaf (*Abutilon theophrasti*), and Ivyleaf Morningglory (*Ipomoea hederacea*) to Glyphosate and Glyphosate Tank Mixtures

Abstract. The introduction of soybean resistant to glyphosate may present opportunities to increase weed control with tank mixtures of glyphosate plus a selective postemergence soybean herbicide. Greenhouse studies were used to determine if combining glyphosate with a selective herbicide increased or decreased response of common lambsquarters, common ragweed, velvetleaf, ivyleaf morningglory, and glyphosate resistant soybean to glyphosate. Tank mixtures of bentazon plus glyphosate at 211 g ae ha⁻¹ increased control of common lambsquarters compared to glyphosate alone. Thifensulfuron at 0.25 g ai ha⁻¹ plus 28% liquid urea-ammonium nitrate (UAN) enhanced common lambsquarters control only when glyphosate was applied at 53 or 105 g ha⁻¹. In 55 out of 80 cases, the addition of bentazon, flumiclorac, chlorimuron, imazethapyr or thifensulfuron to glyphosate increased control of common ragweed compared to glyphosate alone. Tank mixing bentazon, flumiclorac, 35 g ai ha⁻¹ of imazethapyr, 2 g ha⁻¹ of thifensulfuron, or 3 g ai ha⁻¹ of chlorimuron with glyphosate at 211 g ha⁻¹ enhanced velvetleaf control compared to glyphosate alone. However, adding 2 g ha⁻¹ of thifensulfuron or 3 g ha⁻¹ of chlorimuron to glyphosate at 1680 g ha⁻¹ resulted in antagonism. Ivyleaf morningglory control was antagonized when 35 g ha⁻¹ of imazethapyr or 6 g ha⁻¹ of chlorimuron was tank

mixed with glyphosate at 420 g ha⁻¹. Tank mixtures of 420 g ha⁻¹ of glyphosate plus chlorimuron, imazethapyr, or thifensulfuron did not reduce soybean leaf area more than the selective herbicide in the tank mixture applied alone.

INTRODUCTION

Two or more herbicides are commonly applied in a tank mixture to broaden the spectrum of weed control. The efficacy of a tank mix combination may be predicted from the performance of each herbicide when applied alone. Frequently, however, the actual performance of a tank mixture differs from the predicted performance of the herbicide combination. The interaction of herbicides in a combination is described as antagonistic if the actual performance is less than the predicted performance or synergistic if the actual performance is greater than the predicted performance. When the performance of the tank mixture is equivalent to the predicted performance the response is considered additive (4).

The introduction of soybeans resistant to glyphosate may present new opportunities for greater weed control with tank mixtures of glyphosate plus a selective herbicide. Producers may be interested in tank mixing glyphosate with a selective herbicide to obtain residual soil activity and to increase the control of certain annual weeds with glyphosate. Early research on the control of annual weeds with glyphosate has reported inconsistent control of common ragweed (*Ambrosia artemisiifolia* L.) (7, 13), velvetleaf (*Abutilon theophrasti* Medik.) (6, 8, 10), and ivyleaf morningglory (*Ipomoea hederacea* (L.) Jacq.) (6, 16, 17). In the majority of research on glyphosate tank mixtures glyphosate was applied in a tank mixture with selective, soil-applied herbicides in reduced or no-tillage systems

prior to or at planting. Limited information is available on the efficacy of glyphosate tank mixtures that include a selective herbicide commonly applied postemergence.

Antagonism occurred when glyphosate was combined with imazaquin (5), metribuzin plus chlorimuron (5) , 2,4-D (9), atrazine (1, 12), dicamba (9, 12), and bromoxynil (9). The antagonism of weed control reported in these studies was overcome by increasing the rate of glyphosate in the tank mixture. Conversely the diphenyl ether herbicides, lactofen and oxyfluorfen, increased the efficacy of glyphosate on little mallow (*Malva parviflora* L.) (15) and yellow nutsedge (*Cyperus esculentus* L.) (11), respectively, possibly by facilitating the movement of glyphosate through the plasma membrane. Bocion (2) reported a synergistic response in control of some annual weeds when imazapyr was tank mixed with glyphosate.

The objective of this research was to evaluate the potential for antagonistic or synergistic interactions from tank mixtures of glyphosate plus a selective herbicide applied postemergence for control of common lambsquarters (*Chenopodium album* L.), common ragweed, velvetleaf, and ivyleaf morningglory. Glyphosate resistant soybean response to tank mixtures of glyphosate plus a selective herbicide was also determined.

MATERIALS AND METHODS

Common lambsquarters, common ragweed, velvetleaf, ivyleaf morningglory, and glyphosate resistant soybean seeds were planted in BACCTO¹ greenhouse potting soil in 945-ml plastic pots. Pots were surface watered daily. Prior to herbicide application plants were thinned to one per pot and fertilized with 0.1 g of water soluble fertilizer solution (20% N, 20% P₂O₅, 20% K₂O). Common lambsquarters, common ragweed, velvetleaf, and glyphosate resistant soybeans were maintained at 27 C $\pm$ 5 C with a 16-hour photoperiod of natural lighting supplemented with sodium vapor lighting giving a midday photosynthetic photon flux density of 1000 μ E m⁻² s⁻¹. Environmental conditions for studies with ivyleaf morningglory were maintained at 25 C $\pm$ 5 C with a 16 hour photoperiod of natural lighting supplemented with metal halide lighting giving a midday photon flux density of 700 μ E m⁻² s⁻¹.

Applications were made to four-leaf common ragweed and velvetleaf, six-leaf common lambsquarters, and to soybeans with the second trifoliolate leaf fully expanded with a moving nozzle sprayer equipped with a single 8003 even flat fan nozzle² calibrated to deliver 234 L ha⁻¹ at a spray pressure of 207 kPa at a speed of 8.5 km h⁻¹. Applications were made to three-leaf ivyleaf morningglory with a continuous link belt sprayer equipped with an 8001 even flat fan nozzle calibrated

¹Baccto is a product of Michigan Peat Co. Houston, TX 77098.

²Teejet flat fan tips. Spraying Systems Co., North Ave. and Schmale Road, Wheaton, IL 60188.

to deliver 234 L ha⁻¹ at a spray pressure of 207 kPa at a speed of 1.5 km h⁻¹.

Herbicides applied with and without glyphosate were bentazon, chlorimuron, flumiclorac, imazethapyr, and thifensulfuron in velvetleaf and common ragweed studies. Bentazon and thifensulfuron were applied with and without glyphosate in common lambsquarters studies. Glyphosate tank mix partners in studies with ivyleaf morningglory were chlorimuron and imazethapyr. Chlorimuron, imazethapyr, and thifensulfuron were applied with and without glyphosate in glyphosate resistant soybean studies. All treatments included non-ionic surfactant³ at 0.5% v/v. Treatments in studies with chlorimuron, imazethapyr, and thifensulfuron also included 28% UAN⁴ at 4% v/v. Plants were harvested 14 days after treatment and dry weights determined. In soybean studies, leaf area of the third and fourth trifoliolate leaves was determined 14 days after treatment using a LI-3000 portable area meter⁵.

The experimental design of common lambsquarters, common ragweed, velvetleaf, and ivyleaf morningglory studies was a two-factor factorial randomized complete block design with four replications and repeated in time. The two factors in each experiment were the rate of glyphosate and the rate of the tank mix partner. Dry weight data were converted to percent growth reduction values compared to the dry weight of the untreated control. Expected (predicted)

³Activator-90, a mixture of alkyl polyoxyethylene ether and free fatty acids. Produced by Loveland Industries, Inc., PO Box 1289, Greeley, CO 80632.

⁴Abbreviation: 28% UAN, 28% urea ammonium nitrate

⁵LI-COR Inc., PO Box 4425, Lincoln, NE 68504.

growth reduction values for herbicide combinations were calculated using the method described by Colby (3). A herbicide combination was labeled antagonistic if analysis of variance indicated that the observed reduction in growth from a herbicide combination was significantly less than the expected level of growth reduction. Conversely, a herbicide combination was labeled synergistic if the observed reduction in growth was greater than the expected level of growth reduction.

The study with glyphosate resistant soybeans was a randomized complete block design with four replications and repeated in time. Analysis of variance was performed and total leaf area means compared using Fisher's Protected LSD at the 5% level of significance. Analysis of the data revealed no significant treatment by experiment interaction and the data were combined for analysis.

RESULTS AND DISCUSSION

Common Lambsquarters. Common lambsquarters dry weight was reduced 39% by glyphosate at 420 g ae ha⁻¹ and 63% by bentazon at 140 g ai ha⁻¹ (Table 1). A tank mixture of glyphosate at 420 g ha⁻¹ plus bentazon at 140 g ha⁻¹ reduced common lambsquarters dry weight by 93%. The addition of glyphosate to bentazon at 280 or 560 g ha⁻¹ did not enhance or reduce the control of common lambsquarters provided by bentazon alone.

Glyphosate at 211 and 420 g ha⁻¹ plus 28% UAN provided 80 and 89%

control of common lambsquarters, respectively. Adding 0.13 g ai ha⁻¹ of thifensulfuron to 105 g ha⁻¹ of glyphosate plus 28% UAN increased control of common lambsquarters from 64% to 82%. Tank mix combinations of glyphosate plus bentazon or glyphosate plus thifensulfuron were additive in control of common lambsquarters because the actual level of growth reduction from the tank mix combinations was equal to the expected level of growth reduction calculated using Colby's method.

Common Ragweed. Glyphosate at 420 g ha⁻¹ reduced common ragweed growth by 58% (Table 2). A tank mixture of 70 g ha⁻¹ of bentazon plus 420 g ha⁻¹ of glyphosate synergistically increased control of common ragweed to 85%. All tank mixtures of bentazon plus glyphosate provided greater control of common ragweed than glyphosate alone. In experiments with flumiclorac plus glyphosate, glyphosate at 420 g ha⁻¹ reduced the growth of common ragweed by 88%. Higher daily greenhouse temperatures during the flumiclorac plus glyphosate study may explain the greater efficacy of glyphosate on common ragweed in this study. The addition of all rates of flumiclorac to glyphosate at 105 or 211 g ha⁻¹ increased the control of common ragweed provided by glyphosate alone.

Glyphosate at 420 g ha⁻¹ plus 28% UAN reduced common ragweed dry weight by 89 to 93% (Table 3). The addition of 0.3 g ai ha⁻¹ of chlorimuron, 18 g ai ha⁻¹ of imazethapyr or 0.5 g ha⁻¹ of thifensulfuron to 53 g ha⁻¹ of glyphosate plus 28% UAN increased the control of common ragweed compared to glyphosate alone. Several tank mixtures of 211 and 420 g ha⁻¹ of glyphosate plus chlorimuron, imazethapyr or thifensulfuron were calculated to be acting

antagonistically, however, when the calculated level of growth reduction exceeds the maximum level of growth reduction measured, the calculated antagonism should be considered non-significant. In general, tank mixing bentazon, chlorimuron, flumiclorac, imazethapyr or thifensulfuron with glyphosate at 105 or 211 g ha⁻¹ increased common ragweed control compared to glyphosate alone.

Velvetleaf. Glyphosate at 1680 g ha⁻¹ reduced velvetleaf growth by 85% (Table 4). Each of the tank mix combinations of 211 or 420 g ha⁻¹ of glyphosate plus 560 g ha⁻¹ of bentazon or 15 g ai ha⁻¹ of flumiclorac increased the control of velvetleaf compared to glyphosate alone. The addition of 1120 g ha⁻¹ of bentazon to 420 g ha⁻¹ of glyphosate increased control of velvetleaf from 21 to 84%, which was synergistic according to Colby's model.

Glyphosate at 1680 g ha⁻¹ plus 28% UAN reduced velvetleaf dry weight by 78 to 80% (Figures 1, 2, 3). Combining 211 or 420 g ha⁻¹ of glyphosate plus 28% UAN with 35 g ha⁻¹ of imazethapyr or 2 g ha⁻¹ of thifensulfuron increased the control of velvetleaf compared to glyphosate plus 28% UAN alone (Figures 1, 2). The addition of chlorimuron at 1.5 or 3 g ha⁻¹ to glyphosate plus 28% UAN increased the control of velvetleaf provided by glyphosate alone (Figure 3). Adding 0.3 and 0.8 g ha⁻¹ of chlorimuron to glyphosate did not increase control of velvetleaf when the glyphosate rate was greater than 211 g ha⁻¹. Combining 3 g ha⁻¹ of chlorimuron, 71 g ha⁻¹ of imazethapyr or 4 g ha⁻¹ of thifensulfuron with glyphosate at 840 or 1680 g ha⁻¹ plus 28% UAN resulted in antagonism (Figures 1, 2, 3). Although these herbicide combinations were calculated to be acting antagonistically, the control of velvetleaf provided by the tank mixtures was not

less than the level of control provided by glyphosate plus 28% UAN alone. As in common ragweed studies, adding bentazon, chlorimuron, flumiclorac, imazethapyr or thifensulfuron to glyphosate at 105 or 211 g ha⁻¹ usually increased velvetleaf control compared to glyphosate alone.

Ivyleaf Morningglory. Glyphosate at 1680 g ha⁻¹ plus 28% UAN reduced ivyleaf morningglory dry weight by 71 to 73% (Figures 4, 5). The addition of chlorimuron at 12 g ha⁻¹ or imazethapyr at 141 g ha⁻¹ to glyphosate at 211 or 420 g ha⁻¹ increased control of ivyleaf morningglory compared to glyphosate plus 28% UAN alone. This is in contrast to Hydrick and Shaw's research (5) where 36 g ha⁻¹ of imazaquin was antagonistic to 210 g ha⁻¹ of glyphosate on entireleaf morningglory (*Ipomoea hederacea* var. *integriuscula* Gray). Twelve of the 32 tank mixtures applied to ivyleaf morningglory acted antagonistically. However, the level of control of ivyleaf morningglory provided by glyphosate plus 28% UAN alone was not decreased by the addition of chlorimuron or imazethapyr. The antagonism of entireleaf morningglory control reported by Hydrick and Shaw (5) was overcome when the glyphosate rate in the tank mixture was increased to 420 g ha⁻¹. Other research has also indicated that increasing the rate of the non-selective herbicide in the tank mixture can decrease antagonistic responses (1, 9). In contrast to these findings, the frequency of antagonistic interactions in control of ivyleaf morningglory did not decrease as the glyphosate rate increased in the tank mixtures.

Even though a synergistic increase in weed control is the most desirable response from a herbicide combination, an additive response may also be

beneficial since: 1) it may allow for the substitution of another herbicide to attain the same level of weed control at a reduced cost per hectare; 2) combining a herbicide with residual soil activity such as imazethapyr with glyphosate would provide protection against later germinating weeds, particularly black nightshade (*Solanum ptycanthum* Dun.); and 3) tank mixtures of herbicides with different modes of action may reduce the potential for weed resistance, although the development of glyphosate resistant weeds has been termed unlikely (14).

Additivity was the most common interaction observed in each of these studies. An additive response in control of common lambsquarters was observed from each of the 32 glyphosate tank mixtures. Additivity was also observed in control of common ragweed with 69 of the 80 glyphosate tank mixtures. Combinations of reduced rates of bentazon, chlorimuron, flumiclorac, imazethapyr, or thifensulfuron plus glyphosate at 211 or 420 g ha⁻¹ were predominately additive in control of velvetleaf. Antagonism was observed with 38% of the glyphosate tank mixtures applied to ivyleaf morningglory. However, the addition of a tank mix partner did not decrease the level of ivyleaf morningglory control attained with glyphosate alone.

Glyphosate Resistant Soybean. Glyphosate at 420 or 840 g ha⁻¹ plus 28% UAN did not reduce the total leaf area of the third and fourth soybean trifoliolate leaves (Table 5). Thifensulfuron at 2 g ha⁻¹ reduced total leaf area by 44% compared to the untreated control. Combining 420 g ha⁻¹ of glyphosate with 2 g ha⁻¹ of thifensulfuron increased the level of leaf area reduction to 63% compared to the untreated control. None of the other tank mix combinations reduced soybean leaf

area more than the selective herbicide in the tank mix combination applied alone. These results suggest that tank mixing glyphosate with chlorimuron, imazethapyr or thifensulfuron is unlikely to increase the level of soybean injury observed with these herbicides alone.

Conclusions. This research indicates that adding a reduced rate of a selective herbicide to glyphosate may allow producers to decrease the rate of glyphosate needed to control common lambsquarters, common ragweed, and velvetleaf. Adding chlorimuron or imazethapyr to glyphosate to improve annual weed control did not decrease control of ivyleaf morningglory. Additional research needs to be conducted in the field to further evaluate the efficacy of glyphosate tank mixtures for control of annual weeds.

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Table 1. Reduction in common lambsquarters dry weight 2 weeks after POST treatment with tank mixtures of glyphosate plus bentazon or thifensulfuron^{ab}.

Herbicide	Rate	Glyphosate (g ae ha ⁻¹)				
		0	53	105	211	420
	g ai ha ⁻¹	% reduction				
Bentazon	0	0	-6	5	9	39
	70	57	29 (56)	71 (60)	74 (62)	83 (73)
	140	63	65 (61)	76 (65)	89 (66)	93 (77)
	280	90	92 (90)	93 (91)	93 (91)	95 (94)
	560	94	94 (93)	95 (93)	95 (94)	95 (96)
LSD ^c		12				
Thifensulfuron	0	0	48	64	80	89
	0.06	31	49 (64)	75 (75)	80 (84)	87 (93)
	0.13	66	58 (82)	82 (88)	83 (93)	87 (96)
	0.25	81	80 (90)	84 (93)	87 (95)	96 (98)
	0.50	92	89 (96)	94 (97)	95 (98)	94 (99)
LSD		12				
p = 0.05						

^aAll treatments included non-ionic surfactant at 0.5% v/v; treatments in the thifensulfuron plus glyphosate study also included 28% liquid urea-ammonium nitrate at 4% v/v.

^bValues in parentheses are the expected level of percent dry weight reduction calculated for the herbicide combination using Colby's method.

^cLSD values may be used to compare observed levels of dry weight reduction only and do not apply to expected values found in parentheses.

Table 2. Reduction in common ragweed dry weight 2 weeks after POST treatment with tank mixtures of glyphosate plus bentazon or flumiclorac^{ab}.

Herbicide	Rate	Glyphosate (g ae ha ⁻¹)				
		0	53	105	211	420
g ai ha ⁻¹		----- % reduction -----				
Bentazon	0	0	-5	7	39	58
	70	59	62 (57)	69 (58)	81 (72)	85 ⁺ (78) ^c
	140	79	77 (78)	87 (80)	86 (87)	90 (91)
	280	93	93 (93)	91 (94)	90 (96)	95 (99)
	560	93	95 (93)	87 (97)	94 (97)	94 (99)
LSD ^d	----- 13 -----					
Flumiclorac	0	0	5	20	48	88
	2	61	65 (64)	60 (68)	72 (80)	87 (95)
	4	69	78 (71)	82 (75)	81 (83)	90 (96)
	8	88	86 (89)	89 (90)	87 (94)	94 (99)
	15	94	92 (95)	95 (95)	93 (95)	95 (99)
LSD	----- 10 -----					
p = 0.05						

^aAll treatments included non-ionic surfactant at 0.5% v/v.

^bValues in parentheses are the expected level of percent dry weight reduction calculated for the herbicide combination using Colby's method.

^cA negative sign following a number denotes a significant antagonistic response; a positive sign following a number denotes a significant synergistic response.

^dLSD values may be used to compare observed levels of dry weight reduction only and do not apply to expected values found in parentheses.

Table 3. Reduction in common ragweed dry weight 2 weeks after POST treatment with tank mixtures of glyphosate plus chlorimuron, imazethapyr or thifensulfuron^{abc}.

Herbicide	Rate g ai ha ⁻¹	Glyphosate (g ae ha ⁻¹)				
		0	53	105	211	420
		----- % reduction -----				
Chlorimuron	0	0	72	78	89	93
	0.3	50	89 (92)	93 (90)	89 (93)	95 (96)
	0.8	72	89 (92)	90 (93)	91 (97)	94 (97)
	1.5	87	89- (96)	92 (97)	92- (99)	95- (99)
	3.0	89	94 (97)	92 (97)	94- (99)	94- (99)
LSD ^d		----- 8 -----				
Imazethapyr	0	0	76	66	83	89
	9	60	78 (91)	80 (86)	92 (94)	93 (96)
	18	82	91 (95)	89 (94)	91- (97)	93 (97)
	35	85	94 (96)	90 (95)	92 (97)	91- (98)
	71	90	91- (98)	94 (97)	94 (98)	92- (99)
LSD		----- 8 -----				
Thifensulfuron	0	0	69	88	79	91
	0.5	73	92 (92)	91 (97)	96 (93)	94 (98)
	1.0	77	91 (92)	93 (98)	94 (96)	95 (98)
	2.0	89	94 (97)	94 (99)	91- (98)	96 (99)
	4.0	92	94 (97)	95 (99)	95 (98)	95 (99)
LSD		----- 8 -----				
p = 0.05						

^aAll treatments included non-ionic surfactant at 0.5% v/v and 28% liquid urea-ammonium nitrate at 4% v/v.

Table 3 (cont.)

^bValues in parentheses are the expected level of percent dry weight reduction calculated for the herbicide combination using Colby's method.

^cA negative sign following a number denotes an significant antagonistic response; a positive sign following a number denotes a significant synergistic response.

^dLSD values may be used to compare observed levels of dry weight reduction only and do not apply to expected values found in parentheses.

Table 4. Reduction in velvetleaf dry weight 2 weeks after POST treatment with tank mixtures of glyphosate plus bentazon or flumiclorac^{abc}

Herbicide	Rate g ai ha ⁻¹	Glyphosate (g ae ha ⁻¹)				
		0	211	420	840	1680
		----- % reduction -----				
Bentazon	0	0	5	21	63	85
	280	11	37 (15)	41 (29)	55 (67)	69 ⁻ (86)
	560	22	37 (24)	71 (36)	68 (69)	91 (77)
	1120	45	63 (46)	84 ⁺ (54)	92 (78)	90 (91)
	2240	74	70 (73)	93 (77)	91 (87)	94 (96)
LSD ^d		----- 10 -----				
Flumiclorac	0	0	3	17	60	84
	2	39	43 (40)	37 (48)	72 (75)	81 (90)
	4	56	51 (57)	70 (63)	85 (82)	89 (93)
	8	67	72 (67)	74 (71)	83 (86)	92 (94)
	15	81	88 (81)	85 (85)	92 (93)	93 (97)
LSD		----- 11 -----				
p = 0.05						

^aAll treatments included non-ionic surfactant at 0.5% v/v.

^bValues in parentheses are the expected level of percent dry weight reduction calculated for the herbicide combination using Colby's method.

^cA negative sign following a number denotes a significant antagonistic response; a positive sign following a number denotes a significant synergistic response.

^dLSD values may be used to compare observed levels of dry weight reduction only and do not apply to expected values found in parentheses.

Table 5. Total leaf area of the third and fourth trifoliate soybean leaves 2 weeks after POST treatment with tank mixtures of glyphosate plus chlorimuron, imazethapyr or thifensulfuron^a.

Herbicide(s)	Rate(s)	Total leaf area
	g ai ha ⁻¹	cm ²
Untreated control		166
Glyphosate	420	164
Glyphosate	840	163
Chlorimuron	3	130
Chlorimuron	6	79
Imazethapyr	35	153
Imazethapyr	71	97
Thifensulfuron	1	104
Thifensulfuron	2	93
Glyphosate + chlorimuron	420 + 3	127
Glyphosate + chlorimuron	420 + 6	76
Glyphosate + imazethapyr	420 + 35	144
Glyphosate + imazethapyr	420 + 71	111
Glyphosate + thifensulfuron	420 + 1	108
Glyphosate + thifensulfuron	420 + 2	61
LSD _{0.05}		32

^aAll treatments included non-ionic surfactant at 0.5% v/v and 28% liquid urea-ammonium nitrate at 4% v/v.

Figure 1. Reduction in velvetleaf dry weight 2 weeks after postemergence application of glyphosate plus imazethapyr. $LSD_{(0.05)}=9$. The gray bars indicate an antagonistic response and the white bars indicate an additive response according to the multiplicative survival model.

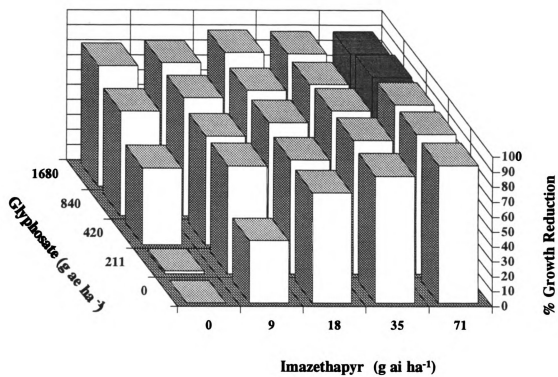


Figure 2. Reduction in velvetleaf dry weight 2 weeks after postemergence application of glyphosate plus thifensulfuron. $LSD_{(0.05)}=7$. The gray bars indicate an antagonistic response and the white bars indicate an additive response according to the multiplicative survival model.

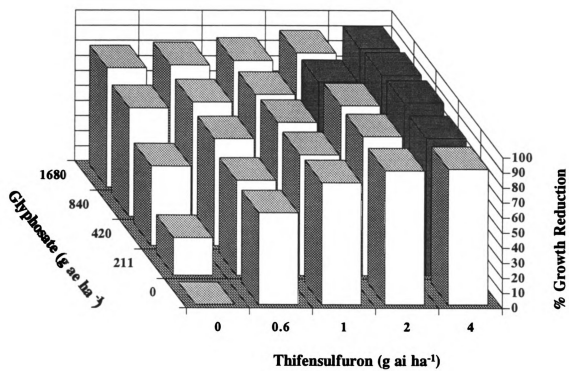


Figure 3. Reduction in velvetleaf dry weight 2 weeks after postemergence application of glyphosate plus chlorimuron. $LSD_{(0.05)}=9$. The gray bars indicate an antagonistic response and the white bars indicate an additive response according to the multiplicative survival model.

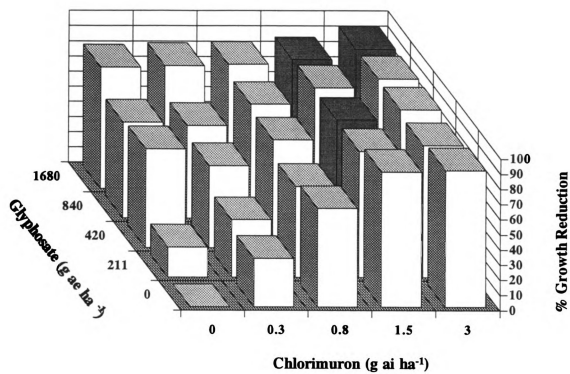


Figure 4. Reduction in ivyleaf morningglory dry weight 2 weeks after postemergence application of glyphosate plus chlorimuron. $LSD_{(0.05)}=11$. The gray bars indicate an antagonistic response and the white bars indicate an additive response according to the multiplicative survival model.

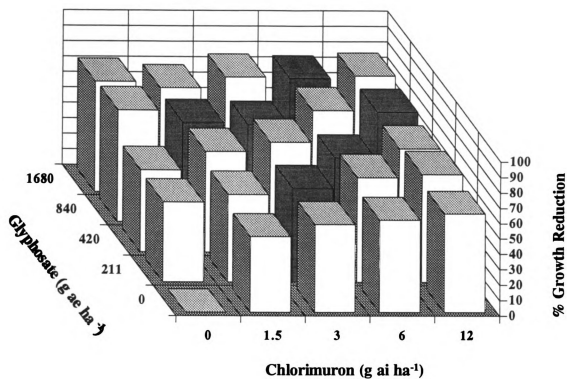
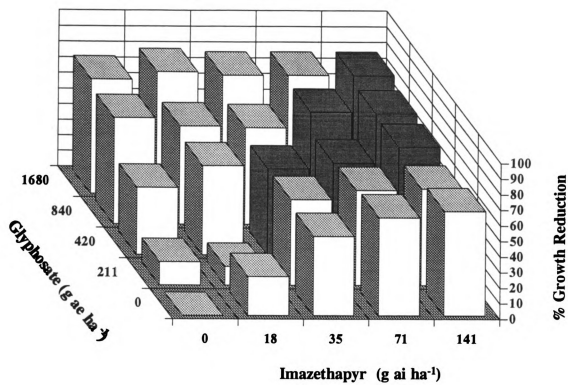


Figure 5. Reduction in ivyleaf morningglory dry weight 2 weeks after postemergence application of glyphosate plus imazethapyr. $LSD_{(0.05)}=13$. The gray bars indicate an antagonistic response and the white bars indicate an additive response according to the multiplicative survival model.



Glyphosate Tank Mixtures for Giant Foxtail (*Setaria faberi*), Redroot Pigweed (*Amaranthus retroflexus*), Velvetleaf (*Abutilon theophrasti*), and Common Lambsquarters (*Chenopodium album*) Control in Glyphosate Resistant Soybean

Abstract. The introduction of soybean resistant to glyphosate will allow applications of glyphosate for postemergence weed control in soybean. Field studies were conducted in 1994 and 1995 to determine if tank mixtures of glyphosate with a reduced rate of a selective herbicide increased control of annual weeds compared to glyphosate alone and/or provided residual soil activity to stop later germinating weeds. Glyphosate at 420 g ae ha⁻¹ plus 0.5% v/v of nonionic surfactant (NIS) provided 88 and 79% control of annual grass and redroot pigweed, respectively. The addition of a selective herbicide to glyphosate did not decrease control of giant foxtail. Tank mixing chlorimuron, imazethapyr, CGA-277476 or AC 299263 with glyphosate at 420 g ha⁻¹ plus NIS plus 28% liquid urea-ammonium nitrate (28% UAN) at 4% v/v increased redroot pigweed control. Tank mixtures of bentazon or CGA-248757 with glyphosate at 420 g ha⁻¹ plus NIS increased velvetleaf control compared to glyphosate alone. Adding chlorimuron, imazethapyr, thifensulfuron, CGA-277476 or AC 299263 to glyphosate at 420 g ha⁻¹ plus NIS plus 28% UAN did not increase velvetleaf control compared to glyphosate plus 28% UAN alone. Glyphosate at 420 g ha⁻¹ plus NIS reduced common lambsquarters dry weight by 92% in 1994, and tank mixtures did not affect common lambsquarters control. Adding 28% UAN to glyphosate at 420 g

ha⁻¹ plus NIS increased common lambsquarters control from 41 to 97% in 1995. Tank mixtures of bentazon or CGA-248757 plus glyphosate at 420 g ha⁻¹ plus NIS increased common lambsquarters control in 1995. In 1994 tank mixing 2 g ai ha⁻¹ of thifensulfuron with glyphosate at 420 g ha⁻¹ plus NIS plus 28% UAN increased soybean injury compared to thifensulfuron alone 3 d after treatment. In 1995 there was no soybean injury from herbicide treatments. By 56 d after application in 1994, glyphosate at 420 g ha⁻¹ plus NIS plus 28% UAN provided 91 and 95% control of velvetleaf and common lambsquarters, respectively. In 1995, tank mixtures of CGA-248757, 35 g ai ha⁻¹ of imazethapyr, or 4 g ai ha⁻¹ of CGA-277476 plus glyphosate provided greater control of velvetleaf 56 d after treatment than glyphosate alone.

INTRODUCTION

Glyphosate is a non-selective, translocated herbicide that effectively controls many annual and perennial weed species. The non-selective nature of glyphosate has limited its use in soybean production to preplant burndown of existing vegetation, primarily in no-till systems. The recent development of soybean genetically engineered to be resistant to postemergence applications of glyphosate will expand the utility of glyphosate in conventional and no-till soybean production.

Since glyphosate has primarily been applied for control of winter annual and perennial weeds in no-till, limited information is available on the efficacy of glyphosate for control of summer annual weeds. Previous research indicated that low rates of glyphosate provide excellent control of giant foxtail (*Setaria faberi* Herrm.) (11, 18, 24) and shattercane (*Sorghum bicolor* (L.) Moench) (18). The level of control of common lambsquarters (*Chenopodium album* L.) and common ragweed (*Ambrosia artemisiifolia* L.) provided by glyphosate varied with weed size and glyphosate rate (11, 22). Glyphosate at rates up to 840 g ha⁻¹ did not provide consistent control of velvetleaf (*Abutilon theophrasti* Medik.) or ivyleaf morningglory (*Ipomoea hederacea* (L.) Jacq) (11, 23).

Several postemergence herbicides control velvetleaf (4, 9, 12, 16) and morningglories (7) in soybeans. Tank mixtures of a low rate of glyphosate with a reduced rate of a selective herbicide could potentially provide an economical, postemergence herbicide program that controls a broad spectrum of weeds.

Additionally, combining glyphosate with a selective herbicide with soil activity could prevent weeds from germinating later in the season.

Tank mixing a non-selective herbicide with a selective herbicide may result in antagonistic or synergistic interactions. Antagonism occurs when glyphosate, glufosinate or paraquat is combined with a selective soil applied herbicide such as metribuzin or imazaquin (10). The addition of bentazon to glyphosate antagonized control of Canada thistle (20). Conversely, a synergistic response in control of several weed species was reported when imazapyr was combined with glyphosate (3).

Greenhouse studies indicated that combining glyphosate at 420 g ae ha⁻¹ with reduced rates of bentazon, chlorimuron, flumiclorac, imazethapyr or thifensulfuron increased the control of velvetleaf provided by glyphosate alone (14). The objectives of this research were to determine 1) if adding a reduced rate of a selective herbicide to glyphosate improved the control of redroot pigweed, velvetleaf, and common lambsquarters compared to glyphosate alone and 2) if season long weed control in row soybeans was possible with glyphosate alone or glyphosate plus a reduced rate of a selective herbicide with soil activity.

MATERIALS AND METHODS

Experiments were conducted in 1994 and 1995 at Michigan State University. The soil was a Capac sandy clay loam (fine-loamy, mixed, mesic Aeric Ochraqualfs) with 3.5% organic matter and pH of 6.2 in 1994. In 1995, the soil

was a Capac loam with 3.1% organic matter and pH of 6.6. Field plots were chisel-plowed the fall prior to planting and disked and field cultivated each spring. Glyphosate resistant soybean (maturity group 3) from the glyphosate resistant soybean line 40-3-2 (6) were planted May 18, 1994 at a seeding rate of 356,000 seeds ha⁻¹. In 1995, glyphosate resistant soybean (maturity group 2.7) from the glyphosate resistant soybean line 40-3-2 (6) were planted May 10 at a seeding rate of 343,000 seeds ha⁻¹. Plot size was 3 by 10.7 m with a crop row spacing of 76 cm. Herbicides were applied with a tractor-mounted compressed air sprayer delivering 121 L ha⁻¹ at 276 kPa. The boom was positioned 56 cm above the weed canopy and equipped with 80015 flat fan nozzle tips spaced 51 cm apart.

In 1994 bentazon at 280 and 560 g ai ha⁻¹, chlorimuron at 3 and 6 g ai ha⁻¹, imazethapyr at 18 and 35 g ai ha⁻¹, thifensulfuron at 1 and 2 g ai ha⁻¹, and flumiclorac at 8 and 15 g ai ha⁻¹ were applied alone and in combination with 420 g ha⁻¹ of glyphosate. Additional herbicides included in 1995 were CGA-248757 at 1 and 2 g ai ha⁻¹, CGA-277476 at 2 and 4 g ai ha⁻¹, and AC 299263 at 9 and 18 g ai ha⁻¹. Flumiclorac was applied in 1995 but results cannot be presented because the container was mislabeled by the manufacturer and did not contain flumiclorac. The application rates for these herbicides were 25 and 50% of the commercially recommended rates and 420 g ha⁻¹ of glyphosate is equal to 1 pt A⁻¹ of commercial product. Treatments with chlorimuron, imazethapyr, thifensulfuron, CGA-277476 or AC 299263 included 28% liquid urea-ammonium nitrate (28% UAN) at 4% v/v. Glyphosate was applied at 420 and 840 g ha⁻¹ with and without 28% UAN at 4% v/v. All herbicide treatments included the non-ionic surfactant

Activator-90¹ at 0.5% v/v.

Air temperature was 29 C in 1994 and 1995 and relative humidity was 68% in 1994 and 46% in 1995 at the time of treatment. Rainfall in the 7 days prior to herbicide application was 7 cm in 1994 and 0.5 cm in 1995 (Table 1). Common lambsquarters was at the 6- to 8-leaf stage of growth in 1994 and 1995. However, common lambsquarters height was greater in 1994 (5 to 15 cm) than in 1995 (5 cm). Velvetleaf was at the 2- to 6-leaf stage (2.5 to 10 cm) in 1994 and 1995. Redroot pigweed and giant foxtail infested the field site in 1995 and were 1 to 5 cm and 3 to 15 cm in height, respectively, at the time of application.

Visual injury to giant foxtail, redroot pigweed, velvetleaf, and common lambsquarters was determined 7, 14, 21, 28, and 56 days after treatment. The rating scale ranged from 0 (no visible injury) to 100% (complete plant death). Visual injury to glyphosate resistant soybean was evaluated 3, 7, 14, 21, and 28 days after treatment. Injury rating were based on plant stunting, chlorosis, and necrosis. Three velvetleaf at the four-leaf stage and three common lambsquarters at the six-leaf stage were marked with plastic garden stakes² prior to herbicide application. These plants were harvested 21 days after treatment and dry weights determined. The center two soybean rows were harvested each year with a

¹Activator-90, a mixture of alkyl polyoxyethylene ether and free fatty acids. Produced by Loveland Industries, Inc., P.O. Box 1289, Greeley, CO 80632.

²Pyrow Plastics, Inc., 211 Ogden Ave., P.O. Box 505, Lisle, IL 60532.

Massey 10 plot harvesting combine³ on October 27, 1994 and October 13, 1995 and seed yields adjusted to 13.5% moisture.

Each year the study was a randomized complete block design with four replications. The results and discussion of weed control will be based on the dry weight data of plants marked prior to herbicide application unless otherwise stated. The percent reduction in velvetleaf and common lambsquarters dry weight was calculated by $100 - ((\text{plant dry weight} / \text{untreated plant dry weight}) \times 100)$. All data collected was subjected to analysis of variance and means were separated using Fisher's protected LSD at the 5% level of significance. Colby's method was utilized to calculate expected levels of growth reduction for herbicide mixtures (5). A tank mixture was labeled antagonistic if analysis of variance indicated that the observed level of growth reduction was significantly less than the expected level of growth reduction. Conversely, a tank mixture was labeled synergistic if the observed level of growth reduction was significantly greater than the expected level of growth reduction.

RESULTS AND DISCUSSION

Annual grass. Annual grass (predominantly giant foxtail) control was visually evaluated in 1995 only. Glyphosate at 420 g ha⁻¹ with or without 28% UAN provided 88% control (Table 2). Although giant foxtail was the predominant

³Massey-Ferguson 10 Plot Combine. Kincaid Equipment Manufacturing, P.O. Box 400, Haven, KS 67543.

grass species at this site a small population of barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.) was also present in many of the plots. A large proportion of the grass not controlled in plots treated with 420 g ha⁻¹ of glyphosate was barnyardgrass (personal observation). The control of annual grass provided by all tank mix combinations except imazethapyr was equal to the annual grass control provided by glyphosate alone. Adding imazethapyr at 18 or 35 g ha⁻¹ to glyphosate plus 28% UAN improved annual grass control compared to glyphosate alone.

Redroot pigweed. Control of redroot pigweed was visually evaluated in 1995 only. Glyphosate at 420 g ha⁻¹ provided 79% control of redroot pigweed (Table 2). Adding bentazon, CGA-248757, or thifensulfuron to glyphosate at 420 g ha⁻¹ did not improve control. Tank mixtures of chlorimuron, imazethapyr, CGA-277476 or AC 299263 plus glyphosate at 420 g ha⁻¹ plus 28% UAN increased control of redroot pigweed compared to glyphosate alone.

Velvetleaf. Velvetleaf dry weight was reduced 69 and 33% by 420 g ha⁻¹ of glyphosate in 1994 and 1995, respectively (Table 3). The addition of 560 g ha⁻¹ of bentazon to 420 g ha⁻¹ of glyphosate increased control of velvetleaf to 93 and 74% in 1994 and 1995, respectively. The addition of 8 or 15 g ha⁻¹ of flumiclorac to 420 g ha⁻¹ of glyphosate increased control of velvetleaf in 1994, however the increase was not determined to be significant at the 5% level. In 1995, the addition of 1 or 2 g ha⁻¹ of CGA-248757 to 420 g ha⁻¹ of glyphosate increased control of velvetleaf to 97%.

The addition of 28% UAN to glyphosate at 420 g ha⁻¹ increased velvetleaf

control by 15% in 1994 and 1995 (Table 3). Adding imazethapyr to glyphosate plus 28% UAN reduced control of velvetleaf by 25% in 1994. Adding 3 or 6 g ha⁻¹ of chlorimuron or 1 g ha⁻¹ of thifensulfuron to 420 g ha⁻¹ of glyphosate plus 28% UAN resulted in antagonism in 1994. This is in contrast to other research in which tank mixtures of imazethapyr at 140 g ha⁻¹ plus 28% UAN with glyphosate at 630 g ha⁻¹ provided greater control of tall morningglory (*Ipomoea purpurea* (L.) Roth) than glyphosate at 630 or 840 g ha⁻¹ ⁴. In 1995, tank mixtures of 18 g ha⁻¹ of imazethapyr, chlorimuron, 1 g ha⁻¹ of thifensulfuron, CGA-277476 or AC 299263 plus 420 g ha⁻¹ of glyphosate plus 28% UAN did not increase or decrease control of velvetleaf compared to glyphosate plus 28% UAN alone. The addition of 35 g ha⁻¹ of imazethapyr or 2 g ha⁻¹ of thifensulfuron to 420 g ha⁻¹ of glyphosate plus 28% UAN resulted in antagonism in 1995. In 1995, visual velvetleaf control was greater than the percent reduction in velvetleaf dry weight. A greater proportion of the velvetleaf population was at the three-leaf stage than at the four-leaf stage at the time of herbicide application in 1995. Since dry weight data reflect control of four-leaf velvetleaf and visual evaluations reflect overall velvetleaf control, greater control of 3-leaf velvetleaf may explain the better visual velvetleaf control.

Velvetleaf control (visually evaluated) 56 d after herbicide application in 1994 was 71% from glyphosate at 420 g ha⁻¹ (Table 4). Adding 28% UAN to glyphosate at 420 g ha⁻¹ improved control of velvetleaf to 91% 56 d after herbicide

⁴University of Illinois. 1994. Annual weed control research report. p 128.

application. None of the tank mixtures provided greater velvetleaf control 56 d after application than glyphosate at 420 g ha⁻¹ plus 28% UAN. In 1995, velvetleaf control 56 d after herbicide application was 50% from glyphosate at 420 g ha⁻¹ plus 28% UAN. Tank mixing CGA-248757, 35 g ha⁻¹ of imazethapyr or 4 g ha⁻¹ of CGA-277476 with glyphosate at 420 g ha⁻¹ plus 28% UAN increased velvetleaf control 56 d after application compared to glyphosate alone.

Common lambsquarters. Glyphosate at 420 g ha⁻¹ reduced common lambsquarters dry weight by 92 and 41% in 1994 and 1995, respectively (Table 5). The addition of 28% UAN to 420 g ha⁻¹ of glyphosate increased common lambsquarters control in 1995 but not in 1994. The addition of bentazon or flumiclorac to 420 g ha⁻¹ of glyphosate did not increase or decrease control of common lambsquarters in 1994. In 1995 the addition of 280 or 560 g ha⁻¹ of bentazon to 420 g ha⁻¹ of glyphosate increased common lambsquarters control to 93 and 91%, respectively. Combining 2 g ha⁻¹ of CGA-248757 with 420 g ha⁻¹ of glyphosate synergistically increased control of common lambsquarters in 1995.

Glyphosate at 420 g ha⁻¹ plus 28% UAN reduced common lambsquarters dry weight by 85 and 97% in 1994 and 1995, respectively (Table 5). Combining 6 g ha⁻¹ of chlorimuron or 1 g ha⁻¹ of thifensulfuron with 420 g ha⁻¹ of glyphosate plus 28% UAN increased control of common lambsquarters to 93 and 94% in 1994, respectively. In 1995, adding chlorimuron, imazethapyr, thifensulfuron or AC 299263 to 420 g ha⁻¹ of glyphosate did not increase or decrease control of common lambsquarters. The tank mixture of 4 g ha⁻¹ of CGA-277476 plus 420 g ha⁻¹ of glyphosate plus 28% UAN resulted in antagonism.

Visually evaluated control of common lambsquarters 56 d after herbicide application was at least 90% from glyphosate and all glyphosate tank mixtures in 1994 (Table 4). In 1995, control of common lambsquarters from glyphosate at 420 g ha⁻¹ plus 28% UAN was only 12% by 56 d after herbicide application. A large proportion of the common lambsquarters present in the plots 56 d after treatment in 1995 emerged after herbicide application (personal observation). Tank mixing chlorimuron, 35 g ha⁻¹ of imazethapyr, CGA-277476 or 18 g ha⁻¹ of AC 299263 with glyphosate at 420 g ha⁻¹ plus 28% UAN increased common lambsquarters control 56 d after herbicide application compared to glyphosate alone. The tank mixture of CGA-277476 at 4 g ha⁻¹ plus glyphosate at 420 g ha⁻¹ plus 28% UAN provided the greatest control of common lambsquarters (76%) by 56 d after herbicide application.

The reduced efficacy of glyphosate at 420 g ha⁻¹ in 1995 may have been due to the limited rainfall 7 days prior to herbicide application (Table 1). Studies have shown that glyphosate absorption decreases with increasing moisture stress (1, 13). The lower relative humidity at the time of application in 1995 (46%) may also have contributed to the reduced weed control from glyphosate observed in 1995. Absorption and translocation of glyphosate decreased with decreasing relative humidity (15, 25).

The addition of 28% UAN to glyphosate at 420 g ha⁻¹ increased visual velvetleaf and common lambsquarters control in 1995. Other researchers have reported enhanced glyphosate activity when glyphosate is combined with liquid nitrogen fertilizer or ammonium sulfate (17, 19). Analysis of the water used as a

spray carrier in the field studies revealed high levels of iron (1.1 mg L^{-1}) and calcium carbonate (478 mg L^{-1}). The presence of calcium or iron ions in water used as a spray carrier can reduce the efficacy of glyphosate (17, 21). Thelen (21) reported that the ammonium ion in 28% UAN or ammonium sulfate competes with calcium for a bonding site on the glyphosate molecule. The NH_4^+ -glyphosate complex was more readily absorbed than the calcium salt of glyphosate. The enhanced efficacy of glyphosate plus 28% UAN in field studies may result from increased absorption of glyphosate under conditions of moisture stress.

Glyphosate Resistant Soybean. In 1994 and 1995 there was little or no visual response of soybean to glyphosate at 420 g ha^{-1} plus 28% UAN 3 d or longer after application (Table 6). Application of glyphosate at 420 g ha^{-1} plus 28% UAN plus 2 g ha^{-1} of thifensulfuron resulted in 22% soybean injury 3 d after treatment. Thifensulfuron at 2 g ha^{-1} plus 28% UAN resulted in only 11% soybean injury by 3 d after treatment (data not shown). The level of soybean injury from chlorimuron or imazethapyr plus glyphosate tank mixtures was equal to the level of injury from the same rate of chlorimuron or imazethapyr applied alone (data not shown). In 1995 there was no soybean injury from any of the herbicide treatments (data not shown). Variability by year in glyphosate resistant soybean response to acetolactate synthase (ALS) inhibiting herbicides was also reported by researchers in North Carolina⁵.

Soybean treated with glyphosate alone or in tank mixtures yielded the same

⁵Personal communication. Alan York. North Carolina State University, Raleigh, N.C.

as or slightly greater than the handweeded control in 1994 (Table 6). In 1995 glyphosate at 840 g ha⁻¹ did not reduce soybean yield since the yield of soybean that were handweeded and treated with glyphosate at 840 g ha⁻¹ with or without 28% UAN was comparable to the handweeded control. Soybean treated with glyphosate at 420 g ha⁻¹ yielded less than the handweeded control due to weed interference. However, the yield of soybean treated with glyphosate at 420 g ha⁻¹ plus 28% UAN or glyphosate at 840 g ha⁻¹ with or without 28% UAN was comparable to the handweeded control. Soybean treated with bentazon at 260 g ha⁻¹ plus glyphosate at 420 g ha⁻¹, CGA-248757 at 1 g ha⁻¹ plus glyphosate at 420 g ha⁻¹, or thifensulfuron at 2 g ha⁻¹ plus glyphosate at 420 g ha⁻¹ plus 28% UAN also yielded less than the handweeded control due to weed interference. The yield of soybean treated with all other tank mixtures of glyphosate plus a selective herbicide was comparable to the handweeded control.

Glyphosate at 420 or 840 g ha⁻¹ plus 28% UAN provided at least 85% control of velvetleaf in 1994, giant foxtail in 1995, and common lambsquarters in 1994 and 1995, but failed to control velvetleaf in 1995. Glyphosate at 840 g ha⁻¹ plus 28% UAN provided 88% control of redroot pigweed in 1995. Greenhouse studies indicated that adding a reduced rate of a selective herbicide to glyphosate at 420 g ha⁻¹ could increase velvetleaf control compared to glyphosate alone (14). In contrast, in the field adding a reduced rate of chlorimuron, imazethapyr or thifensulfuron to 420 g ha⁻¹ of glyphosate rarely increased and in some cases decreased control of velvetleaf. Since the ratio of herbicides and the amount and type of additives used in herbicide combinations was similar in the greenhouse

and field, environmental conditions may account for the different interactions observed in the two environments. The dry weight reduction observed from applications of reduced rates of herbicides was greater in the greenhouse (data not shown) compared to the field. Optimal growing conditions in the greenhouse may have resulted in increased absorption and activity of these herbicides at reduced rates. The increased effectiveness of the selective herbicides in the greenhouse may have overcome any reduction in glyphosate's activity in the greenhouse studies.

Glyphosate at 420 g ha⁻¹ plus 28% UAN provided season long control of velvetleaf and common lambsquarters in 1994. In 1995, however, tank mixing 35 g ha⁻¹ of imazethapyr or 4 g ha⁻¹ of CGA-277476 with glyphosate at 420 g ha⁻¹ plus 28% UAN improved late season control of velvetleaf and common lambsquarters compared to glyphosate alone.

Antagonistic interactions were observed more frequently when chlorimuron, imazethapyr or thifensulfuron was tank mixed with glyphosate. Research has indicated that tank mixing a herbicide that inhibits the ALS enzyme with a translocatable herbicide such as an aromatic oxyphenoxypyropanoate herbicide can reduce control (8). Chlorimuron, imazethapyr, and thifensulfuron may be reducing the translocation of glyphosate in velvetleaf, causing a decrease in control compared to glyphosate alone. Further research investigating the absorption and translocation of these herbicides when applied in combination may identify the basis for the antagonistic interactions.

This research indicates that adding a reduced rate of an ALS inhibiting

herbicide to glyphosate may decrease control of velvetleaf compared to glyphosate alone. However, control of common lambsquarters, redroot pigweed, and annual grass with glyphosate was not reduced when the ALS inhibiting herbicides were combined with glyphosate. Therefore if velvetleaf is not a problem weed a soybean producer may still combine imazethapyr with glyphosate to provide residual soil activity and control late-germinating eastern black nightshade (*Solanum ptycanthum* Dun.). The addition of 560 g ha⁻¹ of bentazon or 2 g ha⁻¹ of CGA-248757 to glyphosate increased the control of velvetleaf compared to glyphosate alone and did not decrease control of common lambsquarters, redroot pigweed or annual grass. However, neither bentazon or CGA-248757 will provide residual soil activity to stop later germinating weeds (2, 26).

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Table 1. Rainfall accumulation at East Lansing, MI in 1994 and 1995.

Time	1994	1995
	————— cm —————	
14 d prior to treatment	8.6	0.9
7 d prior to treatment	7.3	0.5
0 to 14 d following treatment	10.0	3.1
14 to 28 d after treatment	8.6	4.4

Table 2. Control of annual grass and redroot pigweed in 1995 with glyphosate and glyphosate tank mixtures^{ab}.

Herbicide(s)	Rate(s)	Visual growth reduction	
		Annual grass	Redroot pigweed
	g ai ha ⁻¹	%	%
Glyphosate	420	88	79
Glyphosate	840	94	73
Glyphosate + UAN	420	88	74
Glyphosate + UAN	840	89	88
Glyphosate + bentazon	420 + 280	87	81
Glyphosate + bentazon	420 + 560	84	84
Glyphosate + CGA-248757	420 + 1	92	74
Glyphosate + CGA-248757	420 + 2	87	74
Glyphosate + chlorimuron + UAN	420 + 3	90	93
Glyphosate + chlorimuron + UAN	420 + 6	91	95
Glyphosate + imazethapyr + UAN	420 + 18	97	97
Glyphosate + imazethapyr + UAN	420 + 35	96	96
Glyphosate + thifensulfuron + UAN	420 + 1	88	79
Glyphosate + thifensulfuron + UAN	420 + 2	89	84
Glyphosate + CGA-277476 + UAN	420 + 2	94	86
Glyphosate + CGA-277476 + UAN	420 + 4	91	92
Glyphosate + AC 299263 + UAN	420 + 9	93	90
Glyphosate + AC 299263 + UAN	420 + 18	90	95
LSD _(0.05)		6	12

^aAll treatments included non-ionic surfactant at 0.5% v/v.

^bUAN, 28% liquid-urea ammonium nitrate, was applied at 4% v/v.

Table 3. Control of velvetleaf from glyphosate and glyphosate tank mix combinations 21 days after treatment.^{abcd}

Herbicide(s)	Rate(s) g ai ha ⁻¹	Dry weight reduction		Visual growth reduction	
		1994	1995	1994	1995
Glyphosate	420	69	33	88	76
Glyphosate	840	81	57	94	89
Glyphosate + UAN	420	85	48	92	84
Glyphosate + UAN	840	88	60	95	90
Glyphosate + bentazon	420 + 280	79 (63)	63 (79)	80 (88)	76 (83)
Glyphosate + bentazon	420 + 560	93 (80)	74 (76)	98 (94)	74 (84)
Glyphosate + flumiclorac	420 + 8	87 (84)		87 (92)	
Glyphosate + flumiclorac	420 + 15	88 (86)		83 (91)	
Glyphosate + CGA-248757	420 + 1		97 (84)		86 (91)
Glyphosate + CGA-248757	420 + 2		97 (99)		98 (99)
Glyphosate + imazethapyr + UAN	420 + 18	61 ⁻ (92)	72 (70)	78 ⁻ (97)	82 ⁻ (95)
Glyphosate + imazethapyr + UAN	420 + 35	60 ⁻ (94)	60 ⁻ (83)	76 ⁻ (98)	84 ⁻ (96)
Glyphosate + chlorimuron + UAN	420 + 3	66 ⁻ (94)	48 (77)	86 ⁻ (97)	82 ⁻ (93)
Glyphosate + chlorimuron + UAN	420 + 6	76 ⁻ (96)	61 (81)	95 (97)	84 ⁻ (95)
Glyphosate + thifensulfuron + UAN	420 + 1	61 ⁻ (89)	60 (66)	73 ⁻ (96)	87 ⁻ (95)
Glyphosate + thifensulfuron + UAN	420 + 2	71 (90)	44 ⁻ (76)	88 ⁻ (97)	91 ⁻ (97)

Table 3 continued

Herbicide(s)	Rate(s) g ai ha ⁻¹	Dry weight reduction		Visual growth reduction	
		1994	1995	1994	1995
		----- % -----	----- % -----	----- % -----	----- % -----
Glyphosate + CGA-277476 + UAN	420 + 2		55 (68)		88 ⁻ (97)
Glyphosate + CGA-277476 + UAN	420 + 4		60 (69)		89 ⁻ (96)
Glyphosate + AC 299263 + UAN	420 + 9		46 (60)		85 ⁻ (97)
Glyphosate + AC 299263 + UAN	420 + 18		54 (67)		85 ⁻ (96)
LSD _(0.05) ^c		21	27	8	6

^aAll treatments included nonionic surfactant at 0.5% v/v.

^bUAN, 28% liquid-urea ammonium nitrate, was applied at 4% v/v.

^cValues in parentheses are the expected level of dry weight reduction or visual growth reduction calculated for the herbicide combination using Colby's method.

^dA negative sign denotes an significant antagonistic response; a positive sign denotes a significant synergistic response.

^eLSD values may be used to compare observed levels of dry weight reduction or visual growth reduction only and do not apply to expected values in parentheses.

Table 4. Control of velvetleaf and common lambsquarters from glyphosate and glyphosate tank mixtures 56 days after treatment^{a,b}.

Herbicide(s)	Rate(s) g ai ha ⁻¹	Velvetleaf		Common lambsquarters	
		1994	1995	1994	1995
		----- % -----	----- % -----	----- % -----	----- % -----
Glyphosate	420	71	51	91	8
Glyphosate	840	91	59	90	19
Glyphosate + UAN	420	91	50	95	12
Glyphosate + UAN	840	93	65	95	35
Glyphosate + bentazon	420 + 280	86	28	95	18
Glyphosate + bentazon	420 + 560	91	35	95	22
Glyphosate + flumiclorac	420 + 8	69		93	
Glyphosate + flumiclorac	420 + 15	85		95	
Glyphosate + CGA-248757	420 + 1		74		3
Glyphosate + CGA-248757	420 + 2		89		10
Glyphosate + thifensulfuron + UAN	420 + 1	74	54	91	20
Glyphosate + thifensulfuron + UAN	420 + 2	79	51	95	23
Glyphosate + chlorimuron + UAN	420 + 3	84	36	95	30
Glyphosate + chlorimuron + UAN	420 + 6	90	51	95	38

Table 4 continued

Herbicide(s)	Rate(s) g ai ha ⁻¹	Velvetleaf		Common lambsquarters	
		1994	1995	1994	1995
		----- % -----	----- % -----	----- % -----	----- % -----
Glyphosate + imazethapyr + UAN	420 + 18	84	50	93	25
Glyphosate + imazethapyr + UAN	420 + 35	89	66	95	28
Glyphosate + CGA-277476 + UAN	420 + 2		59		59
Glyphosate + CGA-277476 + UAN	420 + 4		76		76
Glyphosate + AC 299263 + UAN	420 + 9		54		24
Glyphosate + AC 299263 + UAN	420 + 18		60		60
LSD _(0.05)		6	13	4	14

^aAll treatments included non-ionic surfactant at 0.5% v/v.

^bUAN, 28% liquid-urea ammonium nitrate, was applied at 4% v/v.

Table 5. Control of common lambsquarters from glyphosate and glyphosate tank mixtures 21 days after treatment. ^{abcd}

Herbicide(s)	Rate(s) g ai ha ⁻¹	Dry weight reduction		Visual growth reduction	
		1994	1995	1994	1995
		----- % -----	----- % -----	----- % -----	----- % -----
Glyphosate	420	92	41	98	40
Glyphosate	840	95	82	99	68
Glyphosate + UAN	420	85	97	99	66
Glyphosate + UAN	840	92	85	99	91
Glyphosate + bentazon	420 + 280	96 (99)	93 (85)	98	60 (45)
Glyphosate + bentazon	420 + 560	95 (100)	91 (87)	99	63 (58)
Glyphosate + flumiclorac	420 + 8	93 (93)		96	
Glyphosate + flumiclorac	420 + 15	93 (93)		97	
Glyphosate + CGA-248757	420 + 1		91 ⁺ (55)		53 (45)
Glyphosate + CGA-248757	420 + 2		81 (69)		56 (52)
Glyphosate + chlorimuron + UAN	420 + 3	91 (81)	82 (97)	97	76 (68)
Glyphosate + chlorimuron + UAN	420 + 6	93 (86)	90 (97)	97	82 ⁺ (70)
Glyphosate + thifensulfuron + UAN	420 + 1	94 (95)	88 (97)	95	74 (76)
Glyphosate + thifensulfuron + UAN	420 + 2	91 (97)	84 (98)	97	74 ⁻ (80)
Glyphosate + imazethapyr + UAN	420 + 18	87 (87)	87 (95)	96	82 (76)
Glyphosate + imazethapyr + UAN	420 + 35	91 (92)	81 (96)	96	82 (80)

Table 5. continued

Herbicide(s)	Rate(s) g ai ha ⁻¹	Dry weight reduction		Visual growth reduction	
		1994	1995	1994	1995
		----- % -----		----- % -----	
Glyphosate + CGA-277476 + UAN	420 + 2		100 (95)		85 (81)
Glyphosate + CGA-277476 + UAN	420 + 4		74 (97)		84 (81)
Glyphosate + AC 299263 + UAN	420 + 9		85 (97)		79 (85)
Glyphosate + AC 299263 + UAN	420 + 18		91 (97)		79 (86)
LSD _(0.05) ^e		6	24	3	9

^aAll treatments included nonionic surfactant at 0.5% v/v.

^bUAN, 28% liquid-urea ammonium nitrate, was applied at 4% v/v.

^cValues in parentheses are the expected level of dry weight reduction or visual growth reduction calculated for the herbicide combination using Colby's method.

^dA negative sign denotes an significant antagonistic response; a positive sign denotes a significant synergistic response.

^eLSD values may be used to compare observed levels of dry weight reduction or visual growth reduction only and do not apply to expected values in parentheses.

Table 6. Visual injury to glyphosate resistant soybean 3 days after herbicide application and glyphosate resistant soybean yield^{ab}.

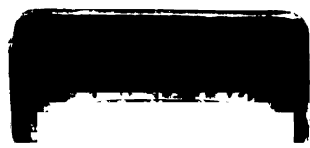
Herbicide(s)	Rate(s)	Soybean injury	Soybean yield	
		1994	1994	1995
	g ai ha ⁻¹	%	kg ha ⁻¹	
Glyphosate	420	0	2217	2625
Glyphosate	840	2	2285	3441
Glyphosate + UAN	420	3	1803	3385
Glyphosate + UAN	840	1	2427	3385
Glyphosate + bentazon	420 + 280	3	2287	2998
Glyphosate + bentazon	420 + 560	6	1967	3119
Glyphosate + flumiclorac	420 + 8	5	2364	
Glyphosate + flumiclorac	420 + 15	6	2041	
Glyphosate + CGA-248757	420 + 1			2786
Glyphosate + CGA-248757	420 + 2			3030
Glyphosate + thifensulfuron + UAN	420 + 1	11	1992	3129
Glyphosate + thifensulfuron + UAN	420 + 2	22	1390	3022
Glyphosate + chlorimuron + UAN	420 + 3	14	2012	3345
Glyphosate + chlorimuron + UAN	420 + 6	22	1815	3443
Glyphosate + imazethapyr + UAN	420 + 18	4	2139	3333
Glyphosate + imazethapyr + UAN	420 + 35	12	2208	3177
Glyphosate + CGA-277476 + UAN	420 + 2			3416
Glyphosate + CGA-277476 + UAN	420 + 4			3197
Glyphosate + AC 299263 + UAN	420 + 9			3102
Glyphosate + AC 299263 + UAN	420 + 18			3621
Glyphosate + handweed	840	0	2131	3547
Glyphosate + UAN + handweed	840	0	1962	3588

Table 6 continued

Herbicide(s)	Rate(s)	Soybean injury	Soybean yield	
		1994	1994	1995
	g ai ha ⁻¹	%	kg ha ⁻¹	
Handweeded control			1433	3453
Untreated			1798	780
LSD _(0.05)		6	672	428

^aAll treatments included non-ionic surfactant at 0.5% v/v.

^bUAN, 28% liquid-urea ammonium nitrate, was applied at 4% v/v.



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