2. EFFICACY OF GLUFOSINATE AND GLYPHOSATE ON ANNUAL AND PERENNIAL WEEDS IN LIBERTY-LINK® AND ROUNDUP-READY® SOYBEANS AS INFLUENCED BY AMMONIUM SULFATE OR PELARGONIC ACID

2.1 ABSTRACT

The efficacy of glufosinate and glyphosate on annual and perennial weeds as well as the influence of ammonium sulfate (AMS) or pelargonic acid (PA) on the efficacy of glufosinate or glyphosate treatments were investigated in greenhouse and field studies. The safety of these treatments to Liberty-Link® and Roundup-Ready® soybeans was also investigated. Greenhouse studies showed that weeds varied in their sensitivity to glufosinate and glyphosate with common milkweed having the highest glufosinate tolerance and common lambsquarters having the highest glyphosate tolerance measured as reduction of fresh weight 10 days after treatment (DAT). Giant foxtail was the most sensitive species to both glufosinate and glyphosate. Dose response studies with PA alone showed differential sensitivity among the three annual weeds, as well as a considerable level of PA herbicidal activity. Glufosinate plus 5% (w/v) AMS was more efficacious than glufosinate alone on horsenettle and common milkweed, but not on the annual weeds common lambsquarters, sicklepod, and giant foxtail. Pelargonic acid at 3% (v/v) lowered the rate of glufosinate needed to reduce fresh weights in all weeds except sicklepod. Glyphosate plus 5% (w/v) AMS increased glyphosate efficacy on giant foxtail, horsenettle, and common milkweed compared to glyphosate alone. Glyphosate plus 3% (v/v) pelargonic acid significantly lowered the rate of glyphosate needed to reduce fresh weight in all weeds compared to glyphosate alone. A field study with glufosinate and glyphosate alone, and in combination with AMS and PA, showed a slight decrease in control of morningglory species with glyphosate or glufosinate treatments containing 3% (v/v) PA versus the herbicides alone at 23 DAT. Combinations of glufosinate or glyphosate with AMS did not significantly damage transgenic soybeans

engineered for resistance to each of these herbicides. However, glufosinate or glyphosate combinations with 3% (v/v) PA showed a rate dependent decrease in fresh weight, with up to a 40% reduction in fresh weight at 1 kg/ha glufosinate or 2 kg/ha glyphosate. Herbicide injury to soybeans in field studies was evident at earlier ratings but no longer evident at 23 DAT. Regrowth of the perennial weeds horsenettle and common milkweed was significantly less with glyphosate treatments versus glufosinate treatments. Treatments containing AMS and PA affected the amount of regrowth of perennials compared to herbicide treatments alone, at low rates.

Nomenclature: Glufosinate, 2-amino-4-(hydroxymethylphosphinyl) butanoic acid; Glyphosate, *N*-(phosphonomethyl)glycine; PA, pelargonic acid (nonanoic acid); AMS, ammonium sulfate; giant foxtail, *Setaria faberi* Herrm.; common lambsquarters, *Chenopodium album* L.; and sicklepod *Cassia obtusifolia* L.; horsenettle, *Solanum carolinense* L.; common milkweed, *Ascleipias syriaca* L.; *pat*, phospinothricin-acetyltransferase; *bar*, bialaphos resistance; EPSPS, 5-enolpyruvylshikimate-3-phosphate synthase.

2.2 INTRODUCTION

Glufosinate, a rapid acting postemergence herbicide, is being incorporated into field cropping systems with the use of glufosinate tolerant, or Liberty-Link® crops (Bertges et al., 1994). Glufosinate tolerance is conferred to plants by incorporation of either the *pat* gene (phosphinothricin-acetyltranserfase) or the *bar* gene (bialaphos resistance), whose protein product inactivates glufosinate by acetylation (Mullner et al., 1993). Liberty-Link® corn (*zea mays* L.) was approved for commercialization in 1997, and Liberty-Link® soybean varieties are currently under development.

Roundup-Ready® soybeans contain a glyphosate insensitive EPSP synthase gene introduced from *Agrobacterium* sp. conferring tolerance to the non-selective herbicide glyphosate (Padgette et al., 1995). Roundup-Ready® soybeans were commercialized in 1996 and have been increasing in planted acreage every year.

Research comparing the phytotoxicity of glyphosate and glufosinate has shown that the rate of development of injury symptoms from glufosinate is greater than from glyphosate, however over time glyphosate injury matches or exceeds glufosinate injury at an equal herbicide concentration. (Carlson and Burnside, 1984; Wilson et al., 1985; Ikuenobe, 1992). Steckel et al. (1997) reported that glufosinate efficacy on annual weed species varies with rate and weed growth stage at time of treatment. A study investigating the regrowth potential of perennial weeds after treatment with glufosinate or glyphosate found that the projected number of new viable shoots was up to 30 times greater in glufosinate versus glyphosate treatments in Canada thistle, and 2.5 times greater in hemp dogbane (Welch and Ross, 1997). In contrast to glyphosate, glufosinate is not mobile in plants and as a result its efficacy on perennial weeds is low.

Ammonium sulfate (AMS) has been reported to increase the phytoxicity of many herbicides including glyphosate (Blair, 1975; Nalewaja and Matysiak, 1993; O'Sullivan et al., 1981; Suwunnamek and Parker, 1975; Turner and Loader, 1975, 1981). Pelargonic acid, a naturally occuring nine-carbon fatty acid, causes extremely rapid and non-selective desiccation of green tissue. Pelargonic acid (PA), sold under the trade name Scythe®, has been claimed to increase absorption of glyphosate, while concurrently causing more rapid desiccation of treated plants (Savage and Zorner, 1996). With the introduction of new herbicide resistant cropping systems, research on the influence of commonly used synergists such as ammonium sulfate, or other promising synergists such as pelargonic acid, in combination with glufosinate or glyphosate on weed control and crop safety is needed.

The specific objectives of the present study were to first determine the efficacy of glufosinate and glyphosate on three annual and two perennial weed species, as well as to compare the control of annual weeds with different rates of PA alone. The second objective was to determine if the potential synergists AMS or PA increase the efficacy of glufosinate or glyphosate on annual and perennial weed species. The third objective was to determine if these additive-herbicide combinations are effective and safe for use in Liberty-Link® and Roundup-Ready® soybeans. The final objective was to determine if these combinations effect the amount of regrowth of perennial weed species after treatment with glufosinate or glyphosate.

2.3 MATERIALS AND METHODS

2.3.1 Chemicals, weed seed, and transgenic soybean seed

Liberty-Link® (variety LL 5547) maturity group IV, and Roundup-Ready® (variety Asgrow 4501) maturity group III soybean seed was used for greenhouse and field studies. Seeds of common lambsquarters, giant foxtail, and sicklepod were obtained from Azlin Seed Company (Leland, MS). Seeds of common milkweed were collected along highway 460 roadsides in Montgomery Co., VA in fall 1997. Rootstocks of horsenettle were collected from a cattle pasture outside of Blacksburg, VA.

Glufosinate used in greenhouse and field studies was formulated Liberty® herbicide obtained from AgrEvo, Inc. USA (Wilmington, DE). Glyphosate used for greenhouse and field studies was formulated Roundup-Ultra® obtained from Monsanto Co., (St. Louis, MO). Pelargonic acid used for greenhouse and field studies was formulated Scythe® obtained from Mycogen Co., (San Diego, CA). Ammonium sulfate was technical grade purchased from Sigma Co., (St. Louis, MO).

2.3.2 Greenhouse studies

Dose response studies with PA were conducted on annual weeds including giant foxtail (5 leaf stage), common lambsquarters (6-8 leaf stage), and sicklepod (1-2 leaf stage). Plants were treated with 0, 1, 2, or 3% (v/v) PA with a track sprayer delivering 237L/ha. Freshweights were taken 10 DAT.

These annual weeds and two perennial weeds, including horsenettle and common milkweed, were used in interaction studies. Annual weeds and common milkweed were grown from seeds in 450-ml styrofoam cups containing Metro-Mix 360 (Scotts-Sierra Horticultural Products Co., Marysville, OH), in a greenhouse at 25±2° C where natural sunlight was supplemented with mercury halide lights providing 650 μmol/m^2/sec and 16 hour day length. Horsenettle was grown in flats from rootstocks and transplanted to styrofoam cups. When weeds reached 5-7 cm height (horsenettle: 4-5 leaves, common milkweed: 3 leaf pairs, sicklepod: 1-2 leaves, common lambsquarters: 4-6 leaf pairs, and giant foxtail: 3 leaves) they were treated with either glufosinate or glyphosate at 0, 0.0625, 0.125, or 0.250 kg/ha alone and in combinations with 5% (w/v) AMS or 3% (v/v) PA. Treatments were applied with a track sprayer delivering 237 L/ha. Plants were harvested 10 DAT, by cutting at soil level and measuring fresh weights.

For regrowth studies, seed grown common milkweed and transplanted horsenettle were grown in 450-ml styrofoam cups until they reached 10-12 cm (horsenettle: 6-8 leaves, common milkweed: 4-5 leaf pairs). Plants were then treated with either glufosinate or glyphosate at 0, 0.5, 1.0, 1.5, or 2.0 kg/ha alone or in combinations with 5% (w/v) AMS or 3% (v/v) PA. Treatments were applied with a track sprayer delivering 237L/ha. Fresh weights were taken ten DAT, and remaining root structures were allowed to grow and develop regrowth for 60 days following harvest. Fresh weights of the amount of regrowth were taken.

Soybean studies with glufosinate or glyphosate in combination with AMS or PA were conducted on 15-18 cm tall Liberty-Link® (var. 5547 LL) or Roundup-Ready® (var. Asgrow 4501) soybeans planted in 450-ml styrofoam cups. When plants reached the V2 stage, they were treated with either glufosinate at 0, 0.25, 0.5, 0.75, or 1.0 kg/ha or glyphosate at 0, 0.5, 1.0, 1.5, or 2.0 kg/ha alone or in combinations with 5% (w/v) AMS or 3% (v/v) PA. Fresh weights were taken 10 DAT.

2.3.3 Field studies

Field studies were conducted in Montgomery Co., VA. Roundup-Ready® and Liberty-Link® soybeans were treated as separate experiments. Soybeans were planted in 76.2-cm rows with plot lengths of 22.9 m. When soybeans reached the V3 stage, they were treated using a logarithmic sprayer with an output of 415.5 L/ha delivering glyphosate or glufosinate rates of 9, 4.5, 2.25, 1.12, 0.56, 0.28, 0.14 kg ai/ha within each plot at 3.6 meter intervals. Treatments included untreated control, glyphosate or glufosinate alone, or glyphosate or glufosinate plus 2.8 kg/ha AMS as a typical field use rate or plus 3% (v/v) PA. Treatments were arranged in a randomized complete block design with 3 replications. Visual ratings of weed control and crop safety were taken 3, 9, 16, 23, 30, and 45 DAT. Soybeans were hand-harvested and thrashed.

2.3.4 Experimental design and data analysis

Greenhouse interaction studies were conducted as a 3-way, herbicide by additive by herbicide rate factorial. Factorials were arranged in randomized complete block designs with 3 to 9 replications. Experiments were repeated at least twice. Field studies were also conducted as randomized complete blocks. Analysis of variance was conducted using SAS® (Cary, NC) and experiments were combined where possible. Following analysis of variance, treatment means were separated using Fischer's Protected LSD test at the 5% probability level.

2.4 RESULTS AND DISCUSSION

2.4.1 Glufosinate and glyphosate efficacy on annual and perennial weeds.

Annual and perennial weed species varied in their relative tolerance to treatments of glufosinate or glyphosate (Figures 2.1, 2.2, 2.7, 2.8). In glufosinate treatments, giant foxtail was the most sensitive tested weed and common milkweed the most tolerant, with a 60% and 5% reduction in fresh weight compared to control plants at 0.125 kg/ha glufosinate respectively. Horsenettle, common lambsquarters, and sicklepod fresh weights were all reduced approximately 50% by application of 0.125 kg/ha glufosinate.

Weeds treated with glyphosate also varied in their sensitivity with giant foxtail again being the most sensitive species tested, and common lambsquarters the most glyphosate tolerant. Fresh weight reductions of 58% and 10%, respectively, were observed following treatment with 0.125 kg/ha glyphosate. Horsenettle, common milkweed and sicklepod fresh weights were reduced approximately 20-30% with 0.125 kg/ha glyphosate.

Glufosinate, a more rapid acting herbicide, seems to have higher activity on annual weeds than glyphosate, while giving poorer control of perennial weeds, whereas glyphosate, a slower acting herbicide, had lower activity on annual species, yet gave better control of common milkweed.

2.4.2 Dose response of PA on annual weeds

Dose response studies on the effect of PA on small annual weed species showed that PA has considerable herbicidal activity, causing up to a 70% reduction in fresh weight at 3% (v/v) (Figure 2.6). Annual weeds differed in their sensitivity to PA. Common sicklepod was the most tolerant, showing only a 6% decrease in fresh weight at 2% (v/v) PA versus the untreated control, followed by common lambsquarters, with a 33% decrease. Giant foxtail, with a 65% decrease, was the most sensitive.

2.4.3 AMS and PA synergism of glufosinate and glyphosate

The effects of AMS and PA on treatments of glufosinate or glyphosate in greenhouse studies varied with species, as well as rate of glufosinate or glyphosate.

AMS plus glufosinate treatments decreased the amount of fresh weight relative to glufosinate alone plus in horsenettle at 0.25 kg/ha and for common milkweed at all glufosinate rates investigated (Figures 2.1 and 2.7). Fresh weight loss was also calculated as a percent of the treatment control, (5% (w/v) AMS alone or 3% (v/v) PA alone), to determine if there was an interaction between the herbicide and the additive, or if the fresh weight loss was simply a function of the herbicidal activity of AMS or PA. AMS seemed to be slightly antagonistic to glufosinate fresh weight reduction in common lambsquarters and sicklepod (Figure 2.1).

PA plus glufosinate treatments reduced of fresh weight compared to glufosinate treatments alone in common lambsquarters and horsenettle at lower glufosinate rates, and giant foxtail and common milkweed at all glufosinate rates. PA plus glufosinate had no significant effect on sicklepod compared to glufosinate alone. PA at 3% (v/v) alone caused considerable injury in all weed species except for sicklepod. Fresh weight reduction with glufosinate in common lambsquarters were less relative to the PA control than relative to the overall control, demonstrating antagonism of glufosinate by PA in this species. Fresh weight reduction was either increased or the same in all other species, when compared to reductions from glufosinate alone, indicating either a synergistic interaction or no interaction (Figures 2.1 and 2.7).

In glyphosate treatments, AMS increased the efficacy of glyphosate in common lambsquarters and horsenettle at the 0.125 and 0.25 kg/ha glyphosate rate, common milkweed at the 0.125 kg/ha rate, and giant foxtail at all rates tested. PA treatments were very effective in reducing fresh weight when combined with glyphosate in all annual weeds at all glyphosate rates, in horsenettle at 0.125 kg/ha, and common milkweed at all rates except for 0.25 kg/ha glyphosate. The fresh weight decrease as a percent of the PA control reflected these findings, with synergistic interactions in annual weeds at all glyphosate rates, and in perennial weeds at some rates (Figures 2.2 and 2.8).

Pline et al. (1999a) found that AMS treatments had higher absorption of ^{14}C-glufosinate than treatments without AMS in horsenettle, and lower absorption in common lambsquarters in the presence of AMS. These studies suggest that the increased efficacy of AMS plus glufosinate in horsenettle is due to increased absorption, and the decreased efficacy of AMS plus glufosinate in common lambsquarters could be due to antagonism of absorption. Pline et al. (1999a) also showed that pelargonic acid had no significant effect on ^{14}C-glufosinate absorption in any of the species tested. Thus, the increased efficacy of glufosinate in PA plus glufosinate treatments could be due at least partially to the phytotoxic effect of PA.

Field studies showed few significant differences in weed control 6 or 23 DAT in glufosinate or glyphosate treatments alone, or with AMS and PA (Tables 2.1 and 2.2). Glyphosate plus AMS provided significantly better control of common ragweed (6 DAT) and morningglory species (6 and 23 DAT) than glyphosate alone. Glyphosate or glufosinate treatments with PA showed reduced weed control versus the herbicide alone at 0.14 kg/ha glyphosate on giant foxtail (23 DAT), and at various rates of glufosinate or glyphosate plus PA on morningglory species (23 DAT). Glufosinate plus PA enhanced control of yellow nutsedge over glufosinate alone (6 DAT). These data suggest that the benefits received by AMS or PA in combination with glyphosate or glufosinate in some weeds are transitory, with long term weed control unaffected.

The use of AMS or PA in combination with glufosinate or glyphosate appears to be beneficial for control of particular weed species at particular herbicide rates. For glufosinate treatments, greenhouse studies showed enhanced fresh weight reduction with additives in perennial weeds, but not in annual weeds. For glyphosate treatments, additives enhanced fresh weight reduction somewhat in both annuals and perennials. The observed interactions between herbicides and additives are likely due to either enhanced herbicide absorption or enhanced, rapid desiccation of green tissues. The final level of weed control, however, appears to be essentially equivalent in most weed species investigated with or without the addition of AMS or PA.

2.4.4 AMS or PA effects on perennial regrowth following herbicide treatment

Regrowth of perennial weed species after herbicide treatment is a large problem in no-till and conventional tillage systems. Large colonies of perennial weeds can often compete with crops in entire areas of a field, even after herbicide treatment (Evetts and Burnside, 1973). The present studies showed significant differences in the potential for weeds to regrow following herbicide treatments. Glyphosate treatments significantly reduced the regrowth of common milkweed and horsenettle as compared to glufosinate treatments (Figure 2.3). Differences were the greatest at the glufosinate or glyphosate rates of 1.5 and 2 kg/ha. At 2.0 kg/ha, regrowth from glyphosate treated common milkweed was approximately 60 fold less than regrowth from plants treated with glufosinate. In horsenettle, regrowth after treatment with 2.0 kg/ha glyphosate was 5-fold less than in plants treated with 2.0 kg/ha glufosinate.

The addition of the synergists AMS and PA to glufosinate or glyphosate also caused some differences in the amount of regrowth. Differences were detected only at the 0.5 kg/ha glyphosate or glufosinate rates. AMS significantly reduced the amount of regrowth of glufosinate and glyphosate treated common milkweed at 0.5 kg/ha. AMS did not seem to affect the amount of regrowth of any other glufosinate or glyphosate treatments in common milkweed or horsenettle. This suggests that in common milkweed, AMS enhances uptake or translocation of glufosinate or glyphosate at 0.5 kg/ha rate, and that the synergistic effect is reduced as the herbicide rate increases. Pline et al. (1999a) found that translocation of ^{14}C-glufosinate out of the treated leaf and to the roots of common milkweed was increased with the addition of AMS versus glufosinate alone.

PA plus glufosinate treatments showed no significant differences from glufosinate treatments alone in either common milkweed or horsenettle. However, significant differences were observed with glyphosate treatments. In common milkweed, at 0.5 kg/ha glyphosate, treatments with the addition of PA caused approximately a ten-fold decrease in the amount of regrowth versus treatments with glyphosate alone. However, PA had the opposite effect in horsenettle. At 0.5 kg/ha glyphosate, regrowth of horsenettle was equal to the untreated control, indicating possible antagonism of glyphosate with the addition of PA. This antagonism was overcome at higher rates of glyphosate.

These results indicate that the addition of AMS to intermediate rates of glufosinate or glyphosate could reduce the regrowth potential of common milkweed. PA combinations proved only minimally successful in reducing regrowth and even antagonistic in the case of glyphosate on horsenettle.

2.4.5 Safety of AMS or PA combinations on transgenic soybeans

In order for synergist-herbicide combinations to be used effectively in transgenic soybean cropping systems, they must be proven safe to the crop. Greenhouse (Figure 2.4), and field studies (Tables 2.1 and 2.2) indicate that treatments with the addition of AMS to glufosinate or did not cause significantly different levels of crop response than treatments of the herbicides alone at rates as high as 1-2 kg/ha.

PA, which has some herbicidal ability, caused considerable damage to both Liberty-Link® and Roundup-Ready® soybeans in both greenhouse and field studies. In greenhouse studies, up to a 40% loss in fresh weight was measured with PA plus 1 kg/ha glufosinate or PA plus 2 kg/ha glyphosate (Figures 2.4 and 2.9). In the treatments containing 3% (v/v) PA, it appears that an increasing rate of either glyphosate or glufosinate increased the phytotoxicity of the treatment to soybeans. This increase of phytotoxicity at the same rate of PA could be due to at least two factors. First, the mechanism of resistance (altered EPSPS enzyme, Roundup-Ready®; or *PAT* enzyme, Liberty-Link®) could be being overcome by an increase in glyphosate or glufosinate absorption with the addition of PA. Secondly, the addition of a higher rate of glufosinate or glyphosate is also adding more of the adjuvants found in the glyphosate or glufosinate formulation to the spray solution containing 3% (v/v) PA. The increased amount of surfactants contained in the spray solution due to a higher rate of glyphosate or glufosinate could act to enhance PA phytotoxicity by increasing its ability to spread over the leaf surface.

Pline (1999b) found that absorption of ^{14}C-glufosinate in Liberty-Link® soybeans was not significantly different in the presence or absence of PA. In Roundup-Ready® soybeans, absorption of ^{14}C-glyphosate in the presence of PA was either significantly lower, or not significantly different from absorption in treatments of glyphosate alone, depending on time. These data dispute the first hypothesis where the resistance mechanism is overcome by a dramatic increase in herbicide absorption in the presence of PA.

Field studies also found significant injury (10-50%) in Liberty-Link® and Roundup-Ready® soybeans treated with either glyphosate or glufosinate in combination with 3% PA (Tables 2.1 and 2.2, Figure 2.9). Injury was the most dramatic at the first rating date of 6 DAT and gradually decreased until 16 DAT where no visual injury was present in PA treatments (Table 2.2). Glufosinate and glufosinate plus AMS also showed some phytotoxicity at rates of 2.25 kg/ha and higher which also disappeared by 16 DAT. Yield data showed no significant differences between treatments with the herbicide alone or combinations with AMS or PA, suggesting that initial injury by PA or glufosinate is overcome and has no long term effect on crop vigor (Table 2.5).

The results presented in this study suggest that weed species differ in their tolerance to glufosinate and glyphosate applications. Annual weeds are controlled very well by glufosinate, with perennial weeds being controlled slightly better using glyphosate. The herbicide rate required to achieve similar levels of fresh weight reduction in most weeds was higher for glyphosate than glufosinate. The benefits of using AMS or PA in combination with glyphosate or glufosinate are dependent on many factors including weed species, herbicide rate, and time after application. Additives seemed to increase glufosinate efficacy in perennial weeds but not annual weeds, whereas the use of additives with glyphosate increased efficacy to some extent in all weed species. Greenhouse studies measuring growth in terms of fresh weight reduction showed larger differences between AMS and PA treatments than field studies using visual ratings.

Glufosinate or glyphosate treatments including AMS were as safe on Liberty-link® and Roundup-Ready® soybeans as treatments using the herbicide alone. However, 3% (v/v) PA in combination with glufosinate or glyphosate caused increasing injury with increasing rate of glufosinate of glyphosate. Field studies showed that this soybean injury was transitory with no visual injury after 23 days in PA treatments and yields of plots treated with PA being similar to those with glufosinate treatments alone. Untreated plots yielded lower than herbicide treated plots due to competition with weeds.

For perennial weed problems, glyphosate was much more effective in reducing regrowth than glufosinate. The addition of AMS to glufosinate or glyphosate proved beneficial at some herbicide rates. PA treatments had no significant effect on regrowth versus glufosinate or glyphosate alone, other than causing more rapid tissue necrosis.

The herbicidal activity of PA alone varies by species of annual weeds. In sensitive weeds such as giant foxtail, a 3% (v/v) PA rate caused up to a 70% loss in fresh weight. However, the efficacy of PA without a companion herbicide is very dependent on coverage, with significant regrowth from lateral buds occurring in larger, more vigorous weeds. Combinations with glufosinate or glyphosate significantly reduced the amount of regrowth from untreated lateral buds.

PA and AMS should be further investigated as additives with other, slower acting herbicides such as ALS inhibitors. The desiccating action of PA in most cases does not seem to inhibit the absorption or long term efficacy of glufosinate or glyphosate as would be expected from a more rapidly acting herbicide. This desiccation, in combination with a slower acting herbicide could provide growers with the immediate results that are appealing, while not inhibiting long-term control. AMS is a relatively inexpensive additive for herbicides and the benefits received in some species, such as quicker development of visual injury symptoms, increased short-term efficacy, and in some cases reduced regrowth of perennial weed species could make it a practical option for growers.

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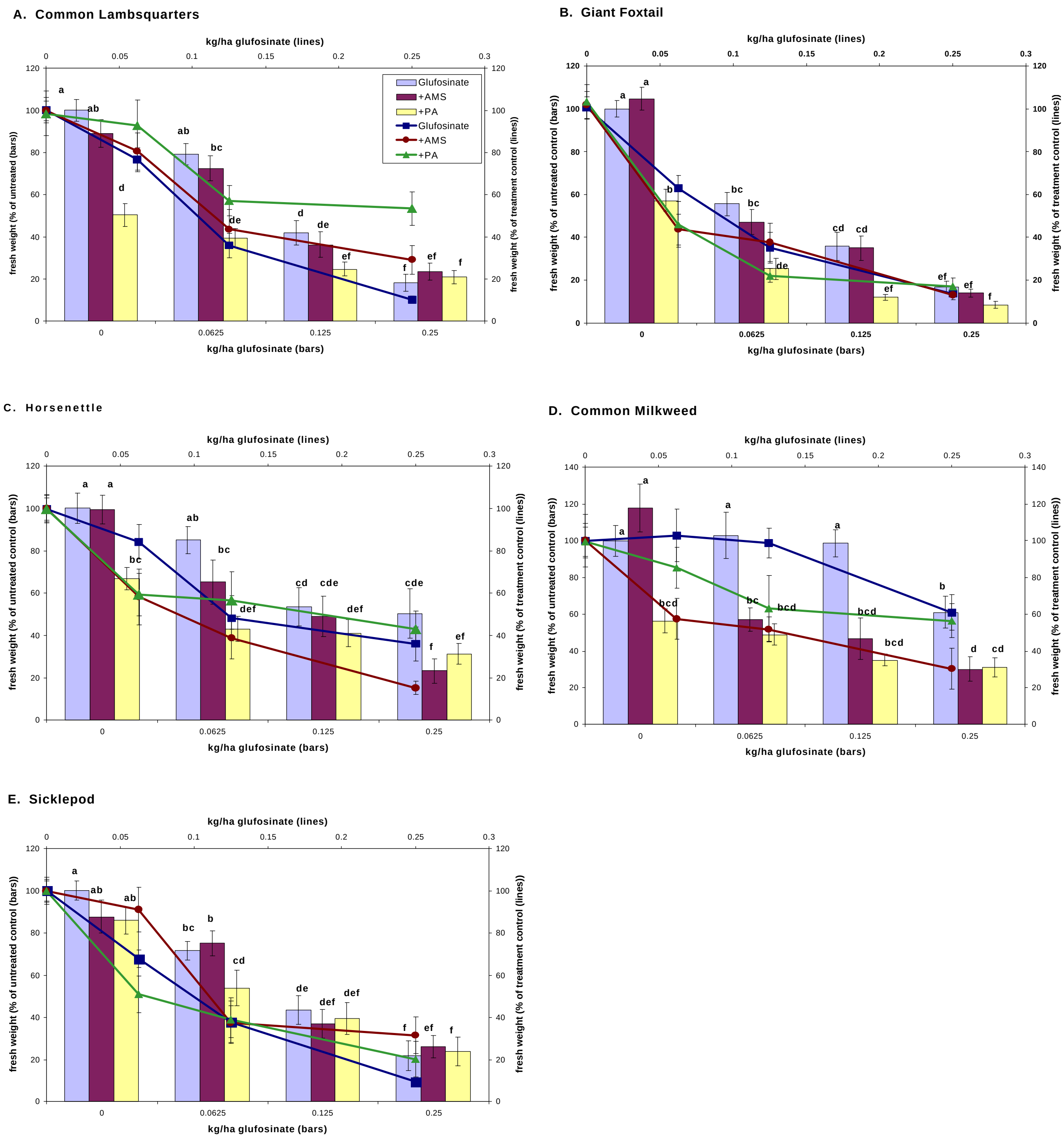


Figure 2.1. Effect of AMS or PA on glufosinate efficacy on five weed species.

A-E: Plants treated with varying glufosinate rates either alone or in combination with 5% (w/v) AMS or 3% (v/v) PA. Fresh weights taken 10 DAT: A: common lambsquarters, B: giant foxtail, C: horsenettle, D: common milkweed, E: sicklepod. Bars represent shoot fresh weights as a percent of the non-treated control of each species (left y-axis and bottom x-axis). Lines represent shoot fresh weight as a percent of each treatment control, ie. 5% (w/v) AMS alone (right y-axis and top x-axis). Means of each weed species were separated using Fisher's protected $LSD_{0.05}$. Means in each graph followed by the same letter are not significantly different.

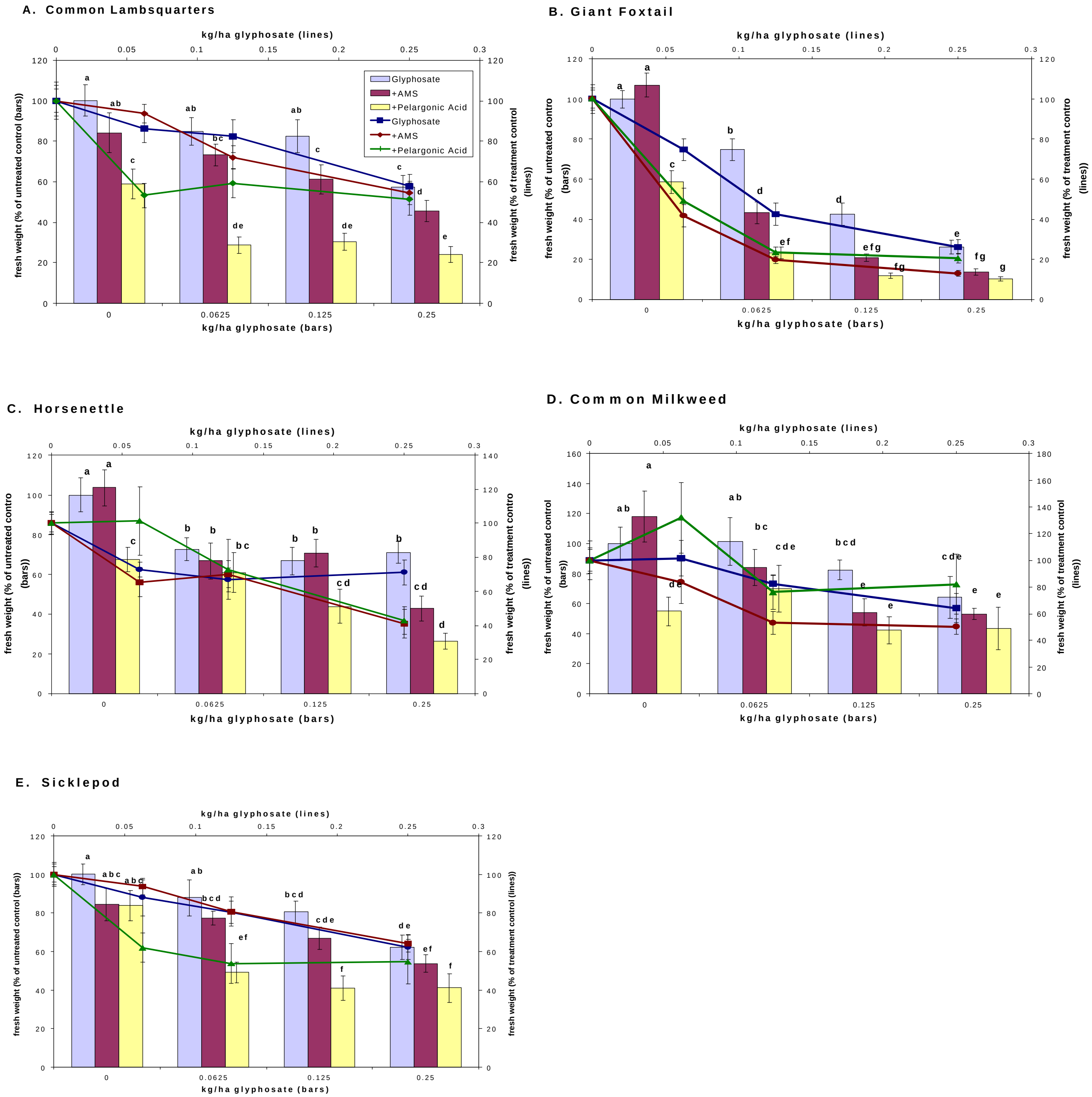


Figure 2.2. Effect of AMS or PA on glyphosate efficacy on five weed species.

A-E: Plants treated with varying glyphosate rates either alone or in combination with 5% (w/v) AMS or 3% (v/v) PA. Fresh weights taken 10 DAT: A: common lambsquarters, B: giant foxtail, C: horsenettle, D: common milkweed, E: sicklepod. Bars represent shoot fresh weights as a percent of the non-treated control of each species (left y-axis and bottom x-axis). Lines represent shoot fresh weight as a percent of each treatment control, i.e. 5% (w/v) AMS alone (right y-axis and top x-axis). Means of each weed species were separated using Fisher's protected $LSD_{0.05}$. Means in each graph followed by the same letter are not significantly different.

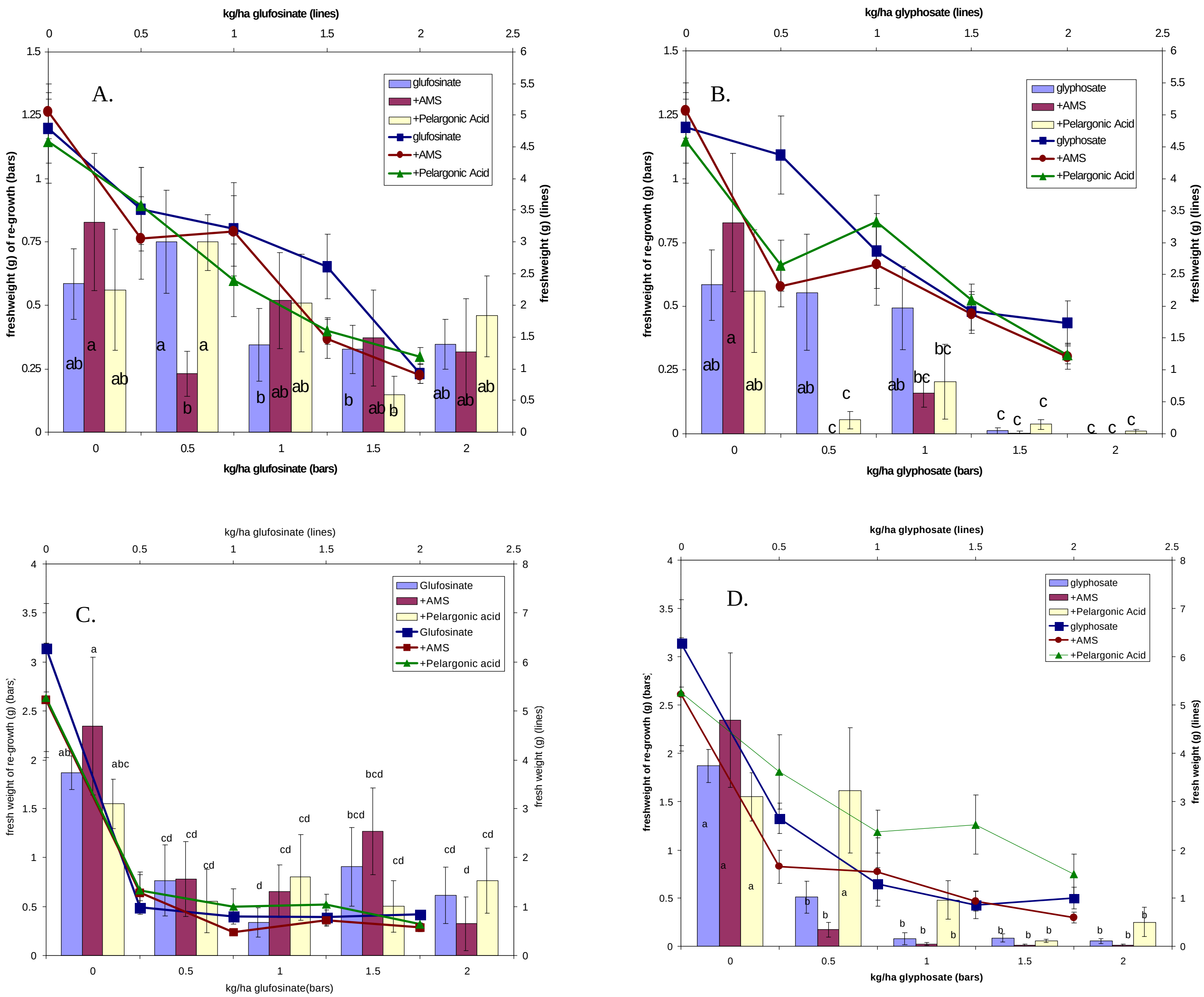


Figure 2.3 Regrowth of common milkweed and horsenettle following treatment with glufosinate or glyphosate alone or in combinations with AMS and PA.

A: various rates of glufosinate alone or in combination with 5% (w/v) AMS or 3% (v/v) PA on common milkweed, B: various rates of glyphosate alone or in combination with 5% (w/v) AMS or 3% (v/v) PA on common milkweed, C: various rates of glufosinate alone or in combination with 5% (w/v) AMS or 3% (v/v) PA on horsenettle, D: various rates of glyphosate alone or in combination with 5% (w/v) AMS or 3% (v/v) PA on horsenettle. Lines represent the fresh weight (g) of plants 10 days after herbicide treatment (right y-axis and top x-axis). Bars represent the fresh weight (g) of regrowth 70 days after herbicide treatment (left y-axis and bottom x-axis). Means were separated using Fisher's Protected $LSD_{0.05}$. Means with the same letter in each graph are not significantly different.

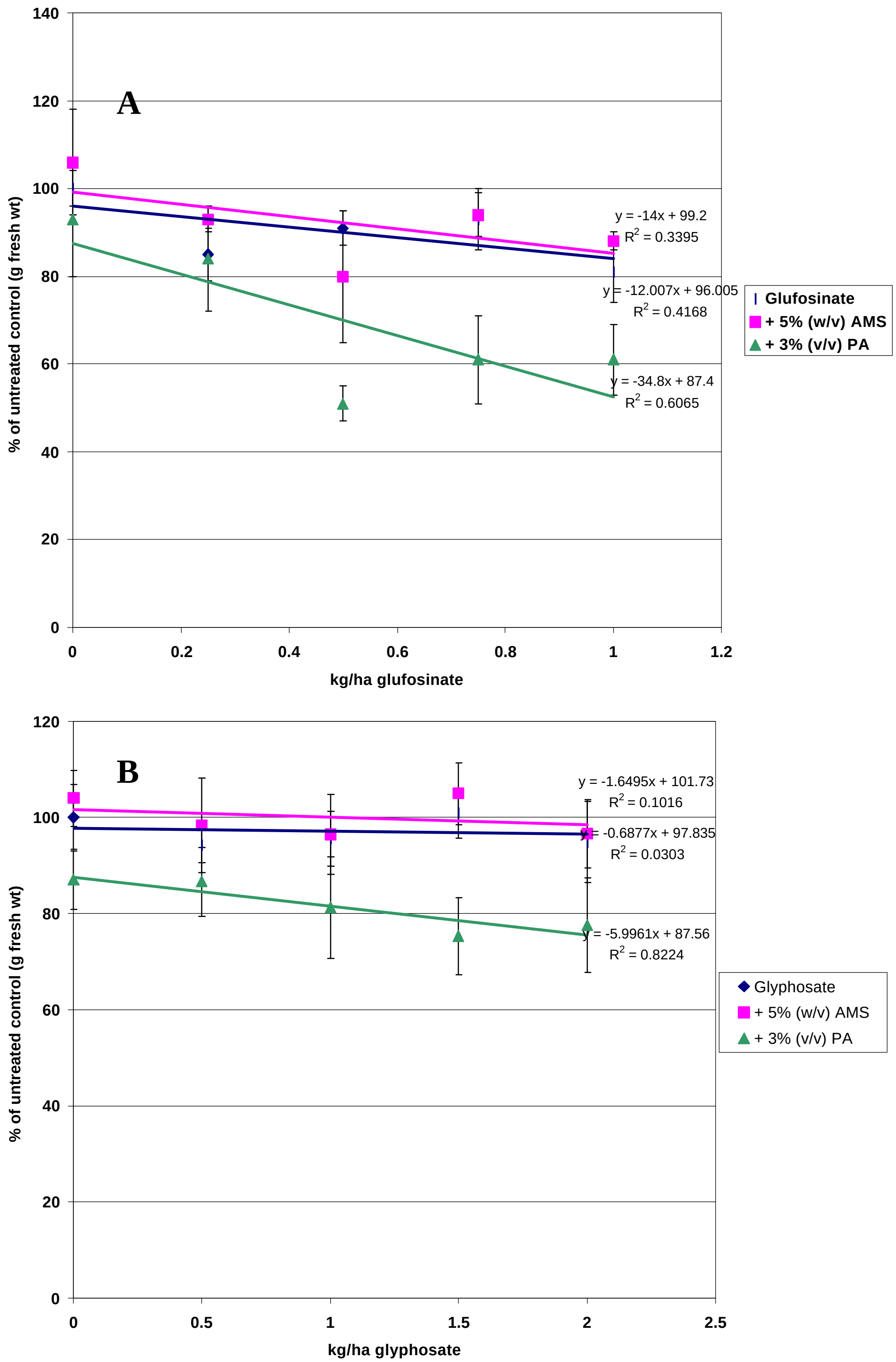


Figure 2.4. Effect of AMS and PA combinations with glyphosate or glufosinate on Roundup-Ready® or Liberty-Link® soybeans.

A. Glufosinate alone or with the addition of 5% (w/v) AMS or 3% (v/v) PA on Liberty-Link Soybeans. B. Glyphosate alone or with the addition of 5% (w/v) AMS or 3% (v/v) PA on Roundup-Ready Soybeans. Linear or non-linear curves were fit to the data and plotted. Error bars represent the standard error of each treatment.

A. Glufosinate	***SETFA***			***AMBEL***			***CHEAL***			***AMARE***			***IPOMEA spp.***			***CYPES***			***Liberty Link Soys***		
kg/ha	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA
0.14	99	98	100	100	100	100	95	97	97	100	97	98	99	95	97	83	87	92	0	0	13
0.28	97	97	100	100	100	100	93	100	94	95	100	100	97	93	99	82	86	93	0	0	13
0.56	96	96	100	100	100	100	100	99	99	98	97	99	99	98	98	85	90	94	0	2	13
1.12	95	97	100	100	100	100	100	100	100	100	100	100	100	99	98	89	91	95	5	3	12
2.25	95	97	100	100	100	100	100	100	100	100	100	100	100	100	100	92	90	95	10	5	15
4.5	97	98	100	100	100	100	100	100	100	100	100	100	100	100	99	98	95	98	17	12	17
9	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	98	98	100	33	23	17
LSD/weed @ .05:			7.0			0.0			3.9			3.3			4.1			6.9			13.4

B. Glyphosate	***SETFA***			***AMBEL***			***CHEAL***			***AMARE***			***IPOMEA spp.***			***CYPES***			***Roundup-Ready***		
kg/ha	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA
0.14	96	98	92	50	85	72	87	84	97	95	92	88	23	37	27	52	50	53	0	0	10
0.28	99	97	93	57	85	72	92	80	96	96	92	90	22	43	25	53	50	50	0	0	10
0.56	100	99	98	68	87	85	95	80	96	94	92	91	22	32	25	53	53	50	0	0	10
1.12	100	100	98	75	87	75	97	90	100	97	93	95	25	33	27	52	55	52	0	0	10
2.25	100	98	100	77	88	87	98	98	97	99	97	95	28	30	27	53	55	55	0	2	10
4.5	100	100	100	77	88	98	98	98	100	100	97	100	35	38	25	53	55	55	0	0	10
9	100	100	100	83	98	98	100	99	97	100	100	100	47	43	37	57	65	50	0	0	37
LSD/weed @ .05:			6.0			22.0			13.9			10.0			21.9			8.7			8.4

Table 2.1. Field ratings from Liberty-Link and Roundup-Ready soybean plots of 6 DAT

Values are % control based on visual injury ratings of the weeds giant foxtail (SETFA), common ragweed (AMBEL), common lambsquarters (CHEAL), redroot pigweed (AMARE), morningglory spp. (IPOMEA spp.), yellow nutsedge (CYPES) or percent injury in Liberty-Link and Roundup-Ready soybeans. Treatments were glufosinate or glyphosate alone, in combination with 2.8 kg/ha AMS, or in combination with 3% (v/v) Pelargonic Acid (PA). A: Glufosinate treatments—6 DAT, B: Glyphosate treatments—6 DAT. $LSD_{0.05}$ was determined for each weed within either Liberty-Link or Roundup-Ready Soybeans using Fisher's Protected LSD test.

A. Glufosinate	SETFA			AMBEL			CHEAL			AMARE			IPOMEA spp.			CYPES			Liberty Link Soys		
kg/ha	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA
0.14	98	100	97	100	100	100	92	87	87	92	93	95	98	92	85	87	93	90	0	0	0
0.28	97	100	100	100	100	100	90	87	92	97	92	98	98	98	87	88	93	95	0	0	0
0.56	100	100	100	100	100	100	97	98	95	97	95	98	100	97	92	97	95	98	0	0	0
1.12	100	98	100	100	100	100	98	98	98	100	97	98	93	97	95	93	98	100	0	0	0
2.25	100	100	100	100	100	100	99	100	100	100	100	98	100	100	97	99	100	93	0	0	0
4.5	100	97	100	100	100	100	100	99	100	98	100	100	98	100	100	98	100	100	0	0	0
9	99	100	100	100	100	100	100	100	97	100	100	98	100	100	90	100	100	92	3	3	0
LSD/weed @ .05:			3.5			0.0			6.5			7.7			7.6			7.5			2.9

B. Glyphosate	SETFA			AMBEL			CHEAL			AMARE			IPOMEA spp.			CYPES			Roundup-Ready		
kg/ha	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA	Alone	+AMS	+PA
0.14	95	97	85	100	100	97	92	93	100	92	97	88	75	85	63	90	90	97	0	0	0
0.28	97	97	92	95	97	100	88	92	100	93	92	90	77	87	77	93	93	92	0	0	0
0.56	97	93	95	98	98	97	97	90	98	93	88	93	78	83	83	92	85	98	0	0	0
1.12	100	93	97	100	100	98	98	97	100	100	93	97	85	83	85	96	90	97	0	0	0
2.25	98	97	98	100	100	100	98	100	100	100	95	100	87	85	88	98	92	97	0	0	0
4.5	96	98	93	97	100	100	95	100	97	100	98	100	97	91	90	95	95	100	0	0	0
9	99	100	97	100	100	100	100	100	97	100	98	100	83	92	80	100	98	90	0	0	0
LSD/weed @ .05:			9.1			4.6			8.9			7.2			10.3			8.1			0.0

Table 2.2. Field ratings from Liberty-Link and Roundup-Ready soybean plots of 23 DAT.
Values are % control based on visual injury ratings of the weeds giant foxtail (SETFA), common ragweed (AMBEL), common lambsquarters (CHEAL), redroot pigweed (AMARE), morningglory spp. (IPOMEA spp.), yellow nutsedge (CYPES) or percent injury in Liberty-Link and Roundup-Ready soybeans. Treatments were glufosinate or glyphosate alone, in combination with 2.8 kg/ha AMS, or in combination with 3% (v/v) Pelargonic Acid (PA). A: Glufosinate treatments—23 DAT, B: Glyphosate treatments—23 DAT. $LSD_{0.05}$ were determined for each weed within either Liberty-Link or Roundup-Ready Soybeans using Fisher's Protected LSD test.

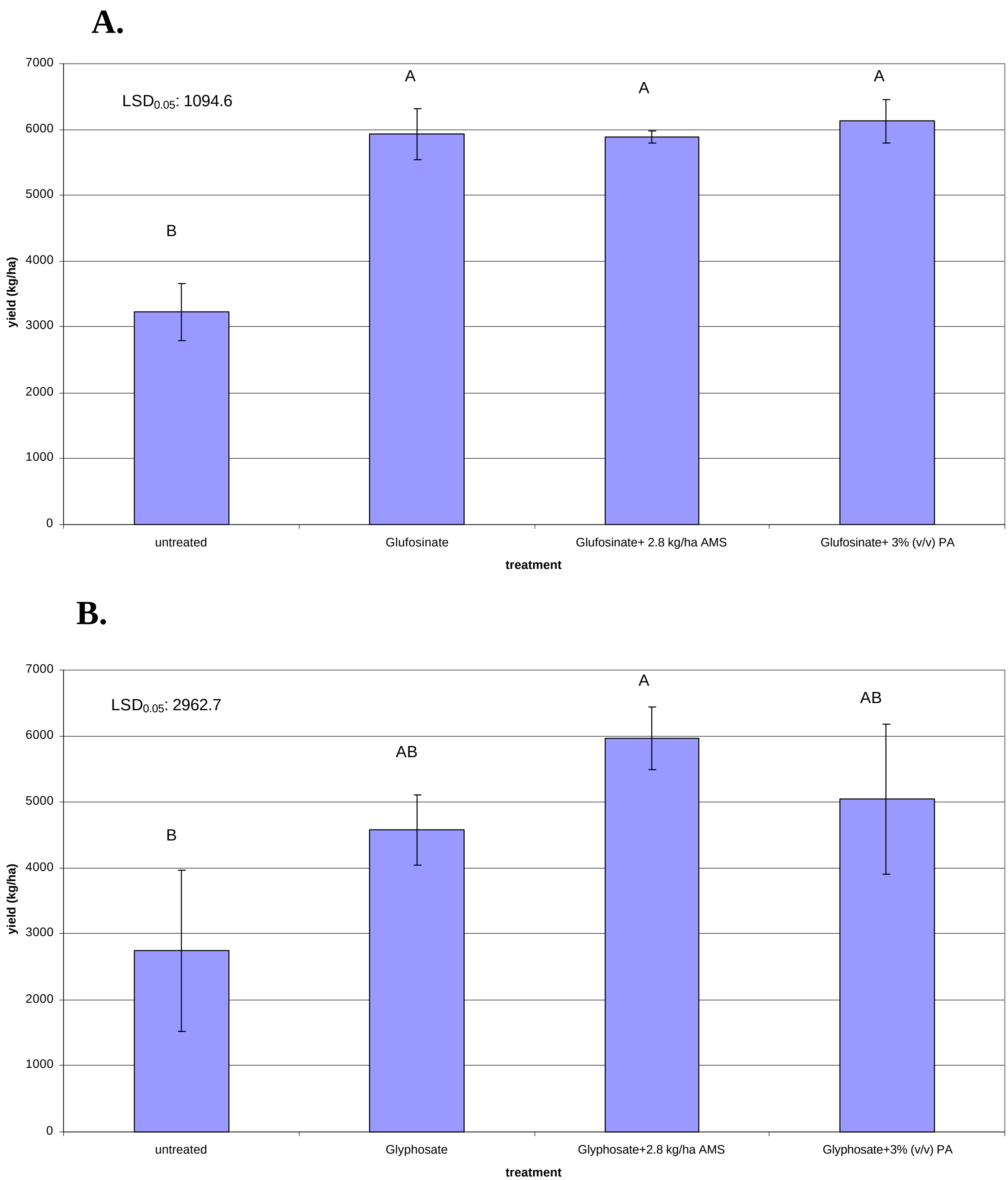


Figure 2.5. Yield of Liberty-Link (A.) and Roundup-Ready (B.) soybeans harvested from field plots at 4 kg/ha rates.

Treatments included 4 kg/ha glufosinate alone or in combination with 2.8 kg/ha AMS or 3% (v/v) PA (A.) or (B.) 4 kg/ha glyphosate alone or in combination with 2.8 kg/ha AMS or 3% (v/v) PA. A 0.37 m^2 portion of each plot was hand harvested and yields extrapolated to kg/ha. Means separated using Fisher's LSD test with α=0.05. Means with the same letter in each soybean variety are not significantly different.

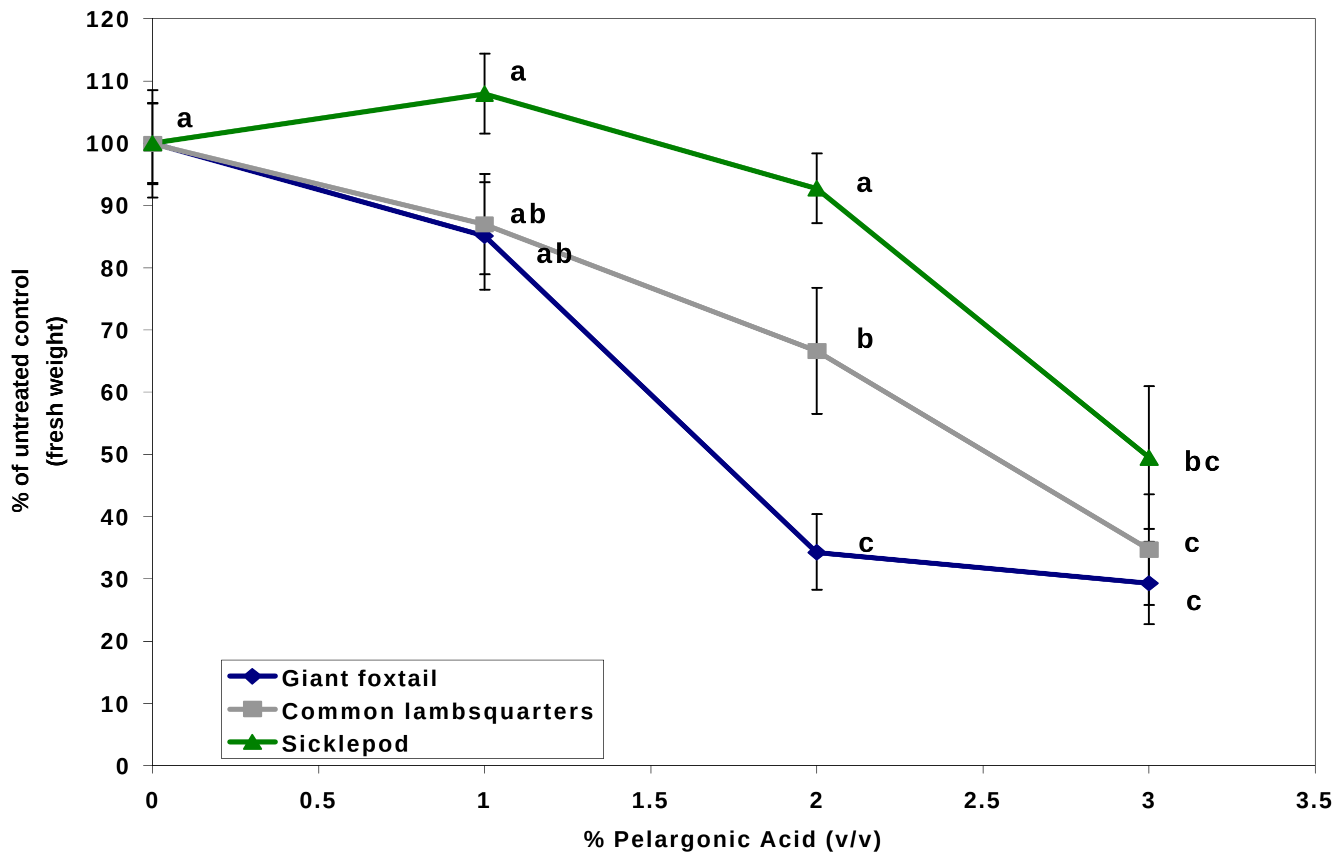


Figure 2.6. Pelargonic acid dose responses on annual weeds.

Means are plotted as % fresh weight of untreated control. Error bars represent the standard error, and means were separated using Fisher's Protected LSD test at α=0.05. Means with the same letter are not significantly different.

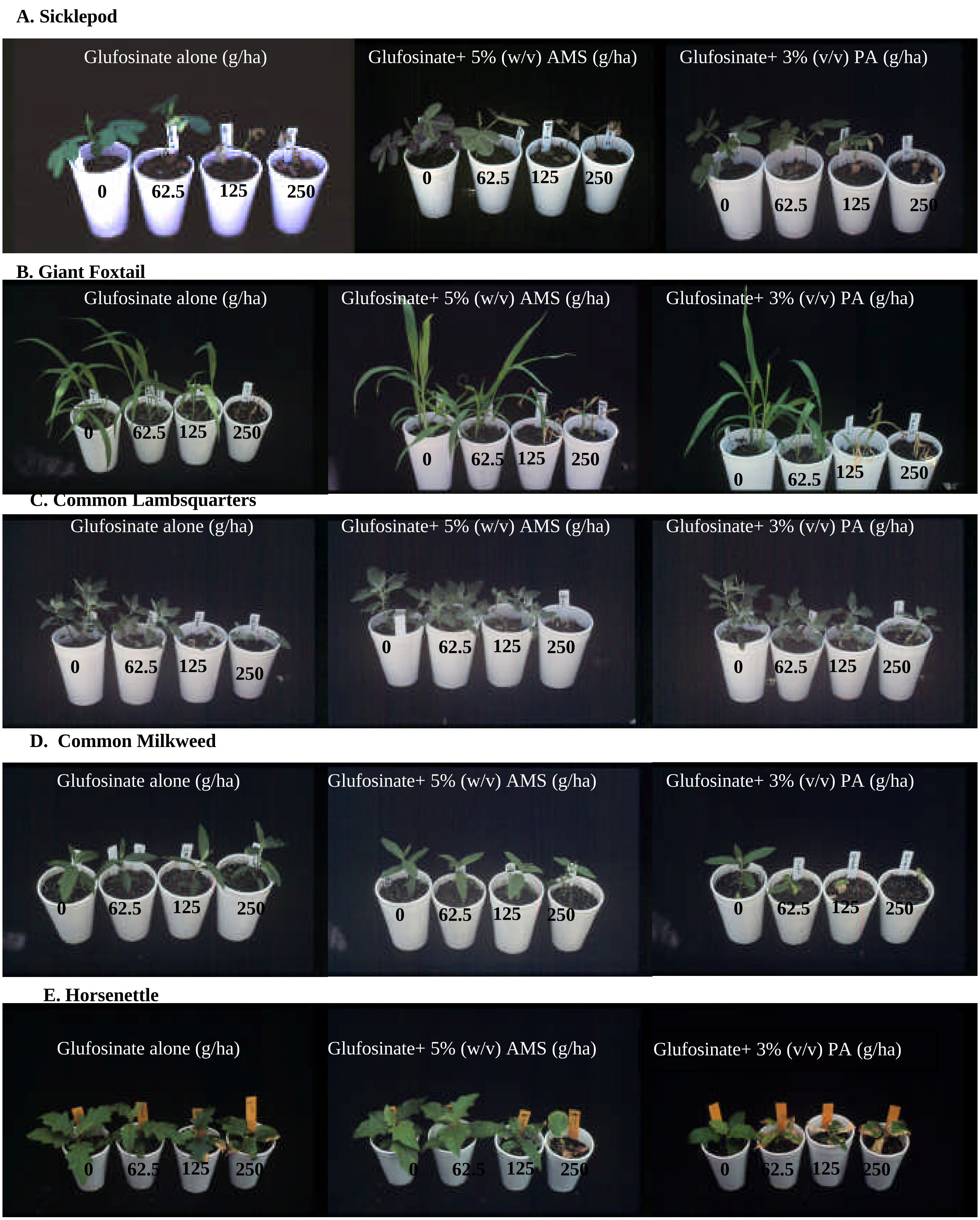
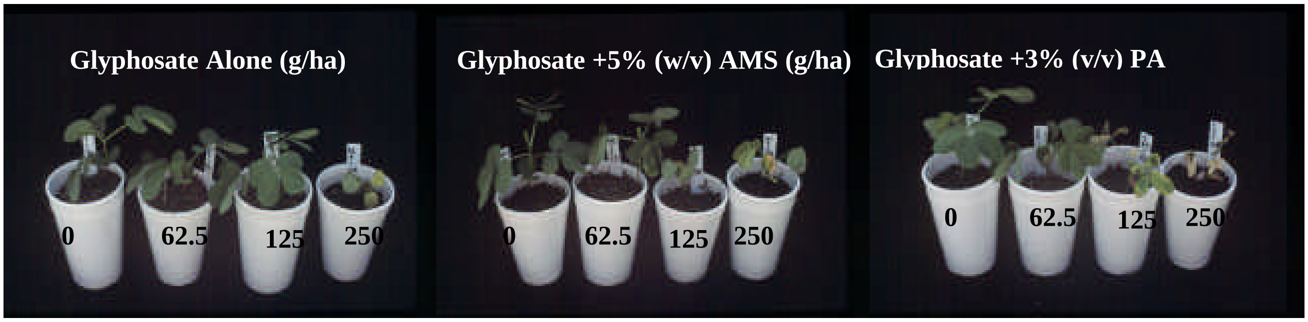
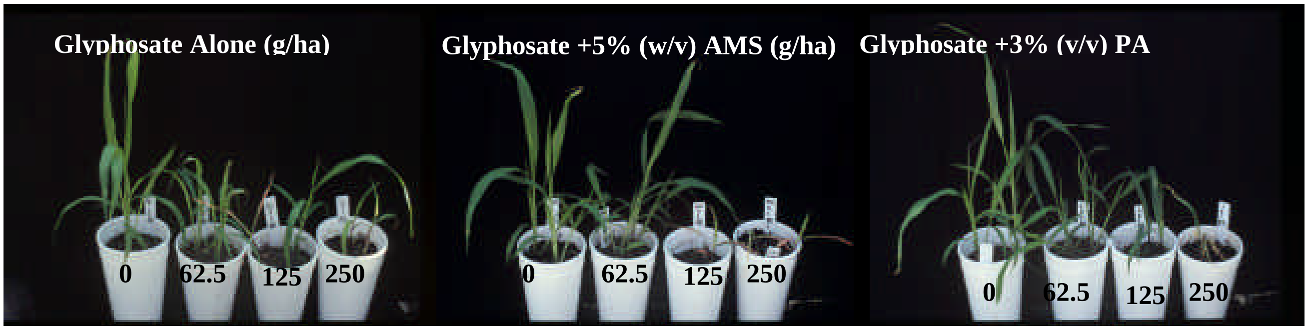


Figure 2.7. Photographs depicting injury by glufosinate and additives.

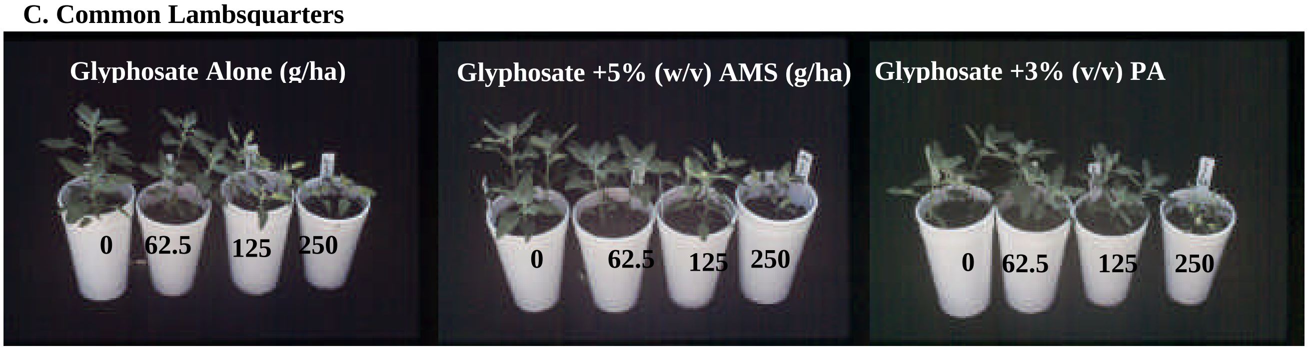
A. Sicklepod



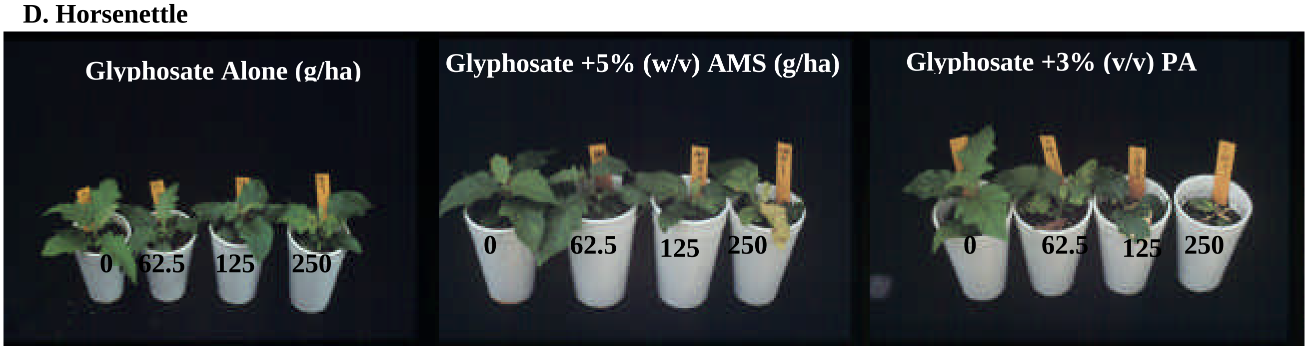
B. Giant foxtail



C. Common Lambsquarters



D. Horsenettle



E. Common Milkweed

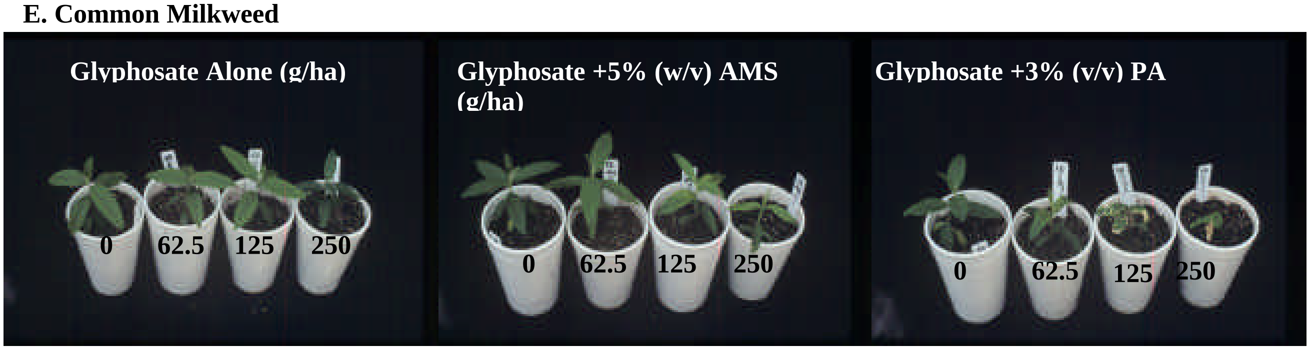


Figure 2.8. Photographs depicting injury by glyphosate and additives.

0, 0.125, 0.25, 0.5, 0.75, 1.0 kg/ha glufosinate

1.0 kg/ha glufosinate alone

0, 0.125, 0.25, 0.5, 0.75, 1.0 kg/ha glufosinate + 3% (v/v) PA.

1.0 kg/ha glufosinate + 3% (v/v) PA.

Figure 2.9. Pictures of the effect of glufosinate and 3% (v/v) PA plus glufosinate on Liberty-Link Soybeans in Greenhouse studies and Field Studies.

A1: greenhouse study, glufosinate alone. A2: greenhouse study, glufosinate plus PA. B1: field study, glufosinate alone. B2: field study, glufosinate + PA.