Integrated weed management and herbicide application parameters for herbicide-resistant soybean in Kansas

by

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Abstract

Integrated weed management and herbicide application practices were assessed in field and greenhouse studies to improve weed control in herbicide-resistant soybeans (*Glycine max* (L.) Merr.) grown in Kansas. The field study was conducted to evaluate weed control, soybean yield, and profitability in two herbicide-resistant soybean systems and two row spacings. 2,4-D-, glyphosate-, and glufosinate- resistant (Enlist E3) and isoxaflutole-, glyphosate-, and glufosinate-resistant (LLGT27) soybeans were planted in 38- and 76-cm row spacing for four site-years. Three herbicide treatments were evaluated in each system: pre-emergence herbicide only (PRE), PRE followed by early post-emergence (POST), and POST plus overlapping residual (POR). Weed control was evaluated every 2 weeks after PRE application through R7 soybean. Weed biomass was collected before POST applications and at R7 soybean. Soybean yield was recorded at harvest. Data were subjected to analysis of variance and means separation. In Ottawa during 2020, POST and POR treatments resulted in ≥ 99% control for all species four WAT, while PRE resulted in ≥ 84% control. Similarly, control at Ashland Bottoms was ≥ 90% for POST and POR treatments, while PRE resulted in 7% for isoxaflutole- 62% for 2,4-D-resistant soybeans. All treatments resulted in ≥ 95% control at Scandia in 2021. Row spacing had a minimal effect on weed control and mixed results for yield. In the greenhouse study, the objective was to determine the effect of herbicide combination, optimize carrier volume, and evaluate weed height on weed control. Co-applications of combinations of 2,4-D choline, glyphosate, and glufosinate were applied in carrier volumes of 93-, 140-, and 187- L ha^{-1} to 5-, 10-, and 20-cm Palmer amaranth (*Amaranthus palmeri* S. Watson) and large crabgrass (*Digitaria sanguinalis* L.). Visual ratings and above ground biomass were collected four weeks after treatment. Water-sensitive paper was also sprayed with the same herbicide combinations and carrier volumes to evaluate differences in spray coverage. Data were subjected to analysis of variance and means separation. Carrier volume did not affect Palmer amaranth or large crabgrass control. Control of 5-, 10-, and 20-cm Palmer amaranth was 100%, ≥ 91%, and 6.7 to 79%, respectively, and variation was caused by the herbicide combinations. 2,4-D plus glyphosate provided the greatest Palmer amaranth control. Large crabgrass control pooled for both experiments was ≥ 82% when treatments were applied at 5 cm, but control of 10- or 20-cm large crabgrass was reduced to 51 to 56%. There was a carrier volume by herbicide co-application interaction for the number of droplets deposited and percent area covered on water-sensitive paper. Co-applications containing glufosinate had more droplets than those not containing glufosinate. 2,4-D plus glyphosate had the smallest percent area covered, compared to the other herbicide co-applications. Data from the field study confirms that two-pass herbicide programs are superior to PRE- only programs, regardless of the inclusion of a layered residual herbicide. However, this research did not evaluate the impact of layered residual herbicides on weed seed production, which is crucial for long-term weed management. Results from the greenhouse study suggest that under ideal conditions, carrier volume is less important than herbicide combination and weed size for control of Palmer amaranth and large crabgrass.

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Chapter 1 - Literature Review

Introduction

Summer annual weeds compete with soybean (*Glycine max* (L.) Merr.) for resources and reduce yield to 79% if left uncontrolled (Bensch et al. 2003). Integrated weed management is needed for maximum weed control and to slow the development of herbicide resistant weed populations. Soybeans planted in narrow rows have the potential to canopy sooner compared to wide rows, thus improving weed control and yield. Soybean varieties resistant to glyphosate, glufosinate, and 2,4-D (Enlist E3) and glyphosate, glufosinate, and isoxaflutole (LLGT27) enable applications of herbicides not previously used in soybeans. The use of herbicide combinations made possible by these herbicide-resistant soybean traits should be evaluated in combination with integrated management practices such as narrow row spacings and optimized for application parameters such as carrier volume.

Troublesome weeds

Palmer amaranth (*Amaranthus palmeri* S. Watson) and common waterhemp (*Amaranthus tuberculatus* J. D. Sauer) are common and troublesome weeds in soybean production throughout the soybean-producing areas of the United States (Van Wychen 2019). Palmer amaranth and waterhemp have been reported to produce over 200,000 seeds per plant, with Palmer amaranth production as many as 600,000 seeds per plant in some environments (Keeley et al. 1987, Sellers et al. 2003, Webster and Grey 2015). Viable seeds will germinate rapidly under ideal conditions. Sellers et al. (2003) reported Palmer amaranth emergence within five days after planting, while common waterhemp took 14 to 17 days. Steckel et al. (2004) furthered that research and reported all Palmer amaranth seeds emerged on the first day when they alternated the temperature from 18 C to 42 C. After emergence, diaheliotropism allows Palmer amaranth to track the sun, utilize resources, and grow rapidly (Ehleringer and Forseth 1980, Ward et al. 2013). The rapid growth rate (Jha and Norsworthy 2009) allows these plants to reach 2 m tall (Sauer 1955). Davis et al. (2015) found that Palmer amaranth survival increases with accumulating growing degree days. Phenotypic plasticity allows Palmer amaranth and waterhemp to be successful in many environments (Costea et al. 2005, Jha and Norsworthy 2009).

Another factor that makes Palmer amaranth and waterhemp troublesome is the occurrence of herbicide resistance. Numerous populations resistant to one or more herbicides have been reported throughout the United States, including synthetic auxins, ALS-, microtubule assembly-, PSII-, EPSP synthetase-, glutamine synthetase-, PPO-, long-chain fatty acid synthesis-, and HPPD inhibitor herbicides (Heap, 2022). In fact, Palmer amaranth in Kansas has been found to be resistant to ALS-, PS II-, HPPD-, PPO-, EPSPS-inhibitor herbicides, and synthetic auxins (Shyam et al. 2021).

The combination of high seed production, germination rate, and ability to adapt has inhibited soybean production. Palmer amaranth has reduced soybean yields by 68% in Arkansas (Klingaman and Oliver 1994) and 79% in Kansas (Bensch et al. 2003), early emerged Palmer amaranth caused greater losses (Bensch et al. 2003). Common waterhemp has been reported to cause up to 63% yield loss in soybean (Bensch et al. 2003).

Large crabgrass (*Digitaria sanguinalis* (L.) Scop.) is another common weeds in soybean production systems in the United States (Van Wychen 2019). Aguyoh and Masiunas (2003) reported large crabgrass can produce 900 to 3,100 seeds per plant. Large crabgrass emerges when the temperature ranges from 15 C to 35 C (King and Oliver 1994). Plants can form a dense mat of biomass (Basinger et al. 2019) and grow 90-cm tall (Oreja et al. 2021). This is problematic for farmers, as the large crabgrass will use the available water and nutrients.

Large crabgrass populations resistant to ACCase inhibitor herbicides have been reported in the United States, with populations resistant to PSII- and ALS- inhibitor herbicides in other regions of the world (Heap 2022). ACCase-inhibitor herbicide resistance in Canada was reported to be caused by the overexpression of the ACCase gene (Laforest et al. 2017). Herbicide resistant weeds could impact crop yields.

Basinger et al. (2019) suggested that large crabgrass at a density of 16 plants m^{-1} can reduce soybean yields up to 37%, which is similar to Palmer amaranth. Soybean can interfere with large crabgrass. Oreja et al (2021) reported that the soybean canopy reduced solar radiation and maximum temperatures thereby impacting large crabgrass by reducing the total biomass produced.

Integrated weed management in soybeans

The increasing prevalence of herbicide-resistant weeds necessitates integrated weed management (Davis et al. 2015, Dent 1995, King and Oliver 1994, Shyam et al. 2021, Wallace et al. 2019, Ward et al. 2013). Integrated weed management incorporates chemical, cultural, mechanical, and biological, methods to control weeds. Chemical methods use herbicides to control weeds (Norsworthy et al. 2012). Cultural weed control involves using different methods to grow a crop, such as changing the row spacing or soybean variety (Johnson et al. 1998). Mechanical weed control involves physically removing the undesirable plants by tilling, mowing, cutting, hoeing, and hand removal (Knezevic et al. 2019). Biological weed control involves using living organisms to control weeds (Hoeft et al. 2001).

Row spacing

Soybean row spacing influences the rate of canopy closure, weed control, and soybean yield. Narrow rows canopy sooner, intercepting more light, potentially suppressing more weeds (Dalley et al. 2004, Yelverton and Coble 1991). Bell et al. (2015) studied the effect of row spacing and canopy closure in soybeans with 19-, 45-, and 90-cm row spacings in Arkansas. The first year of the experiment was the dry year of 2012 and the 19-cm rows took 85 days after planting to reach 90% canopy, whereas the 90-cm rows never canopied (Bell et al. 2015). The next year had more normal rainfall and the 19- and 90-cm rows reached 90% canopy by 40 and 50 days after planting, respectively (Bell et al. 2015). Bell's findings were similar to Dalley et al. (2004), who reported that 19-cm rows have greater light interception 36 to 47 days after emergence. These researchers also reported that soybeans planted in 19-, 38-, and 76-cm rows had approximately 98%, 97%, and 18% of light interception, respectively. Harder et al. (2007) found that 19- and 38-cm rows reached 95% light interception 1 week before 76-cm rows with populations less than 198,000 plants ha^{-1} and 2 weeks before populations greater than 296,000 plants ha^{-1}.

The relationship between canopy closure and weed control is more varied. Bell et al. (2015) and McDonald et al. (2021) reported no effect on weed control. Harder et al.(2007) reported that 19-cm rows had a 78% reduction in weed densities compared to the 76-cm rows 5 week after treatment, which was roughly at canopy closure. Similarly, weed biomass in 19-cm rows was reduced by 34 % when compared to the 76-cm rows grown at 296,000 to 309,000 soybean plants ha^{-1} (Harder et al. 2007).

Dalley et al. (2004) had mixed results in weed biomass for a four-year study. Weed biomass in 19-cm and 38-cm rows was reduced compared to 76-cm rows during three out of four years when one application of glyphosate was applied to 10-cm weeds (Dalley et al. 2004). Interestingly, the year that had no differences in biomass following glyphosate application to 10-cm weeds also had the greatest total weed density (Dalley et al. 2004). Bell et al. (2015) reported different Palmer amaranth densities at harvest of 19-, 26-, and 41- plants m^{-2} in 19-, 45- and 90-cm rows, respectively for the non-treated plots. Plots treated with herbicides had had $\leq$ 2.1 weeds m^{-2} and $\geq$ 86% control of Palmer amaranth at harvest, regardless of row spacing (Bell et al. 2015). McDonald et al. (2021) also evaluated Palmer amaranth density in soybeans and reported 15 Palmer amaranth plants m^{-2} in 76-cm rows, but only 1 plant m^{-2} in 38-cm rows after late post-emergence herbicide applications. Overall, previously published research suggests that planting soybeans in row spacings less than 76 cm can help farmers achieve the ‘zero tolerance’ policy for managing herbicide resistant weeds (Norsworthy et al. 2014).

Soybean yield when planted at different row widths is variable. Yelverton and Coble (1991) found a 20% increase in yield when soybeans were planted in 25-cm rows compared to 102-cm rows. De Bruin and Pederson (2008) and Hanna et al. (2008) found that the 38-cm rows yielded more than the 76-cm rows in Iowa and Indiana, respectively. However, Bell et al. (2015) reported that 45-cm rows yielded 29 and 45% more than the 19-cm and 90-cm row spacing, respectively. Soybeans planted in 45-cm rows were also the most profitable.

Walker et al. (2010), McDonald et al. (2021), and Rich and Renner (2007) reported that soybean yields from 38-cm rows were greater than or similar to 76-cm rows. During the first year, the 38-cm and 76-cm rows had similar yields, while during the second, wetter year narrow rows yielded 18% more than wide rows (McDonald et al. 2021). Rich and Renner (2007) reported similar yield results for 19-cm and 76-cm rows planted at 308,000 seeds ha^{-1} with the same herbicide treatments for two site years. However, in the third site year, 19-cm rows yielded

13% better than 76-cm rows. Berger-Doyle et al. (2014) reported irrigated soybeans yielded better than dryland, but yields were similar for 38-cm and 76-cm rows.

Andrade et al. (2019) reviewed 129 site-years for differences in soybean yield between 38-cm and 76-cm row spacings. Results indicated that overall, soybeans planted in 38-cm rows had 3% greater yields compared to the 76-cm rows in 68% of the experiments in the central United States. The northern and southern regions showed 92- and 84% of the experiments had 18- and 8% greater yields, respectively when soybeans were planted in 38-cm rows. Narrow row spacing was favored when the amount of time soybeans spent in the VE-R3 growth stages is shorter, which is caused by shorter maturity groups and high temperatures early in the season (Andrade et al. 2019). However, Andrade et al. (2019) also reported that producers observed > 5% yield reduction for some soybean growing regions, suggesting factors impacting soybean yield include precipitation, soil type, underlying management practices, and cultivar selection. Walker et al (2010) agrees that narrow-rowed soybean yield is dependent on precipitation amounts and cultivar selection.

Herbicide resistant soybeans

There are many different herbicide-resistant traits available to soybean farmers. Traits include resistance to various combinations of glyphosate, glufosinate, 2,4-D, dicamba, and isoxaflutole. Enlist E3 soybeans are resistant to glyphosate, glufosinate, and 2,4-D, but only the 2,4-D choline formulations are labeled for use (Werle et al. 2021). Enlist E3 soybeans sales started in 2019 but seed was not readily available until 2020. BASF announced that it would be launching LibertyLink GT27 soybeans in the fall of 2018. The LLGT27 soybeans are resistant to glyphosate, glufosinate, and isoxaflutole, an HPPD-inhibiting herbicide that controls broadleaf weeds and grasses preemergence (Pallett et al. 2001).

Herbicide combinations used in the Enlist E3 soybean system effectively control a broad spectrum of weeds with additive and synergistic effects. Craigmyle et al. (2013) found that glufosinate provided 75% control of common waterhemp while 2,4-D provided 78% control: however, the combination of glufosinate and 2,4-D improved control to 98%. Similar results were reported for Palmer amaranth, with 2,4-D controlling Palmer amaranth 68 to 80%, and co-application with glufosinate improving control to 90 to 97% (Merchant et al. 2013). Shyam et al. (2021) reported > 96% control of Palmer amaranth with 2,4-D and glufosinate applied postemergence (POST) when a preemergence (PRE) herbicide was also applied. Lawrence et al. (2018) reported 2,4-D with glyphosate controled 5- to 10-cm glyphosate resistant Palmer amaranth 81% compared to 75% for 2,4-D alone. Co-application of 2,4-D with glyphosate resulted in > 95% control of large crabgrass (Miller and Norsworthy 2016).

However, reduced control or antagonism sometimes occurs, reducing weed control. Control of 15-cm large crabgrass was 75% when glufosinate was applied at 0.59 kg ha^{-1} but adding 2,4-D reduced large crabgrass control by 19% (Craigmyle et al. 2013). Merritt et al. (2021) pooled broadleaf signalgrass, giant foxtail, and barnyard grass control 28 days after treatment of 4 co-applications. Antagonism occurred when 2,4-D was co-applied with clethodim or glyphosate, with control of 44 and 27%, respectively. A split application of glyphosate followed by (fb) 2,4-D improved control to 86% (Merritt et al. 2021). O’Donovan and O’Sullivan (1982) suggest that antagonism that occurs when 2,4-D and glyphosate are co-applied is the result of reduced absorption and translocation.

Residual herbicides

Most cases of herbicide-resistant weeds are associated with post-emergent products (Heap 2022), so preventing weed emergence by applying residual herbicides at planting or early post-emergence (EPOST) can help mitigate resistance. Furthermore, co-applications of pre-emergence herbicide improves weed control (Walsh et al. 2015). Knezevic et al. (2009) reported 51 to 89% control 60 DAT for ivyleaf morningglory, Venice mallow, common lambsquarters, and velvetleaf with sulfentrazone applied PRE. Season-long weed control is improved with overlapping residual herbicide. Aulakh and Jhala (2015) reported control of common lambsquaters, common waterhemp, and velvetleaf was > 90% at harvest when sulfentrazone was co-applied with metribuzin as a PRE fb glufosinate and a Group 15 herbicide. In comparison, when the group 15 residual was not in the POST application, control was reduced to 69 to 70% (Aulakh and Jhala 2015). Similarly, large crabgrass and green foxtail control was > 94% at harvest with a PRE fb POST with a Group 15 residual herbicide compared to > 81% without residual in the POST application (Aulakh and Jhala 2015). Miller and Norsworthy (2016) reported EPOST applications containing residual herbicide provided greater Palmer amaranth control compared to those without. However, McDonald et al. (2021) reported weed control was similar for PRE fb EPOST and PRE fb EPOST + residual herbicide treatments (> 85%), except for dicamba fb dicamba.

Herbicide application parameters

Application parameters like carrier volume and droplet size affect weed control. Herbicide efficacy will normally increase with increasing carrier volume (Knoche 1994). Using a specific carrier volume for co-application of herbicide will influence efficacy (Butts et al. 2018, Creech et al. 2015b). Creech et al. (2015b) evaluated velvetleaf control by glufosinate applied at carrier volumes ranging from 47 to 187 L ha^{-1} and reported that increasing the carrier volume to 140 or 187 L ha^{-1} resulted in greater control (90 and 89%, respectively) than lower volumes, which ranged from 69 to 77%. In the same study, control by glyphosate at all carrier volumes was ≥ 93%. The glufosinate herbicide label recommends carrier volumes of at least 140 L ha^{-1}, but 187 L ha^{-1} is better, especially with a dense weed canopy (BASF Ag Products 2019). However, glyphosate works better at lower carrier volumes (93.5 L ha^{-1}; Bayer Ag Products 2017, Creech et al. 2015b, Knoche 1994).

Limited research exists on the effects of carrier volume when multiple herbicides are combined. Meyer et al. (2016) evaluated different carrier volumes for co-applications of dicamba applied with glyphosate, glufosinate and *S*-metolachlor and reported greater control at 187 L ha^{-1} compared to 94 L ha^{-1}. Striegel et al. (2021) studied PRE herbicides applied at carrier volumes from 23.8 to 167.2 L ha^{-1} and reported no differences for weed control or biomass in soybean.

Using the correct droplet size for a single herbicide or multiple herbicides co-applied is important for maintaining efficacy (Butts et al. 2018). In general, greater mortality is associated with smaller droplets (Knoche 1994). However, if the droplets are too small, evaporation will reduce control, especially in low humidity environments (Ramsey et al. 2002). When the operating pressure of the sprayer is increased, droplet size will decrease (Creech et al. 2015a, Czaczyk et al. 2012). Meyer et al. (2015) observed a decrease in Palmer amaranth, velvetleaf, and barnyardgrass control when the droplet size increased during one year of a two-year study. Droplet size is impacted by nozzle type, orifice size, and herbicide (Creech et al. 2015a, Nuyttens et al. 2007). Glufosinate decreased droplet size 18% compared to water alone but increasing the carrier volume reduced the effects the active ingredient had on droplet size (Creech et al. 2015a).

The size of the weeds at application also affects the control. Chahal et al. (2015) reported a 15% reduction in control when Enlist Duo (glyphosate + 2,4-D) was applied to 20-cm compared to 10-cm tall glyphosate- resistant common waterhemp. Similarly, common waterhemp control with glufosinate alone in the greenhouse was less when 30-cm plants were sprayed compared to 15-cm plants (Craigmyle et al. 2013). Control of both weed sizes was increased when 2,4-D was added, with the 15- and 30-cm common waterhemp having at least 95 and 82% control, respectively (Craigmyle et al. 2013). Similarly, 15-cm large crabgrass was controlled 46 to 78% with glufosinate alone and the 30 cm was controlled 25 to 55% (Craigmyle et al. 2013).

Conclusion

Troublesome weeds can cause major yield loss in soybeans. Integrated weed management practices, such as narrow row spacing, promotes canopy closure, and herbicide-resistant soybeans allow applications of multiple effective herbicides. Incorporating residual herbicides in post-emergent applications can improve season-long weed control. Increased carrier volume improves coverage and spray disposition resulting in greater weed control. When these practices are coupled with post-emergent herbicide applications targeting smaller weeds, soybean yield loss is mitigated. Therefore, the focus of the studies presented herein was to determine the effects of row spacing, post-emergent residual herbicides, carrier volume, and weed size at application on weed control and soybean yield in Kansas.

References

Aguyoh JN, Masiunas JB (2003) Interference of large crabgrass (*Digitaria sanguinalis*) with snap beans. Weed Sci 51:171–176

Andrade JF, Rattalino Edreira JI, Mourtzinis S, Conley SP, Ciampitti IA, Dunphy JE, Gaska JM, Glewen K, Holshouser DL, Kandel HJ, Kyveryga P, Lee CD, Licht MA, Lindsey LE, McClure MA, Naeve S, Nafziger ED, Orlowski JM, Ross J, Staton MJ, Thompson L, Specht JE, Grassini P (2019) Assessing the influence of row spacing on soybean yield using experimental and producer survey data. Field Crops Res 230:98–106

Aulakh JS, Jhala AJ (2015) Comparison of glufosinate-based herbicide programs for broad-spectrum weed control in glufosinate-resistant soybean. Weed Technol 29:419–430

BASF Ag Products (2019) Liberty 280 SL Herbicide Label. http://www.cdms.net/ldat/ldG9N000.pdf. Accessed August 8, 2020

Basinger NT, Jennings KM, Monks DW, Jordan DL, Everman WJ, Hestir EL, Waldschmidt MD, Smith SC, Brownie C (2019) Interspecific and intraspecific interference of Palmer amaranth (*Amaranthus palmeri*) and large crabgrass (*Digitaria sanguinalis*) in sweetpotato. Weed Sci 67:426–432

Bayer Ag Products (2017) Roundup Power MAX Herbicide Label. https://s3-us-west-1.amazonaws.com/agrian-cg-fs1-

production/pdfs/Roundup_PowerMAX1e_Herbicide_Label.pdf. Accessed August 8, 2020

Bell HD, Norsworthy JK, Scott RC, Popp M (2015) Effect of row spacing, seeding rate, and herbicide program in glufosinate-resistant soybean on palmer amaranth management. Weed Technol 29:390–404

Bensch CN, Horak MJ, Peterson D (2003) Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci 51:37–43

Berger-Doyle J, Zhang B, Smith S, Chen P (2014) Planting date, irrigation, and row spacing effects on agronomic traits of food-grade soybean. Adv Crop Sci Tech 2:4

Butts TR, Samples CA, Franca LX, Dodds DM, Reynolds DB, Adams JW, Zollinger RK, Howatt KA, Fritz BK, Hoffmann WC, Kruger GR (2018) Spray droplet size and carrier volume effect on dicamba and glufosinate efficacy. Pest Manag Sci 74:2020–2029

Chahal P, Aulakh JS, Rosenbaum K, Jhala AJ (2015) Growth stage affects dose response of selected glyphosate-resistant weeds to premix of 2,4-D Choline and glyphosate (Enlist Duo^{TM} Herbicide*). J Agr Sci 7:1–10

Costea M, Weaver SE, Tardif FJ (2005) The biology of invasive alien plants in Canada. 3. *Amaranthus tuberculatus* (Moq.) Sauer var. *rudis* (Sauer) Costea & Tardif. Can J Plant Sci 85:507–522

Craigmyle BD, Ellis JM, Bradley KW (2013) Influence of weed height and glufosinate plus 2,4-D combinations on weed control in soybean with resistance to 2,4-D. Weed Technol 27:271–280

Creech CF, Henry RS, Fritz BK, Kruger GR (2015a) Influence of herbicide active ingredient, nozzle type, orifice size, spray pressure, and carrier volume rate on spray droplet size characteristics. Weed Technol 29:298–310

Creech CF, Henry RS, Werle R, Sandell LD, Hewitt AJ, Kruger GR (2015b) Performance of postemergence herbicides applied at different carrier volume rates. Weed Technol 29:611–624

Czaczyk Z, Kruger G, Hewitt A (2012) Droplet size classification of air induction flat fan nozzles. J Plant Prot Res 52:415–420

Dalley CD, Kells JJ, Renner KA (2004) Effect of glyphosate application timing and row spacing on weed growth in corn (*Zea mays*) and soybean (*Glycine max*). Weed Technol 18:177–182

Davis AS, Schutte BJ, Hager AG, Young BG (2015) Palmer amaranth (*Amaranthus palmeri*) damage niche in Illinois soybean is seed limited. Weed Sci 63:658–668

De Bruin JL, Pedersen P (2008) Effect of row spacing and seeding rate on soybean yield. Agron J 100:704–710

Dent D (1995) Integrated pest management. SSBM. 378 p

Ehleringer J, Forseth I (1980) Solar tracking by plants. Science 210:1094–1098

Hanna SO, Conley SP, Shaner GE, Santini JB (2008) Fungicide application timing and row spacing effect on soybean canopy penetration and grain yield. Agronomy J 100:1488–1492

Harder DB, Sprague CL, Renner KA (2007) Effect of soybean row width and population on weeds, crop yield, and economic return. Weed Technol 21:744–752

Heap I (2022) The international herbicide-resistant weed database. http://www.weedscience.org/Home.aspx. Accessed January 18, 2022

Hoeft E, Jordan N, Zhang J, Wyse D (2001) Integrated cultural and biological control of Canada thistle in conservation tillage soybean. Weed Sci 49:642–646

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644–651

Johnson GA, Hoverstad TR, Greenwald RE (1998) Integrated weed management using narrow corn row spacing, herbicides, and cultivation. Agronomy J 90:40–46

Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci 35:199–204

King CA, Oliver LR (1994) A model for predicting large crabgrass (*Digitaria sanguinalis*) emergence as influenced by temperature and water potential. Weed Sci 42:561–567

Klingaman TE, Oliver LR (1994) Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). Weed Sci 42:523–527

Knezevic S, Jhala A, Proctor C, Lawrence N, Ogg C, Kruger G (2019) Guide for weed, disease, and insect management in Nebraska. UNL Extension

Knezevic SZ, Datta A, Scott J, Klein RN, Golus J (2009) Problem weed control in glyphosate-resistant soybean with glyphosate tank mixes and soil-applied herbicides. Weed Technol 23:507–512

Knoche M (1994) Effect of droplet size and carrier volume on performance of foliage-applied herbicides. Crop Prot 13:163–178

Laforest M, Soufiane B, Simard M-J, Obeid K, Page E, Nurse RE (2017) Acetyl-CoA carboxylase overexpression in herbicide-resistant large crabgrass (*Digitaria sanguinalis*). Pest Manag Sci 73:2227–2235

Lawrence BH, Bond JA, Eubank TW, Golden BR, Cook DR, Mangialardi JP (2018) Evaluation of 2,4-D–based herbicide mixtures for control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Technol 33:263–271

McDonald ST, Striegel A, Chahal PS, Jha P, Rees JM, Proctor CA, Jhala AJ (2021) Effect of row spacing and herbicide programs for control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in dicamba/glyphosate-resistant soybean. Weed Technol:1–12

Merchant RM, Sosnoskie LM, Culpepper AS, Steckel LE, York AC, Braxton LB, Ford JC (2013) Weed response to 2,4-D, 2,4-DB, and dicamba applied alone or with glufosinate. J Cotton Sci 17:212-218

Merritt LH, Brown-Johnson AE, Meredith AN, Ferguson JC (2021) Comparison of efficacy and detection of clethodim and glyphosate applied with dicamba and 2,4-D through tank mixture and sequential applications. J Agric Food Chem 69:101–111

Meyer CJ, Norsworthy JK, Kruger GR, Barber T (2015) Influence of droplet size on efficacy of the formulated products Engenia^{TM}, Roundup PowerMax®, and Liberty®. Weed Technol 29:641–652

Meyer CJ, Norsworthy JK, Kruger GR, Barber TL (2016) Effect of nozzle selection and spray volume on droplet size and efficacy of engenia tank-mix combinations. Weed Technol 30:377–390

Miller MR, Norsworthy JK (2016) Evaluation of herbicide programs for use in a 2,4-D–resistant soybean technology for control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Technol 30:366–376

Norsworthy JK, Griffith G, Griffin T, Bagavathiannan M, Gbur EE (2014) In-field movement of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) and its impact on cotton lint yield: evidence supporting a zero-threshold strategy. Weed Sci 62:237–249

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60:31–62

Nuyttens D, Baetens K, De Schampheleire M, Sonck B (2007) Effect of nozzle type, size and pressure on spray droplet characteristics. Biosyst Eng 97:333–345

O'Donovan JT, O'Sullivan PA (1982) The antagonistic action of 2,4-d and bromoxynil on glyphosate phytotoxicity to barley (*Hordeum vulgare*). Weed Sci 30:30–34

Oreja FH, Batlla D, de la Fuente EB (2021) Effect of soybean crop structure on large crabgrass (*Digitaria sanguinalis*) growth and seed dormancy. Weed Sci 69:372–378

Pallett KE, Cramp SM, Little JP, Veerasekaran P, Crudace AJ, Slater AE (2001) Isoxaflutole: the background to its discovery and the basis of its herbicidal properties. Pest Manag Sci 57:133–142

Ramsey RJL, Stephenson GR, Hall JC (2002) Effect of relative humidity on the uptake, translocation, and efficacy of glufosinate ammonium in wild oat (*Avena fatua*). Pestic Biochem Phys 73:1–8

Rich AM, Renner KA (2007) Row spacing and seeding rate effects on eastern black nightshade (*Solanum Ptycanthum*) and soybean. Weed Technol 21:124–130

Sauer JD (1955) Revision of the dioecious amaranths. Madrono 13:5–46

Sellers BA, Smeda RJ, Johnson WG, Kendig JA, Ellersieck MR (2003) Comparative growth of six Amaranthus species in Missouri. Weed Sci 51:329–333

Shyam C, Borgato EA, Peterson DE, Dille JA, Jugulam M (2021) Predominance of metabolic resistance in a six-way-resistant Palmer amaranth (*Amaranthus palmeri*) population. Front Plant Sci 11: 614618

Steckel LE, Sprague CL, Stoller EW, Wax LM (2004) Temperature effects on germination of nine Amaranthus species. Weed Sci 52:217–221

Striegel S, DeWerff RP, Arneson NJ, Oliveira MC, Werle R (2021) Pre-emergence herbicides, not carrier volume, impacted weed management in conventional tillage systems. CFTM 7:e20132

Van Wychen (2019) 2019 Baseline survey of the most common and troublesome weeds in the United States and Canada. Weed Science Society of America National Weed Survey Dataset

Walker ER, Mengistu A, Bellaloui N, Koger CH, Roberts RK, Larson JA (2010) Plant population and row-spacing effects on maturity group III soybean. Agron J 102:821–826

Wallace JM, Curran WS, Mortensen DA (2019) Cover crop effects on horseweed (*Erigeron canadensis*) density and size inequality at the time of herbicide exposure. Weed Sci 67:327–338

Walsh KD, Soltani N, Shropshire C, Sikkema PH (2015) Weed control in soybean with imazethapyr applied alone or in tank mix with saflufenacil/dimethenamid-P. Weed Sci 63:329–335

Ward SM, Webster TM, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*): a review. Weed Technol 27:12–27

Webster TM, Grey TL (2015) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) morphology, growth, and seed production in Georgia. Weed Sci 63:264–272

Werle R, Mobli A, Striegel S, Arneson N, DeWerff R, Brown A, Oliveira M (2021) Large-scale evaluation of 2,4-D choline off-target movement and injury in 2,4-D-susceptible soybean. Weed Technol:1–7

Yelverton FH, Coble HD (1991) Narrow row spacing and canopy formation reduces weed resurgence in soybeans (*Glycine max*). Weed Technol 5:169–174

Chapter 2 - Integrated weed management in 2,4-D and isoxaflutole-resistant soybean in Kansas

Abstract

Integrated weed management practices were evaluated in 2,4-D-, glyphosate-, and glufosinate-resistant and isoxaflutole-, glyphosate-, and glufosinate-resistant soybean (*Glycine max* (L.) Merr.) planted in 38- and 76-cm row spacing for four site-years. Three herbicide treatments were evaluated in each system: pre-emergence herbicide only (PRE), PRE fb early post-emergence (POST), and POST plus overlapping residual (POR). PRE herbicides were pyroxasulfone plus isoxaflutole or sulfentrazone, POST herbicides were PRE plus glufosinate plus ammonium sulfate with or without 2,4-D, and POR herbicides were POST plus *S*-metolachlor. Weed control was evaluated every 2 weeks after PRE application through R7 soybean and weed biomass was collected before POST applications and at R7 soybean. Soybean yield was recorded at harvest. Data were subjected to analysis of variance and means separation ($\alpha = 0.05$). Row spacing had a minimal effect on weed control and mixed results for yield. In Ottawa during 2020, POST and POR treatments resulted in $\geq$ 99% control for all species four WAT, while PRE resulted in $\geq$ 84% control. Similarly, control at Ashland Bottoms was $\geq$ 90% for POST and POR treatments, while PRE resulted in 7% for isoxaflutole-resistant soybeans and 62% for 2,4-D-resistant soybeans. All treatments resulted in $\geq$ 95% control at Scandia during 2021. These data confirm that herbicide programs that include POST applications are superior to PRE-only programs, regardless of row spacing in the two soybean varieties evaluated. Additionally, the inclusion of a layered residual herbicide did not improve weed control over POST treatments with no residual control. However, this research did not evaluate weed seed production, which is crucial for long-term weed management.

Introduction

Palmer amaranth (*Amaranthus palmeri* S. Watson), common waterhemp *(Amaranthus tuberculatus* (Moq.) J. D. Sauer), and large crabgrass (*Digitaria sanguinalis* L.) are commonly found in Kansas soybean fields and have the potential to decrease yields by 79, 63,and 50%, respectively (Aguyoh and Masiunas 2003, Bensch et al. 2003). Many populations of these weeds are herbicide resistant. The best way to control herbicide resistant weeds is to use an integrated approach (Davis et al. 2015, Dent 1995, King and Oliver 1994, Norsworthy et al. 2012, Shyam et al. 2021, Wallace et al. 2019, Ward et al. 2013). Cultural practices, like narrow row spacing are a frequently adopted integrated weed management practice. Previous research has reported that 38-cm row spacing promoted canopy closure 1 to 2 weeks sooner than 76-cm rows (Harder et al. 2007). In fact, during dry years, 76-cm rows may never fully canopy (Bell et al. 2015). McDonald et al. (2021) and Bell et al. (2015) reported reduced Palmer amaranth densities in narrow-row soybeans for at least 1 location and Schultz et al. (2015) similarly reported reduced waterhemp density in narrow rows. This is important for potentially preventing weeds from germinating later in the season (Mickelson and Renner 1997). Yields for narrow and wide rowed soybeans vary and tend to favor narrow rows when planted late in the season and adequate moisture is available (Andrade et al. 2019). De Bruin and Pederson (2008) and Hanna et al. (2008) reported > 5% yields increase with narrow rows compared to wide rows. Bell et al. (2015) reported a 44% increase in 45-cm row soybean yield compared to 90-cm rows. During dry years or when heavy rainfall occurs shortly after planting, similar yields tend to be similar between narrow and wide rows (Hanna et al. 2008, McDonald et al. 2021). The research experiments in the northern region regularly observed a 5- to 35% yield increase with narrow rows compared to producers' fields were differences between narrow and wide rows could not be detected

(Andrade et al. 2019). Similarly, in the central region, experiments observed a 5% loss to a 15% gain in yield for narrow-row soybeans compared to wide-row, but producers reported lack of differences. Therefore, Andrade et al. (2019) speculated producers having a > 5% yield loss for narrow rows, potentially because of reduced precipitation, poor water holding capacity of the soil, or differences in management practices (Andrade et al. 2019).

Additionally, chemical control methods are commonly implemented by soybean producers. Incorporating multiple herbicide modes of action is a management strategy that helps slow the selection of herbicide-resistant weeds (Norsworthy et al. 2012). Two soybean varieties genetically engineered to allow the application of different herbicides are Enlist E3 and LLGT27. Enlist E3 soybeans are resistant to glyphosate, glufosinate, and 2,4-D while LLGT27 are resistant to glyphosate, glufosinate, and isoxaflutole. The ability to apply glufosinate and 2,4-D POST or isoxaflutole PRE will improve weed control (Craigmyle et al. 2013, Hay et al. 2019, Merchant et al. 2013, Smith et al. 2019). Co-applications of 2,4-D and glufosinate resulted in 98% control of common waterhemp, compared to 75 to 78% control for a single active ingredient (Craigmyle et al. 2013). Similarly, Merchant et al. (2013) reported 90 to 97% control of Palmer amaranth with the same co-application compared to 68 to 80% control by 2,4-D alone. Isoxaflutole plus metribuzin fb glyphosate has been shown to control grass and broadleaf weeds > 98% (Smith et al. 2019). However, glyphosate resistance is widespread (Heap 2022), therefore glyphosate alone should not be relied on for weed control.

Glufosinate and 2,4-D control emerged weeds. However, summer annual weeds can emerge after POST herbicide applications. Including residual herbicides in POST applications can help provide season-long weed control (Sarangi and Jhala 2019). Sarangi and Jhala (2019) reported PRE fb POST with residual herbicide programs resulted in 98% control of Palmer amaranth compared to 84% without overlapping residual. Similarly, co-applications of *S*-metolachlor with glufosinate increased common waterhemp control 23% at harvest compared to glufosinate alone (Aulakh and Jhala 2015). However, additional residual herbicide in dicamba-resistant soybeans resulted similar Palmer amaranth control compared to treatments without (McDonald et al. 2021).

Management strategies need to be economical for producers to adopt the practice. Harder et al. (2007) and Nelson and Renner (1999) reported narrow-row soybeans had greater gross profit margins compared to wide-row. Sarangi and Jhala (2019) reported a PRE fb POST with residual herbicide program had the greatest gross profit margin. Due to rapid genetic improvements in soybean herbicide resistance, a current economic analysis needs to be completed. Economic partial budgets have been calculated to compare soybeans resistant to glyphosate or glufosinate (Rosenbaum et al. 2013), dicamba and glyphosate or glufosinate (Striegel et al. 2020), and overlapping residual herbicide programs in non-genetically engineered soybean (Sarangi and Jhala 2019). However, weed control and profitability of soybean resistant to glyphosate, glufosinate, and 2,4-D (Enlist E3) or glyphosate, glufosinate, and isoxaflutole (LLGT27) grown in 38- or 76-cm row spacing with corresponding herbicide programs is unknown. The objectives of this study are to evaluate the effects of (1) row spacing (38 cm or 76 cm), (2) herbicide-resistance trait, (3) and herbicide on weed control, soybean yield, and profitability.

Materials and methods

The experiment was conducted at three Kansas State University Agronomy Experiment Fields at Ottawa, KS (38° 32' 21" N, 95° 14 '36"W) during 2020 (OT20) and 2021 (OT21); at Ashland Bottoms (AB21), 9.5 km south of Manhattan, KS (39° 07' 06" N, 96° 38' 08" W) and at

Scandia, KS (SC21) (39° 50' 01" N, 97° 50' 22" W) during 2021. Soils at the Ottawa, Ashland bottoms, and Scandia locations are Woodson silt loam, Reading silt loam, and Crete slit loam, respectively (Soil Survey Staff et al. 2022). OT20, OT21 and AB21 were under rainfed conditions, while SC21 was irrigated. Field sites were tilled with a vertical cultivator (OT20 and OT21) or a field cultivator (AB21 and SC21) within one day prior to planting. Soybeans were planted with a Kinze 3000 planter in 2020 and a custom-built split-row planter in 2021. The split-row vacuum planter was made with John Deere XP row units with double-disk openers. It is capable of planting 4, 76-cm rows or 7, 38-cm rows. The target seeding rate was 345,000 seeds ha^{-1} in OT20, 387,700 seeds ha^{-1} in AB21, and 395,000 seeds ha^{-1} in both OT21 and SC21 (Table 2.1).

The experimental design was a split-split plot arrangement with 4 replications. The whole plot was soybean trait (LLGT27 and Enlist E3), and the subplot was row spacing (38 and 76 cm). The sub-subplot factor was herbicide program with 5 treatments: nontreated check, PRE, PRE fb POST, PRE fb POST with overlapping residual herbicide, and weed free check (Table 2.2) organized in a random complete block design. Plots were 3 by 9.1 m.

All herbicide applications were made with a CO_2-pressurized backpack sprayer and a 2-m boom with 50.8 cm nozzle spacing. PRE herbicides were applied immediately after planting and POST applications were made when weeds were 7 to 10 cm tall. Herbicides and application parameters are presented in Table 2.2. In OT21 and SC21, POST and POR applications also included clethodim (803 g ha^{-1}) and NIS (0.25% a v/v). See Appendix A.1 and A.2 for more soil information and weather data at the time of application.

Weed control was evaluated between the center 3 and 2 rows for 38-cm and 76-cm rows, respectively using a 0 to 100% scale recorded every 2 weeks after treatment (WAT) until the soybeans reached R7. Weed biomass was sampled from a 0.25 m^2 quadrat randomly placed between the center rows of each plot immediately before POST and POR applications and at R7 soybean. Biomass was dried at 50 C to constant weight. Canopeo measurements were taken 140 cm above the ground 8 weeks after planting. The middle 5 and 2 rows were harvested from the 38- and 76-cm rows, respectively using a plot combine with a platform head. At OT20 and OT21, a model E Gleaner with a Harvest Master 800 grain gauge was used for harvest. At SC21, the same model of combine was used, the Harvest Master was a Single High-Capacity Grain gauge with BDS. In AB21, a Delta model Wintersteiger combine, and Harvest Master 800 grain gauge was used. Yield was adjusted to 13% moisture and 100-seed weights were recorded.

Economic analysis

A partial budget economic analysis was conducted to estimate profit for the different management strategies. Comparisons were made among Enlist E3 and LLGT27, 38-cm and 76-cm rows, and PRE, POST, and POR treatments at OT20, OT21, AB21, and SC21. The rainfed locations were averaged to determine the profitability between soybean trait, row spacing, and herbicide treatment compared to the Enlist E3 78-cm rows. Factors like the tillage cost, taxes, and insurance were not considered in the partial budget analysis because these expenses are fixed. Planting costs were estimated using the K-State Machinery cost calculator (Ibendahl 2020). A 12.2 m planter, requiring a 200 hp tractor using \$0.87/L diesel was used in the calculator. Estimated costs were \$47.88 ha^{-1} for the 38-cm row planter and \$27.06 ha^{-1} for the 76-cm row planter. The 37GB02 and 38EB03 seed prices were obtained from Tarwater Farm and Home Supply in Topeka. Herbicide prices for Zidua SC, Liberty 280 SL, Dual Magnum, Enlist One, AMS, and NIS were based on the approximate cost published in the K-State Research and Extension 2022 chemical weed control guide with prices from 11/1/2021. The price for Alite 27 was estimated based off the 2021 suggested retail price. MKC Coop in Manhattan provided the price of Spartan and herbicides custom applied. The partial budget analysis was conducted on the rain fed fields of OT20, OT21, and AB21 then averaged together. SC21 was also included in the analysis, but it was an irrigated field with similar weed control across all treatments.

Data analysis

Normality and homogeneity assumption were checked with “shapiro.test” (R Core Team 2021) and “leveneTest” (Fox et al. 2021) functions, and transformations did not improve the model (Hebbali 2021). Data were subjected to an analysis of variance ($\alpha = 0.05$), and means were separated with Tukey’s HSD ($\alpha = 0.05$). Fixed factors were herbicide timing, row spacing, and soybean herbicide resistance trait. Replication and replication within row spacing and soybean trait were considered random. The following R packages are listed with their uses: lmerTest, helps to make mixed effect models; car, is a companion to applied regression; emmeans, helps to estimate marginal means; multcompView, helps to summarize multiple paired comparisons; multcomp, allows comparisons of groups of data; and tidyverse, helps to organize data (Fox et al. 2021, Graves and Dorai-Raj 2019, Hothorn et al. 2022, Kuznetsova et al. 2017, Length 2020, R Core Team 2020, Wickham et al. 2019). For weed control results, the nontreated and weed-free checks were removed from the analysis because these treatments had 0% and 100% control, respectively. Additionally, weed biomass was adjusted to a percent of the nontreated check prior to analysis. For the canopy measurements, only the weed free plots were analyzed, as the Canopeo app was not able to distinguish between weeds and soybean.

Results and discussions

Growing conditions varied for OT20, OT21, AB21, and SC21 (Figure 2.1-2.8; Kansas State University 2022, National Climatic Data Center 2021). The 30-year average for rainfall in

Ottawa, KS from May 1st to harvest is 629 mm. However, during 2020 only 355 mm was received during that time frame. OT21 did receive more rain (767 mm), but 312 mm of that occurred before the soybeans were planted. OT20 was warmer than normal in June and OT21 was warmer than normal from August through October. AB21 received 142 mm less precipitation from May 1st to harvest and had a warmer fall than the 30-year average. Scandia was irrigated, receiving a similar amount of water as the 30- year average and had a cooler June with a warmer fall.

Soybean stand counts were collected after emergence, indicating a significant main effect of row spacing for OT20, OT21, and SC21 regardless herbicide treatments and soybean traits (Table 2.3). Table 2.4 highlights the differences between the 38- and 76-cm row spacing. The population reductions in OT20 and OT21 for the 38-cm rows likely occurred due to crusting. The population of soybean plants in AB21 were similar for all treatments. SC21 had the ideal planting conditions and observed better stands in the 38-cm rows than the 76-cm rows. Previous research indicates that weed control can decrease with low populations (Liebert and Ryan 2017) as a result of reduced interspecific competition occurs between crops and weeds (Basinger et al. 2019).

Weed control

The weeds present at POST and POR herbicide application for each location are listed in Table 2.5. Then, Table 2.6 shows the total weed biomass before the POST and POR herbicide treatments were applied. Visual ratings of weed control were analyzed separately for each location because weed species were different at each location. Four and ten weeks after treatment of the POST (WAT) will be described here.

Common waterhemp and Venice mallow control four WAT in OT20 was similar for both soybean traits and showed the importance of a PRE fb POST program, as herbicide treatment was significant (Table 2.7). POST and POR treatments had similar control (98 to 100%) of both weeds and greater control than the PRE treatment (83 to 86%; Table 2.8). Craigmyle et al. (2013) reported a 23% increase in common waterhemp control when 0.45 kg ha^{-1} 2,4-D was added to 0.56 kg ha^{-1} glufosinate. Higher rates of glufosinate (0.65 kg ha^{-1}) were utilized in the current experiment, resulting in weed control $\geq$ 98% for POST herbicide treatments when pooled across soybean trait.

In OT21, common waterhemp control was similar for all treatments four WAT (Table 2.9). There was a 3-way interaction between soybean trait, row spacing, and herbicide treatment for Venice mallow control (Table 2.9). Venice mallow control was ≥ 88% for all treatments except Enlist E3 soybeans grown in 38-cm rows with the PRE herbicide treatment, which had 35% control (Table 2.10).

Four WAT in AB21, Palmer amaranth control was affected by the herbicide treatment (Table 2.11) with the POST and POR treatments having similar control (≥ 99%), and greater control than the PRE treatment (33%; Table 2.12). Conversely, Sarangi and Jhala (2019) reported improved season long Palmer amaranth control with a POR treatment compared to the POST with > 99% and > 92% control, respectively. There was a significant interaction between herbicide timing and soybean trait for ivyleaf morningglory control (Table 2.11). Once again, control by POST and POR treatments was similar (≥83%) for both the LLGT27 and Enlist E3 soybean varieties (Table 2.13). However, control of ivyleaf morningglory by the PRE herbicide treatment was greater in the Enlist E3 trait (71%) compared to the LLGT27 (1%). The Enlist E3 PRE herbicide treatment contained pyroxasulfone plus sulfentrazone, whereas the LLGT27 treatment contained pyroxasulfone plus isoxaflutole. Sulfentrazone is expected to provide greater control of morningglory species than isoxaflutole. For example, Krausz et al. (1998) reported 92% ivyleaf morningglory control eight weeks after planting by sulfentrazone applied alone, whereas Schultz et al. (2015) reported 52 to 76% control at R3 soybean when isoxaflutole was applied in combination with *S*-metolachlor and metribuzin fb EPOST.

At SC21, the analysis of variance indicated no differences in control for yellow foxtail (Table 2.14). Four WAT, all treatments averaged 95% control (data not shown). One reason for the high weed control could be because from May 1st to July 1st, SC21 received 56.6% less precipitation than the 30-year average (Figure 2.7). Cordeau at al. (2018) reported annual weed emergence was reduced 20% when water was limited. Another reason could be because of greater interspecific competition due to greater stand counts than the other locations (Liebert and Ryan 2017).

At OT20 10 WAT, common waterhemp control was influenced by herbicide treatment (Table 2.7) with the POST and POR treatments having similar control, and greater control than the PRE alone ≥ 99% and ≥49%, respectively (Table 2.8). Venice mallow control was improved with the use of herbicide, but when nontreated checks were removed from the analysis, no differences between herbicide treatments were detected (data not shown).

No differences in common waterhemp control were detected at OT21 10 WAT (Table 2.9). The analysis of variance for Venice mallow control detected a significant interaction between herbicide and trait (Table 2.9); however, Tukey's pairwise comparisons test found no differences, with all treatments providing ≥ 88% (Table 2.13). Similarly, SC21 yellow foxtail control had a significant interaction between herbicide treatment, trait, and row spacing (Table 2.14); however, control was ≥ 99% for all treatments (Table A.3).

At AB21 10 WAT, Palmer amaranth control was significant for herbicide treatment (Table 2.11). The POST and POR treatments had similar and greater control than the PRE treatment with ≥ 94% and 49% control, respectively (Table 2.12). Control of Palmer amaranth was similar between soybean traits. However, Merchant et al. (2013) reported that Palmer amaranth control increased 10 to 29% when 2,4-D and glufosinate were co-applied, compared to being applied separate. For ivyleaf morningglory, there was a significant interaction between the herbicide treatment and row spacing (Table 2.11). Control with POST and POR herbicide treatments was similar for Enlist E3 and LLGT27 soybeans (Table 2.10). However, LLGT27 soybeans with PRE herbicide had reduced morningglory control in both the 76- and 38-cm rows with 44% and 20% control, respectively (Table 2.10).

Weed biomass at R7 Soybean

At OT20, OT21, and SC21 there were negligible differences in weed biomass when the soybeans were at R7. AB21 was the only location with differences among soybean trait, row spacing, and herbicide timing (Table 2.15). The 38-cm row LLGT27 soybeans with PRE herbicide had at least twice as much weed biomass as any other treatment combination (Table 2.16). This is likely due to the abundance of ivyleaf morningglory as well as lower than expected Palmer amaranth control associated with low amounts of rainfall in-season.

Canopy cover

The Canopeo app allows the estimation of canopy cover (Patrignani and Ochsner 2015), but is not able to distinguish between weeds and the crop. When only the weed free plots were analyzed, OT20, AB21, and SC21 had a significant main effect of row spacing (Table 2.17). However Tukey’s pairwise comparisons did not detect treatment differences at OT20, where canopy cover ranged from 86 to 92%. In OT21, canopy cover was only 41 to 52% in 2021 (Table

2.18), likely due to limited rainfall after planting until mid-July (Figure 2.5) and low populations (Table 2.4). For AB21 and SC 21, canopy coverage ranged from 79 to 90% 8 weeks after planting depending on row spacing (Table 2.18). The 38-cm rows were 3% more canopied in AB21 and 11% more canopied in SC21 compared to the 76-cm rows. Populations between row spacings were similar at AB21 and greater in the 38-cm rows at SC21 compared to the 76-cm rows (Table 2.4).

100-seed weight

There was a significant main effect of row spacing in OT20 and OT21 and trait in OT20 on 100-seed weight (Table 2.19). No differences were detected in AB21 or SC21. Seeds were 0.3 to 0.4 g heavier when grown in 76-cm rows in OT20 and OT21 compared to 38-cm rows (Table 2.20). De Bruin and Pedersen (2008) also reported mixed results for 100-seed weight of soybeans grown in 38- or 76-cm rows. They reported no difference at two locations; however, at the third location seeds from soybeans grown in 76-cm rows were 0.5 g heavier than 38-cm rows. Additionally, in the current study at OT20, the Enlist E3 trait 100-seed weights were 0.9 g greater than the LLGT27 (Table 2.20). Anda et al. (2020) also reported differences in seed weight between varieties.

Yield

There was a significant interaction between site year, trait, and row spacing (Table 2.21); therefore, yield data will be analyzed separately for each site year (Table 2.22). In OT20 no differences in yield were observed, with all treatments averaging 2688 kg ha^{-1}. However, in OT21, the main effect of herbicide treatment was significant and there was a 2-way interaction between soybean trait and row spacing (Table 2.22). Table 2.23 shows the importance of using herbicide (PRE, POST or POR) to maintain soybean yield.

In OT21 Enlist E3 soybean yield increased 25% when grown in 76-cm rows compared to 38-cm rows, whereas the LLGT27 soybeans yielded similarly in soybean row spacings (Table 2.24). Heavy rains after planting and poorer germination in the narrow-row soybeans could have contributed to the 76-cm Enlist E3 soybeans yielding more. Hanna et al. (2008) also reported that one of their locations received heavy rains after planting, reducing plant population. However, in that instance, wide rows yielded similarly to the narrow rows.

Row spacing by trait was also significant for AB21 (Table 2.22). Yields from Enlist E3 soybeans grown in 38- and 76-cm were similar to each other and greater than yields from LLGT27 soybeans. The 38-cm Enlist E3 soybeans yielded 34% and 135% more than the 76- and 38-cm LLGT27 soybeans, respectively (Table 2.24). The 76-cm LLGT27 soybeans yielded 76% more than the 38-cm LLGT27 soybeans. This was likely to due to poor morningglory control for LLGT27 trait. Howe and Oliver (1987) reported 62 and 81% soybean yield reduction by pitted morningglory at a density of 40 plants m^{-2} for 20-cm and 100-cm rows, respectively. In addition, a dectes stem borer (*Dectes texanus* LeConte) infestation started in September on 38-cm LLGT27 side of the field and worked its way across the field.

In SC21, an interaction between soybean trait and row spacing was detected (Table 2.22). The order of the greatest to least yield was: 38-cm Enlist E3, 38-cm LLGT27, 76-cm LLGT27, and 76-cm Enlist E3 soybeans. The 38-cm Enlist E3 soybeans yielded 11% more than the 76-cm Enlist E3 soybeans (Table 2.24). Andrade et al. (2019) reported similar results, where narrow row soybeans tend to have a yield advantage when planted late.

Economic analysis

Partial budgets analyses are useful to determine the profitability between two practices (NDSU, 2021). Table 2.25 presents the results from the partial budget analysis for OT20, OT21, and AB21 (the rainfed locations) and SC21 (irrigated location) using nontreated Enlist E3 trait grown in 76-cm rows as a baseline. At the rainfed locations, the greatest returns were observed when Enlist E3 soybeans were grown in 76-cm rows and a PRE herbicide treatment was applied (\$457 ha^{-1}; Table 2.25). However, weed control was reduced in the PRE herbicide treatment compared to the POST and POR treatments for many of the weed species evaluated at these rainfed locations. Reduced weed control one year would translate into increased weed seed in the seed bank and increased difficultly to control weeds the next year. The reason that the PRE treatments were more profitable for the Enlist E3 soybeans is due to the added input cost of more herbicide applications when nontreated weed populations did not reduce weeds. Sarangi and Jhala (2019) also reported the greatest profit with a PRE treatment, but just like the current experiment, the PRE treatment had reduced weed control.

Interestingly, added income was reduced for POR treatments compared to POST in the Enlist E3 76-cm rows for OT20 and OT21 (Table 2.25). This was because of slight differences in yield; however, these differences were negligible for OT20 as the analysis of variance for yield shows in Table 2.22 and OT21 as Table 2.23 shows similar yields for POST and POR treatments.

AB21 had greater weed biomass in the plots that were prior to POST and POR application compared to the other locations (19.6 g m^{-2}; Table 2.6). This meant the POST and POR treatments were more profitable than the PRE. The Enlist E3 soybean system grown in 76-cm rows with POST herbicide treatments profited \$845 ha^{-1} compared to the POR herbicide treatment that profited \$906 ha^{-1} (Table 2.25). The additional residual herbicide in the wide rows was associated with greater profit. When looking at the Enlist E3 soybean system grown in the 38-cm rows, POST treatments had \$924 ha^{-1} profit compared to \$901 ha^{-1} for the POR treatment.

This would suggest that with narrow row spacing, overlapping residual herbicide was not critical for this one location and one soybean trait. When herbicide treatments and rainfed locations were averaged together, the most profitable to least profitable systems in our study were Enlist E3 in 76-cm rows, Enlist E3 in 38-cm rows, LLGT27 in 76-cm rows, and LLGT27 in 38-cm rows.

The irrigated location, SC21, reported the greatest profit for Enlist E3 soybeans grown in the 38-cm rows and nontreated. Similarly, within the LLGT27 trait, the herbicide treatment with the greatest was nontreated, regardless of row spacing. This is due to the very low weed pressure, as the nontreated plots averaged 2 g m^{-2} of weed biomass at POST and POR herbicide applications (Table 2.6). The most profitable to least profitable systems at the irrigated location in our study were the Enlist E3 in 38-cm rows, LLGT27 in 38-cm rows, LLGT27 in 76-cm rows, and Enlist E3 in 76-cm rows.

Management considerations

From a weed control standpoint, either POST or POR herbicide treatments are needed, regardless of soybean trait or row spacing. POST treatments tended to be more profitable compared to POR treatments, as both controlled weeds similarly and POR treatments were more costly. However, considering the long-term effects of escaped weeds is critical. Norsworthy et al. (2014) reported a single Palmer amaranth plant left uncontrolled can result in plants spreading across an entire field in 2 years. Both the LLGT27 and Enlist E3 soybeans have their advantages, such as the ability to apply multiple effective modes of action during a growing season. Knowing the weed species present, and herbicide resistance present in the weed population will help decide which soybean trait to use. For example, in Ashland Bottoms during 2021, the primary weeds were morningglory and resistant Palmer amaranth. At this location, the Enlist E3 trait soybean had an at planting application of pyroxasulfone plus sulfentrazone, which prevented morningglory emergence (Table 2.13), compared to the LLGT27 PRE treatment and the POST and POR treatments controlled Palmer amaranth (Table 2.12). Soybean grown in narrow rows have been documented to canopy sooner, increase with weed control, and have competitive yields, compared to wide rows (Andrade et al. 2019, Bell et al. 2015, Dalley et al. 2004). In the current study at the non-irrigated locations, the 76-cm rows were more profitable compared to the 38-cm rows (Table 2.25). However, at the irrigated location, 38-cm rows were more profitable than the 76-cm rows.

Kansas producers may ask what the best weed management strategies in soybeans are. This will vary on a field-to-field basis as precipitation, soil properties, type-, resistance-, and quantity- of weeds changes across the landscape. My research indicates that each herbicide treatment, row spacing, and soybean trait has their place. But in general, using a 2- pass system provided the greatest weed control, regardless of the soybean trait and row spacing. If a dryland producer is considering purchasing a narrow row planter, they should remember that during dry years, a yield advantage is unlikely. In irrigated environments, or years with timely rains, narrow row yields are likely to yield greater than wide rows. Based on these results, Enlist E3 soybeans with a PRE herbicide treatment of Zidua SC plus Spartan provided similar or greater control compared to Zidua SC plus Alite 27 in the LLGT27 system except on Venice mallow. However, Venice mallow is not a common weed and can easily be control with POST and POR herbicide treatments.

References

Aguyoh JN, Masiunas JB (2003) Interference of large crabgrass (*Digitaria sanguinalis*) with snap beans. Weed Sci 51:171–176

Anda A, Soós G, Menyhárt L, Kucserka T, Simon B (2020) Yield features of two soybean varieties under different water supplies and field conditions. Field Crop Res 245:107673

Andrade JF, Rattalino Edreira JI, Mourtzinis S, Conley SP, Ciampitti IA, Dunphy JE, Gaska JM, Glewen K, Holshouser DL, Kandel HJ, Kyveryga P, Lee CD, Licht MA, Lindsey LE, McClure MA, Naeve S, Nafziger ED, Orlowski JM, Ross J, Staton MJ, Thompson L, Specht JE, Grassini P (2019) Assessing the influence of row spacing on soybean yield using experimental and producer survey data. Field Crops Res 230:98–106

Aulakh JS, Jhala AJ (2015) Comparison of glufosinate-based herbicide programs for broad-spectrum weed control in glufosinate-resistant soybean. Weed Technol 29:419–430

Basinger NT, Jennings KM, Monks DW, Jordan DL, Everman WJ, Hestir EL, Bertucci MB, Brownie C (2019) Large crabgrass (*Digitaria sanguinalis*) and Palmer amaranth (*Amaranthus palmeri*) intraspecific and interspecific interference in soybean. Weed Sci 67:649–656

Bell HD, Norsworthy JK, Scott RC, Popp M (2015) Effect of row spacing, seeding rate, and herbicide program in glufosinate-resistant soybean on Palmer amaranth management. Weed Technol 29:390–404

Bensch CN, Horak MJ, Peterson D (2003) Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci 51:37–43

Cordeau S, Wayman S, Reibel C, Strbik F, Chauvel B, Guillemin J-P (2018) Effects of drought on weed emergence and growth vary with the seed burial depth and presence of a cover crop. Weed Biol Manag 18:12–25

Craigmyle BD, Ellis JM, Bradley KW (2013) Influence of weed height and glufosinate plus 2,4-D combinations on weed control in soybean with resistance to 2,4-D. Weed Technol 27:271–280

Dalley CD, Kells JJ, Renner KA (2004) Effect of glyphosate application timing and row spacing on weed growth in corn (*Zea mays*) and soybean (*Glycine max*). Weed Technol 18:177–182

Davis AS, Schutte BJ, Hager AG, Young BG (2015) Palmer amaranth (*Amaranthus palmeri*) damage niche in Illinois soybean is seed limited. Weed Sci 63:658–668

De Bruin JL, Pedersen P (2008) Effect of row spacing and seeding rate on soybean yield. Agron J 100:704–710

Dent D (1995) Integrated pest management. SSBM. 378 p

Fox J, Weisberg S, Price B, Adler D, Bates D, Baud-Bovy G, Bolker B, Ellison S, Firth D, Friendly M, Gorjanc G, Graves S, Heiberger R, Krivitsky P, Laboissiere R, Maechler M, Monette G, Murdoch D, Nilsson H, Ogle D, Ripley B, Venables W, Walker S, Winsemius D, Zeileis A, R-Core (2021) car: Companion to applied regression

Graves S, Dorai-Raj H-PP and LS with help from S (2019) multcompView: Visualizations of paired comparisons

Hanna SO, Conley SP, Shaner GE, Santini JB (2008) Fungicide application timing and row spacing effect on soybean canopy penetration and grain yield. Agron J 100:1488–1492

Harder DB, Sprague CL, Renner KA (2007) Effect of soybean row width and population on weeds, crop yield, and economic return. Weed Technol 21:744–752

Hay MM, Dille JA, Peterson DE (2019) Integrated pigweed (*Amaranthus spp*.) management in glufosinate-resistant soybean with a cover crop, narrow row widths, row-crop cultivation, and herbicide program. Weed Technol 33:710–719

Heap I (2022) The international herbicide-resistant weed database. http://www.weedscience.org/Home.aspx. Accessed January 18, 2022

Hebbali A (2021) levene.test function - RDocumentation. https://www.rdocumentation.org/packages/lawstat/versions/3.4/topics/levene.test. Accessed March 30, 2022

Hothorn T, Bretz F, Westfall P, Heiberger RM, Schuetzenmeister A, Scheibe S (2022) multcomp: Simultaneous inference in general parametric models

Howe OW, Oliver LR (1987) Influence of soybean (*Glycine max*) row spacing on pitted morningglory (*Ipomoea lacunosa*) interference. Weed Sci 35:185-195

Ibendahl G, Griffin T (2020) Kansas state machinery cost tool. Kansas State University Agricultural Economics

Kansas State University (2022) Kansas Mesonet. https://mesonet.k-state.edu/weather/historical/. Accessed April 5, 2022

King CA, Oliver LR (1994) A model for predicting large crabgrass (*Digitaria sanguinalis*) emergence as influenced by temperature and water potential. Weed Sci 42:561–567

Krausz RF, Kapusta G, Matthews JL (1998) Sulfentrazone for weed control in soybean (*Glycine max*). Weed Technol 12:684–689

Kuznetsova A, Brockhoff PB, Christensen RHB (2017) lmerTest Package: Tests in linear mixed effects models. J Stat Softw 82:1–26

Length R (2020) emmeans: Estimated marginal means, aka least-squares means. R package version 153

Liebert JA, Ryan MR (2017) High planting rates improves weed suppression, yield, and profitability in organically-managed, no-till -planted soybean. Weed Technol 31: 536-549

McDonald ST, Striegel A, Chahal PS, Jha P, Rees JM, Proctor CA, Jhala AJ (2021) Effect of row spacing and herbicide programs for control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in dicamba/glyphosate-resistant soybean. Weed Technol:1–12

Merchant RM, Sosnoskie LM, Culpepper AS, Steckel LE, York AC, Braxton LB, Ford JC (2013) Weed response to 2,4-D, 2,4-DB, and dicamba applied alone or with glufosinate. J Cotton Sci 17:212-218

Mickelson JA, Renner KA (1997) Weed control using reduced rates of postemergence herbicides in narrow and wide row soybean. J Prod Agric 10:431–437

National Climatic Data Center (2021) NOAA NCEI U.S. Climate normals quick access. https://www.ncei.noaa.gov/access/us-climate-normals/#dataset=normals-monthly&timeframe=30&location=KS&station=USW00053974. Accessed April 5, 2022

[NDSU] North Dakota State University (2021) Agriculture law and management: Partial budget analysis. College of Agriculture, Food Systems, and Natural Resources, NDSU Dept 2200.

https://www.ag.ndsu.edu/aglawandmanagement/agmgmt/coursematerials/partialbudgetanalysis#:~:text=A%20partial%20budget%20analysis%20is,will%20increase%20or%20dec rease%20profit.&text=It%20determines%20only%20the%20CHANGE,from%20changing%20a%20production%20practice. Accessed: March 2, 2022

Nelson KA, Renner KA (1999) Weed management in wide- and narrow-row glyphosate resistant soybean. J Prod Agric 12:460–465

Norsworthy JK, Griffith G, Griffin T, Bagavathiannan M, Gbur EE (2014) In-field movement of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) and its impact on cotton lint yield: evidence supporting a zero-threshold strategy. Weed Sci 62:237–249

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60:31–62

Patrignani A, Ochsner TE (2015) Canopeo: a powerful new tool for measuring fractional green canopy cover. Agron J 107:2312–2320

R Core Team (2020) R: The R Project for Statistical Computing. https://www.r-project.org/. Accessed February 15, 2022

R Core Team (2021) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing

Rosenbaum K, Massey R, Bradley K (2013) Comparison of weed control, yield, and net income in conventional, glyphosate-resistant, and glufosinate-resistant soybean. Crop Manag 12:1–9

Sarangi D, Jhala AJ (2019) Palmer amaranth (*Amaranthus palmeri*) and velvetleaf (*Abutilon theophrasti*) control in no-tillage conventional (non–genetically engineered) soybean using overlapping residual herbicide programs. Weed Technol 33:95–105

Schultz JL, Weber M, Allen J, Bradley KW (2015) Evaluation of weed management programs and response of FG72 soybean to HPPD-inhibiting herbicides. Weed Technol 29:653–664

Shyam C, Borgato EA, Peterson DE, Dille JA, Jugulam M (2021) Predominance of metabolic resistance in a six-way-resistant Palmer amaranth (*Amaranthus palmeri*) population. Front Plant Sci 11: 614618

Smith A, Soltani N, Kaastra AJ, Hooker DC, Robinson DE, Sikkema PH (2019) Annual weed management in isoxaflutole-resistant soybean using a two-pass weed control strategy. Weed Technol 33:411–425

Soil Survey Staff, Natural Resources Conservation, United States Department of Agriculture (2022) Web soil survey. https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx. Accessed February 15, 2022

Striegel A, Eskridge KM, Lawrence NC, Knezevic SZ, Kruger GR, Proctor CA, Hein GL, Jhala AJ (2020) Economics of herbicide programs for weed control in conventional, glufosinate, and dicamba/glyphosate-resistant soybean across Nebraska. Agron J 112:5158–5179

Wallace JM, Curran WS, Mortensen DA (2019) Cover crop effects on horseweed (*Erigeron canadensis*) density and size inequality at the time of herbicide exposure. Weed Sci 67:327–338

Ward SM, Webster TM, Steckel LE (2013) Palmer amaranth *(Amaranthus palmeri*): a review. Weed Technol 27:12–27

Wickham H, Averick M, Bryan J, Chang W, McGowan L, François R, Grolemund G, Hayes A, Henry L, Hester J, Kuhn M, Pedersen T, Miller E, Bache S, Müller K, Ooms J, Robinson D, Seidel D, Spinu V, Takahashi K, Vaughan D, Wilke C, Woo K, Yutani H (2019) Welcome to the Tidyverse. JOSS 4:1686

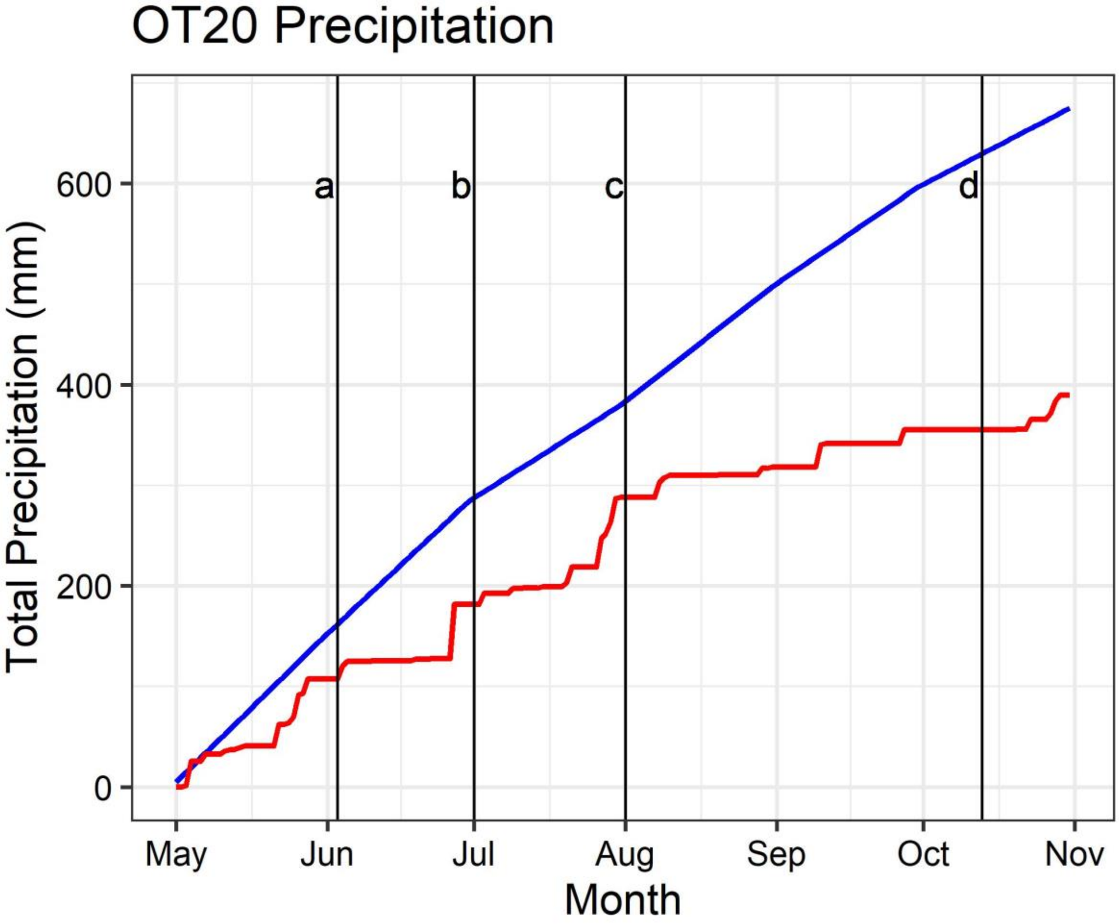

Figure 2.1 Total precipitation in 2020 (red line) and 30-year average total precipitation (blue line) in Ottawa, KS (OT20).

[a] Plant: 6/3/2020
[b] 7 to 10 cm weeds: 7/1/2020
[c] canopeo:8/1/2020
[d] harvest:10/13/2020

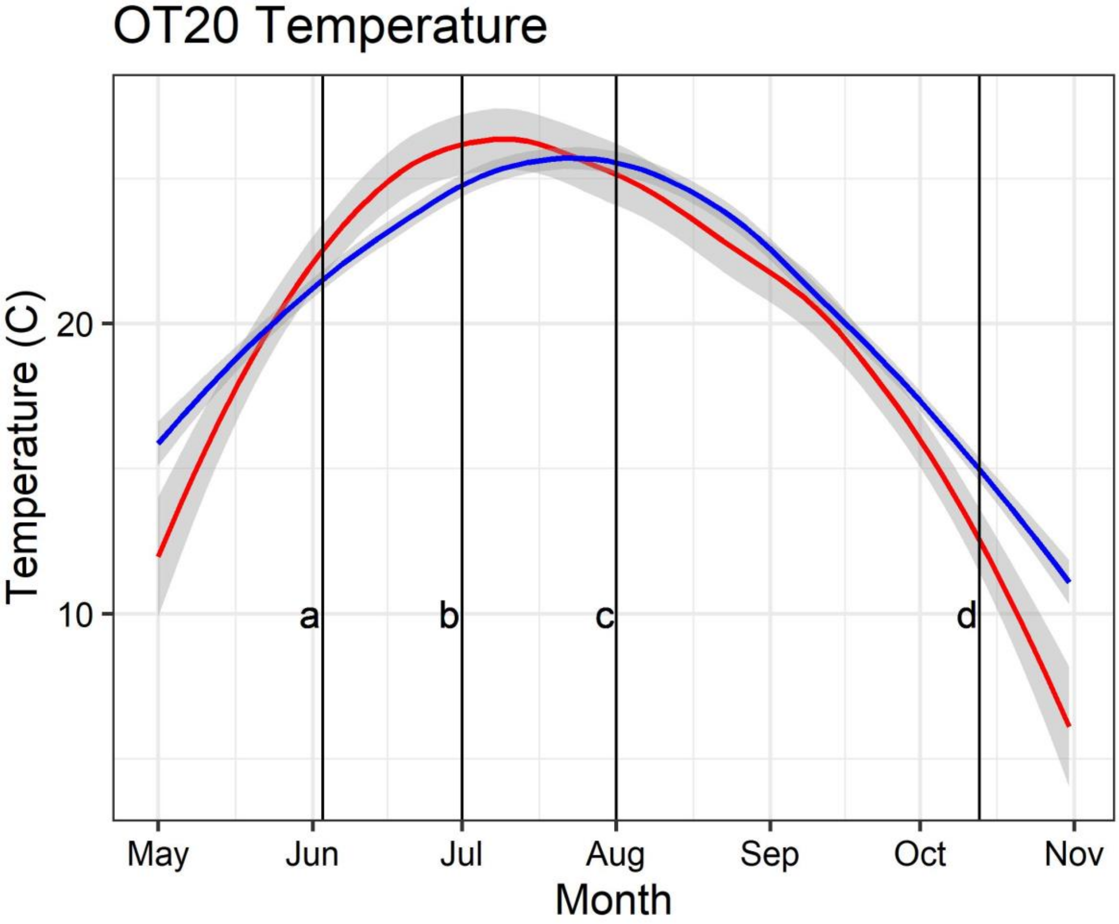

Figure 2.2 Average daily temperature in 2020 (red line) and 30-year average temperature (blue line) in Ottawa, KS (OT20).

[a] Plant: 6/3/2020
[b] 7 to 10 cm weeds: 7/1/2020
[c] canopeo:8/1/2020
[d] harvest:10/13/2020

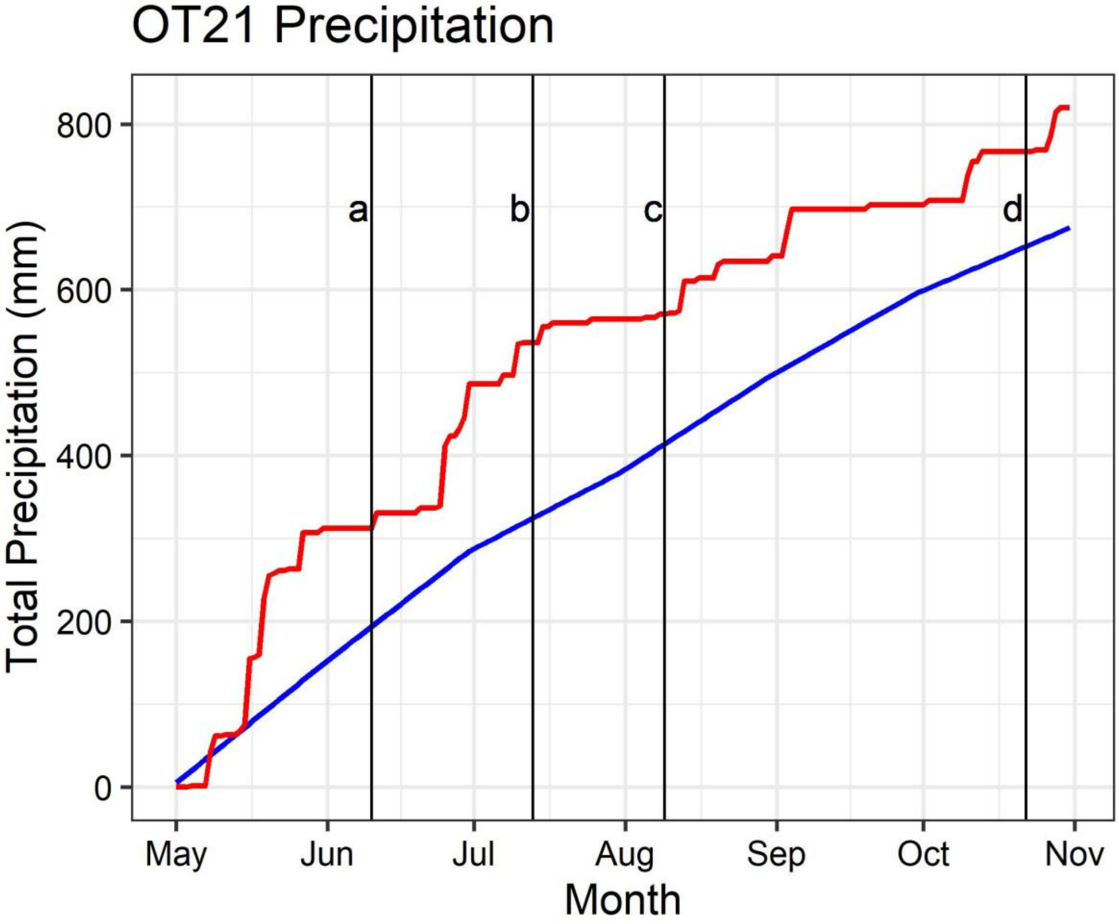

Figure 2.3 Total precipitation in 2021 (red line) and 30-year average total precipitation (blue line) in Ottawa, KS (OT21).

[a] Plant: 6/10/2021
[b] 7 to 10 cm weeds: 7/13/2021
[c] canopeo: 8/9/2021
[d] harvest:10/22/2021

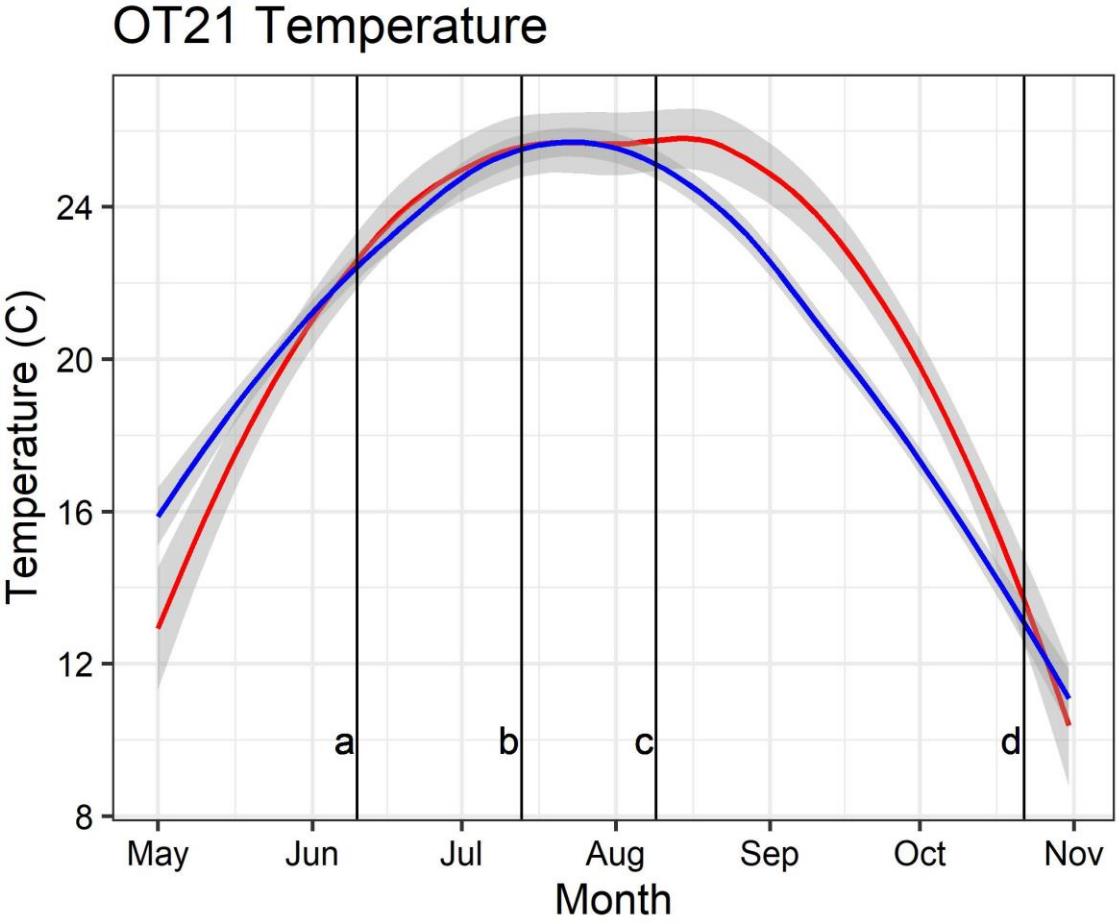

Figure 2.4 Average daily temperature in 2021 (red line) and 30-year average temperature (blue line) in Ottawa, KS (OT21).

[a] Plant: 6/10/2021
[b] 7 to 10 cm weeds: 7/13/2021
[c] canopeo: 8/9/2021
[d] harvest:10/22/2021

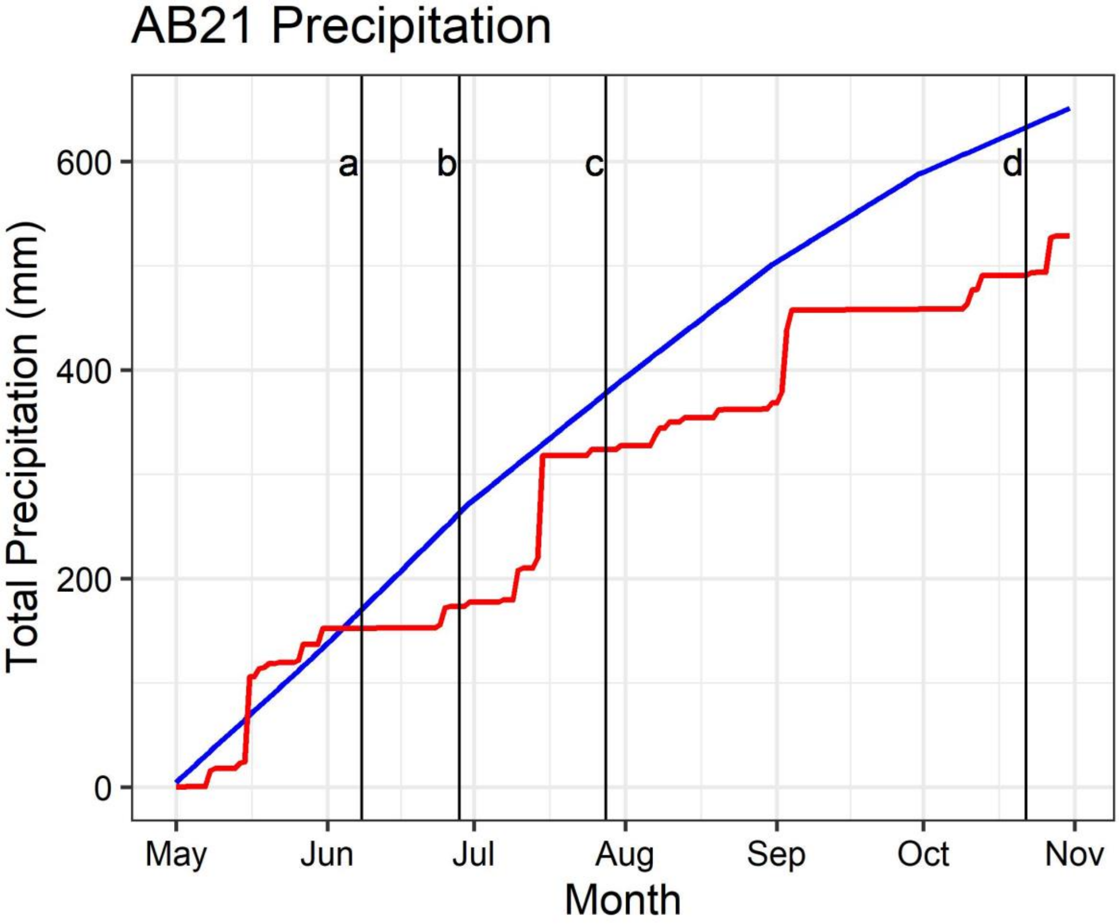

Figure 2.5 Total precipitation in 2021 (red line) and 30-year average total precipitation (blue line) in Ashland Bottoms (AB21).

[a] Plant: 6/8/2021
[b] 7 to 10 cm weeds: 6/28/2021
[c] canopeo:7/28/2021
[d] harvest:10/22/2021

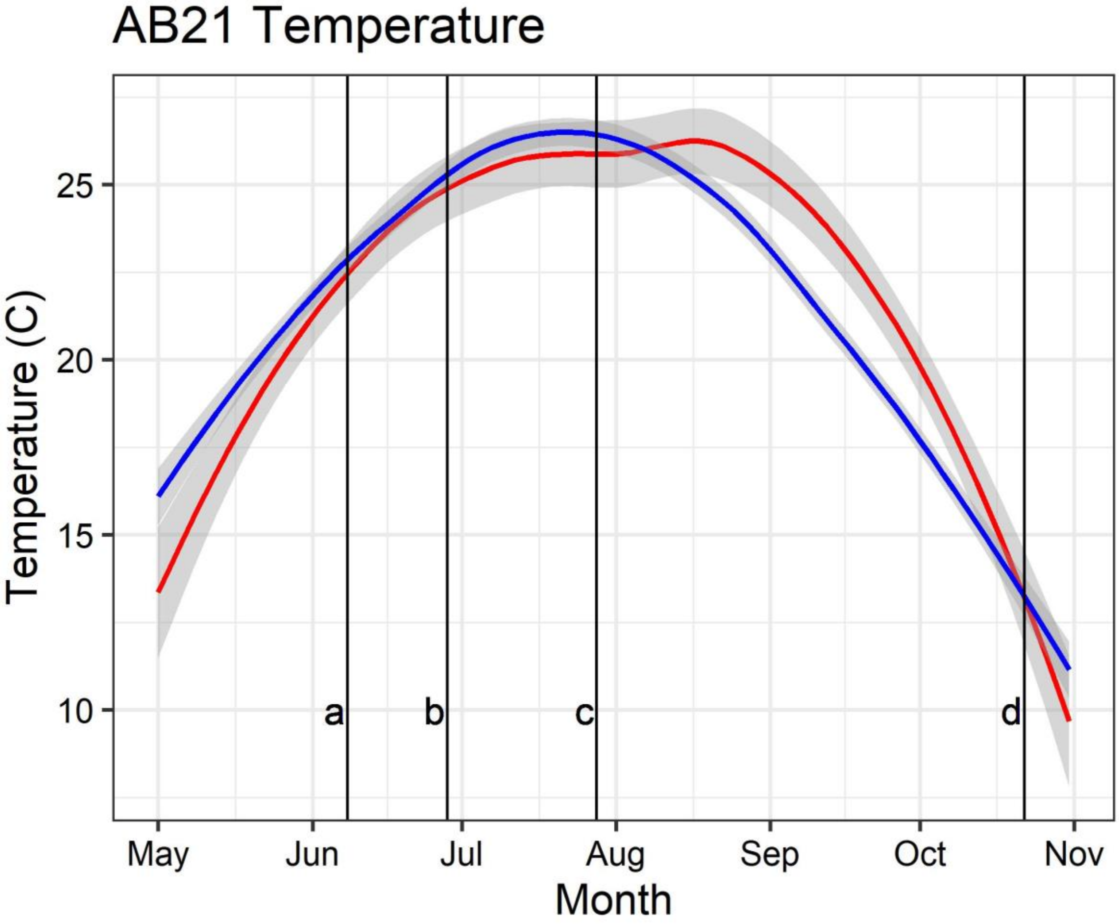

Figure 2.6 Average daily temperature in 2021 (red line) and 30-year average temperature (blue line) in Ashland Bottoms (AB21).

[a] Plant: 6/8/2021
[b] 7 to 10 cm weeds: 6/28/2021
[c] canopeo:7/28/2021
[d] harvest:10/22/2021

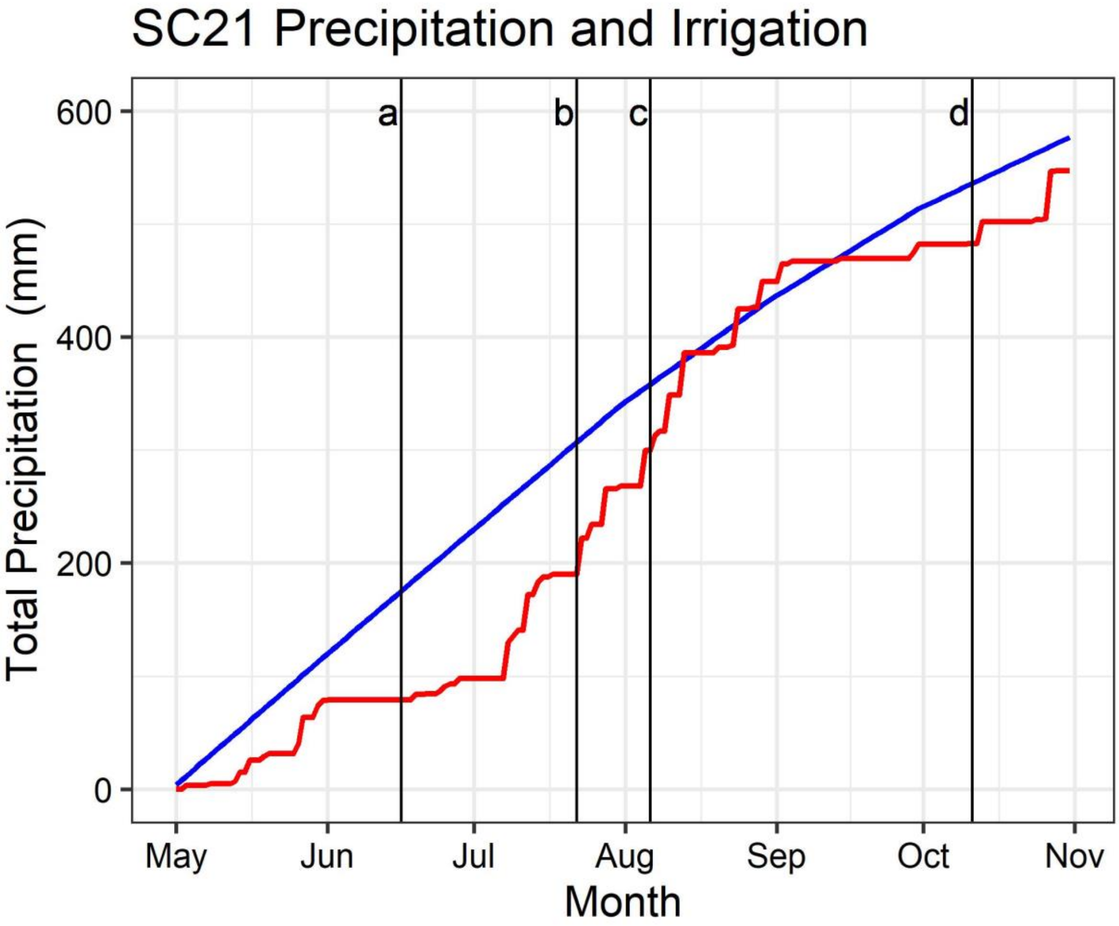

Figure 2.7 Total precipitation (red line) and 30-year average total precipitation (blue line) in Scandia, KS in 2021 (SC21).

[a] Plant: 6/16/2021
[b] 7 to 10 cm weeds: 7/22/2021
[c] canopeo:8/6/2021
[d] harvest:10/11/2021

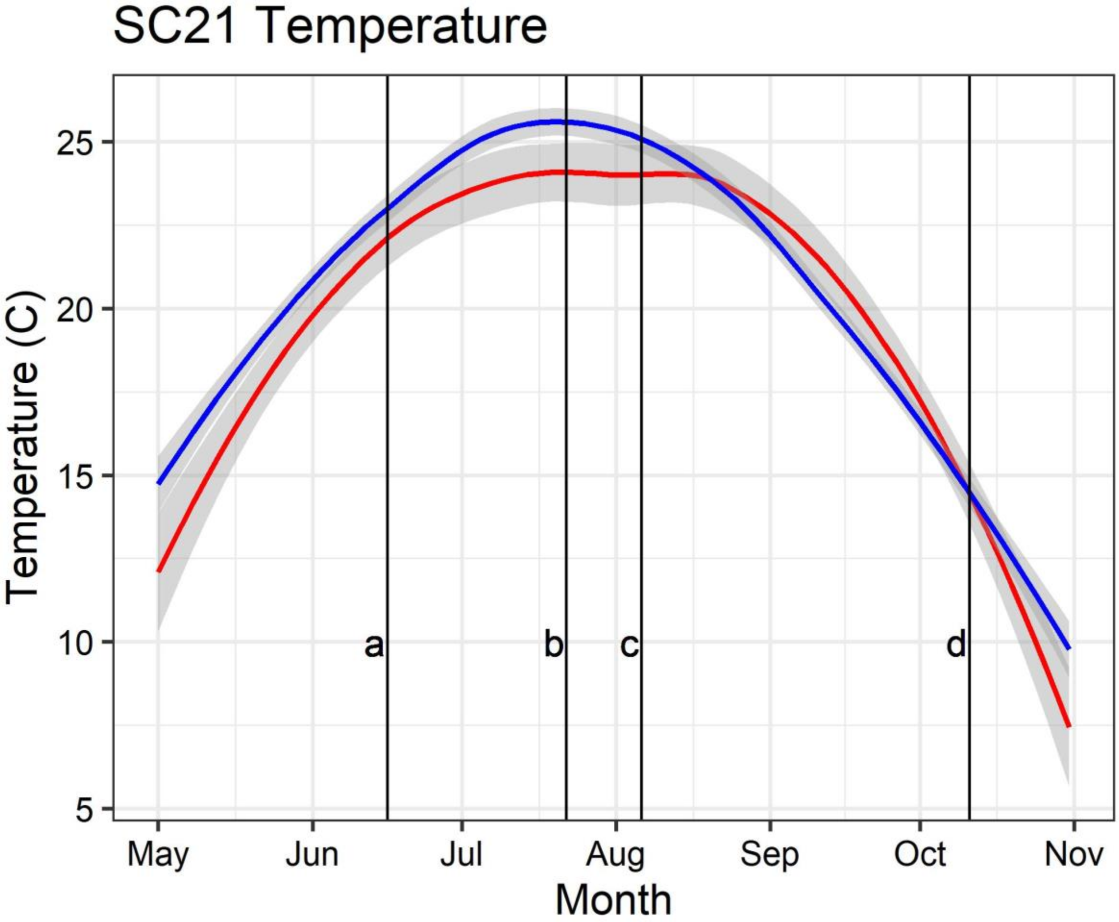

Figure 2.8 Average daily temperature in 2021 (red line) and 30-year average temperature (blue line) in Scandia, KS (SC21).

[a] Plant: 6/16/2021
[b] 7 to 10 cm weeds: 7/22/2021
[c] canopeo:8/6/2021
[d] harvest:10/11/2021

Table 2.1 Site year information: rotation, irrigation, and planting information.

Location	Previous year crop	Irrigation	Targeted seeding rate	LLGT27[a] variety	Enlist E3[a] variety	Seed treatment
			seed ha^{-1}			
OT20[a]	soybean	none	345,000	38GB20	38EB03	None
OT21	soybean	none	395,000	37GB02	38EB03	Servo DPI and Saltro
AB21	corn	none	387,700	37GB02	38EB03	Servo DPI and Saltro
SC21	corn	yes	395,000	37GB02	38EB03	Servo DPI and Saltro

[a] All soybean varieties used were from Stine Seed Company, Adel, Iowa.

[b] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021

Table 2.2 Herbicide treatment timings, active ingredients, rate, trade name and manufacture.

Herbicide Treatments	Timing [ab]	Active ingredients	Rate	Trade name	Manufacture
LLGT27			(g ai/ae ha^{-1})		
Nontreated control		-	-	-	-
PRE	at planting	pyroxasulfone	146	Zidua ® SC	BASF[c]
		isoxaflutole	105	Alite ™ 27	BASF
POST	at planting	pyroxasulfone	146	Zidua ® SC	BASF
		isoxaflutole	105	Alite ™ 27	BASF
	7 to 10 cm weeds	glufosinate	655	Liberty® 280 SL	BASF
POR	at planting	pyroxasulfone	146	Zidua ® SC	BASF
		isoxaflutole	105	Alite ™ 27	BASF
	7 to 10 cm weeds	glufosinate	655	Liberty® 280 SL	BASF
		S-metolachlor	1,419	Dual Magnum	Syngenta[d]
Weed-free	at planting	pyroxasulfone	146	Zidua ® SC	BASF
		isoxaflutole	105	Alite ™ 27	BASF
	7 to 10 cm weeds	glufosinate	655	Liberty® 280 SL	BASF
		S-metolachlor	1,419	Dual Magnum®	Syngenta
		Hand weeded			
Enlist E3					
Nontreated control			-	-	-
PRE	at planting	Pyroxasulfone	146	Zidua ® SC	BASF
		sulfentrazone	280	Spartan® FL 4F	FMC[e]
POST	at planting	Pyroxasulfone	146	Zidua ® SC	BASF
		sulfentrazone	280	Spartan® FL 4F	FMC
	7 to 10 cm weeds	glufosinate	655	Liberty® 280 SL	BASF
		2,4-D choline	1,064	Enlist One™	Corteva[f]
POR	at planting	Pyroxasulfone	146	Zidua ® SC	BASF
		sulfentrazone	280	Spartan® FL 4F	FMC
	7 to 10 cm weeds	glufosinate	655	Liberty® 280 SL	BASF
		S-metolachlor	1,419	Dual Magnum®	Syngenta
		2,4-D choline	1,064	Enlist One™	Corteva
Weed-free	at planting	Pyroxasulfone	146	Zidua ® SC	BASF
		sulfentrazone	280	Spartan® FL 4F	FMC
	7 to 10 cm weeds	glufosinate	655	Liberty® 280 SL	BASF
		S-metolachlor	1,419	Dual Magnum®	Syngenta
		2,4-D choline	1,064	Enlist One™	Corteva
		Hand weeded			

[a] At planting applications were applied at 140 L ha^{-1} with TT110015 nozzles and 245 kPa.

[b] Post-emergence applications contained ammonium sulfate (3,351 g ai ha^{-1}) (N-Pak ® AMS, WinField, St. Paul, MN) and were applied at 187 L ha^{-1} and 262 kPa with TT110002 or AIXR11002 nozzles for the LLGT27 and Enlist E3 soybeans, respectively.

[c] BASF Corporation, Research Triangle Park, NC

[d] Syngenta, Greensboro, NC

[e] FMC Corporation, Philadelphia, PA

[f] Corteva Agriscience, Wilmington, DE

Table 2.3 Analysis of variance of fixed effects and all treatment interactions for the counted soybean populations.

	OT20[a]			OT21			AB21			SC21		
Fixed effects	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value
Herbicide	48	0.84	0.504	57	1.41	0.242	48	0.35	0.842	60	0.48	0.754
Row spacing	12	47.43	< 0.001	57	29.37	< 0.001	12	4.39	0.058	60	41.25	< 0.001
Trait	12	0.07	0.799	57	1.15	0.289	12	0.00	0.979	60	0.08	0.781
Herbicide* row spacing	48	0.80	0.531	57	1.19	0.325	48	0.52	0.720	60	0.62	0.650
Herbicide* trait	48	1.02	0.407	57	1.17	0.336	48	0.55	0.697	60	0.44	0.783
Trait* row spacing	12	0.81	0.387	57	0.18	0.674	12	0.04	0.839	60	0.00	0.958
Herbicide* trait* row spacing	48	1.05	0.394	57	0.59	0.671	48	0.96	0.437	60	0.23	0.919

[a] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021

Table 2.4 Counted soybean populations for 38- and 76-cm rows pooled across soybean trait and herbicide treatment.

Row spacing	OT20 [a]		OT21		AB21[b]		SC21	
	plants ha^{-1}							
38	225,874	b	99,659	b	257,017	a	355,368	a
76	286,202	a	141,625	a	232,267	a	295,872	b

[a] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021

[b] The main effect of row spacing is not significant.

Table 2.5 Dominant weeds with averaged density, height, and diameter across from nontreated control treatments prior to POST and POR applications.

	OT20			OT21				AB21	
Measurement [b]	Venice mallow	common waterhemp	large crabgrass	Venice mallow	common waterhemp	prickly sida	large crabgrass	ivyleaf morningglory	Palmer amaranth[c]
Density	55.3	18.4	7.4	33.2	9.2	18.4	83	160	7.4
Height	8	6.4	2	9.8	8.9	2.1	11.7	-	4.5
Diameter	-	-	-	7.6	7.6	4.2	12.1	-	-

[a] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021

[b] Units: Density, plants m^{-2}; Height, cm; diameter, cm

[c] Measured 1 week prior to herbicide application.

Table 2.6 Average dry weed biomass before POST and POR applications at all locations.

	OT20	OT21	AB21	SC21
	------------------- g m^{-2} -------------------			
nontreated	23.6	36	26	2
PRE [b]	2.4	4.4	19.6	0.4

[a] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021

[b] Prior to POST and POR applications plots were only treated with a PRE. The PRE for all soybean traits and row spacing is pooled together for these averages.

Table 2.7 Analysis of variance of fixed effects and all treatment interactions for common waterhemp and Venice mallow four and ten weeks after POST treatment (WAT) in Ottawa, KS in 2020.

	common waterhemp						Venice mallow					
	4 WAT			10 WAT			4 WAT			10 WAT		
Fixed effects	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value
Herbicide	33	5.42	0.009	33	5.99	0.006	24	3.77	0.038	33	0.36	0.703
Row spacing	33	1.31	0.260	33	0.42	0.521	9	1.32	0.281	33	0.4	0.529
Trait	33	0.44	0.560	33	0.55	0.463	9	2.22	0.170	33	0.16	0.690
Herbicide * row spacing	33	1.21	0.311	33	0.41	0.670	24	0.33	0.720	33	0.4	0.671
Herbicide * trait	33	0.37	0.693	33	0.53	0.593	24	0.57	0.571	33	0.16	0.851
Trait*row spacing	33	0.32	0.576	33	0.20	0.658	9	0.60	0.460	33	0.731	0.399
Herbicide * trait*row spacing	33	0.27	0.765	33	0.19	0.828	24	0.21	0.811	33	0.731	0.489

Table 2.8 Visual ratings of weed control for common waterhemp and Venice mallow four and ten WAT in Ottawa, KS in 2020 pooled across row spacing and soybean trait.

	common waterhemp [b]				Venice mallow			
Herbicide treatment [a]	4 WAT		10 WAT		4 WAT		10 WAT[d]	
PRE	83	b	49	b	86	b	89	a
POST	100	a	100	a	98	a	100	a
POR	100	a	100	a	100	a	100	a
SE[c]	2.65		5.03		1.72		1.86	

[a] Herbicide treatments: PRE (LLGT27), pyroxasulfone + isoxaflutole; POST (LLGT27), PRE fb glufosinate + ammonium sulfate; POR (LLGT27), PRE fb glufosinate + ammonium sulfate + *S*-metolachlor; PRE(Enlist E3), pyroxasulfone + sulfentrazone; POST (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline; POR (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline + *S*-metolachlor

[b] Means separated with Tukey's pairwise comparisons. Similar letters within a column are not different ($p \leq 0.05$).

[c] Abbreviations: SE, standard error

[d] Was not significant

Table 2.9 Analysis of variance of fixed effects and all treatment interactions for common waterhemp and Venice mallow four and ten weeks after POST treatment (WAT) in Ottawa, KS in 2021.

	common waterhemp						Venice mallow					
	4 WAT			10 WAT			4 WAT			10 WAT		
Fixed effects	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value
Herbicide	33	0.25	0.782	33	0.27	0.762	36	8.86	< 0.001	24	1.04	0.369
Row spacing	33	1.13	0.296	33	0.54	0.466	36	5.02	0.031	9	0.02	0.894
Trait	33	1.01	0.323	33	0.51	0.481	36	9.63	0.004	9	1.10	0.322
Herbicide * row spacing	33	0.97	0.390	33	0.54	0.586	36	4.59	0.017	24	0.49	0.621
Herbicide * trait	33	0.61	0.548	33	0.13	0.879	36	10.95	< 0.001	24	3.43	0.049
Trait*row spacing	33	1.18	0.284	33	0.09	0.763	36	5.69	0.022	9	0.26	0.621
Herbicide * trait*row spacing	33	1.02	0.371	33	0.09	0.912	36	7.92	0.001	24	2.63	0.092

Table 2.10 Visual ratings of weed control for Venice mallow four WAT in Ottawa, KS in 2021 and ivyleaf morningglory ten WAT in Ashland Bottoms in 2021.

			OT21[c]	AB21
			Venice mallow	ivyleaf morningglory
Trait	Row spacing	Herbicide treatment [ac]	4 WAT [c]	10 WAT
LLGT27	38	PRE	95 a	20 c
LLGT27	38	POST	98 a	93 a
LLGT27	38	POR	95 a	95 a
LLGT27	76	PRE	88 a	44 b
LLGT27	76	POST	99 a	93 a
LLGT27	76	POR	98 a	96 a
Enlist E3	38	PRE	35 b	95 a
Enlist E3	38	POST	96 a	99 a
Enlist E3	38	POR	96 a	98 a
Enlist E3	76	PRE	93 a	86 a
Enlist E3	76	POST	90 a	99 a
Enlist E3	76	POR	99 a	99 a
SE			6.99	3.97

[a] Herbicide treatments: PRE (LLGT27), pyroxasulfone + isoxaflutole; POST (LLGT27), PRE fb glufosinate + ammonium sulfate; POR (LLGT27), PRE fb glufosinate + ammonium sulfate + *S*-metolachlor; PRE(Enlist E3), pyroxasulfone + sulfentrazone; POST (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline; POR (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline + *S*-metolachlor

[b] Means separated with Tukey's pairwise comparisons. Similar letters within a column are not different ($p \leq 0.05$).

[c] Abbreviation: OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SE, standard error

Table 2.11 Analysis of variance of fixed effects and all treatment interactions for Palmer amaranth and ivyleaf morningglory four and ten weeks after POST treatment (WAT) in Ashland Bottoms in 2021.

	Palmer amaranth						ivyleaf morningglory					
	4 WAT			10 WAT			4 WAT			10 WAT		
Fixed effects	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value
Herbicide	33	6.55	0.004	36	7.74	0.002	33	7.64	0.002	33	18.17	< 0.001
Row spacing	33	0.02	0.880	36	0.28	0.603	33	2.72	0.108	33	1.46	0.235
Trait	33	2.76	0.106	36	1.30	0.262	33	5.47	0.026	33	28.94	< 0.001
Herbicide * row spacing	33	0.02	0.977	36	1.93	0.160	33	0.02	0.977	33	1.13	0.336
Herbicide * trait	33	2.76	0.078	36	2.60	0.088	33	7.93	0.002	33	22.77	< 0.001
Trait*row spacing	33	0.87	0.357	36	0.24	0.629	33	0.00	0.949	33	5.51	0.025
Herbicide * trait*row spacing	33	0.87	0.427	36	1.61	0.215	33	1.69	0.200	33	5.77	0.007

Table 2.12 Visual ratings of weed control for Palmer amaranth four and ten weeks after POST treatment (WAT) in Ashland Bottoms in 2021 pooled across row spacing and soybean trait.

	Palmer amaranth			
Herbicide treatment [a]	4 WAT[b]		10 WAT	
PRE	33	b	49	b
POST	99	a	94	a
POR	99	a	99	a
SE	6.11		5.70	

[a] Herbicide treatments: PRE (LLGT27), pyroxasulfone + isoxaflutole; POST (LLGT27), PRE fb glufosinate + ammonium sulfate; POR (LLGT27), PRE fb glufosinate + ammonium sulfate + *S*-metolachlor; PRE(Enlist E3), pyroxasulfone + sulfentrazone; POST (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline; POR (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline + *S*-metolachlor

[b] Means separated with Tukey's pairwise comparisons. Similar letters within a column are not different ($p \leq 0.05$).

Table 2.13 Visual ratings of weed control for ivyleaf morningglory four WAT at Ashland Bottoms 2021 and Venice mallow ten WAT in Ottawa, KS 2021 pooled across row spacing.

		AB21		OT21	
		ivyleaf morningglory		Venice mallow	
Trait	Herbicide treatment [a]	4 WAT [b]		10 WAT	
		-----------------------%		-----------------------	
LLGT27	PRE	1	c	96	a
LLGT27	POST	83	ab	98	a
LLGT27	POR	84	ab	96	a
Enlist E3	PRE	71	b	88	a
Enlist E3	POST	93	a	94	a
Enlist E3	POR	92	a	96	a
SE[c]		5.36		3.08	

[a] Herbicide treatments: PRE (LLGT27), pyroxasulfone + isoxaflutole; POST (LLGT27), PRE fb glufosinate + ammonium sulfate; POR (LLGT27), PRE fb glufosinate + ammonium sulfate + *S*-metolachlor; PRE(Enlist E3), pyroxasulfone + sulfentrazone; POST (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline; POR (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline + *S*-metolachlor

[b] Means separated with Tukey's pairwise comparisons. Similar letters within a column are not different ($p \leq 0.05$).

[c] Abbreviations: AB21, Ashland Bottoms 2021; OT21, Ottawa, KS 2021; SE, standard error

Table 2.14 Analysis of variance of fixed effects and all treatment interactions for yellow foxtail four and ten weeks after POST treatment (WAT) in Scandia, KS 2021.[a]

	yellow foxtail					
	4 WAT			10 WAT		
	df	F-value	P-value	df	F-value	P-value
Herbicide	24	0.73	0.490	24	0.63	0.541
Row spacing	9	2.36	0.159	9	4.66	0.059
Trait	9	1.15	0.312	9	3.12	0.111
Herbicide * row spacing	24	2.28	0.124	24	3.41	0.050
Herbicide * trait	24	1.14	0.337	24	2.58	0.097
Trait*row spacing	9	2.69	0.135	9	6.66	0.030
Herbicide * trait*row spacing	24	2.65	0.091	24	5.33	0.012

Table 2.15 Analysis of variance of fixed effects and all treatment interactions for dry weed biomass as a percent of the non-treated check at R7 growth stage in soybean.

	OT20[a]			OT21			AB21			SC21		
Fixed effects	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value
Herbicide	33	3.04	0.061	24	0.58	0.567	24	6.58	0.005	36	1.60	0.216
Row spacing	33	1.51	0.228	9	1.53	0.247	12	0.82	0.383	36	1.00	0.324
Trait	33	0.91	0.348	9	2.62	0.140	12	8.00	0.015	36	1.60	0.214
Herbicide * row spacing	33	1.51	0.236	24	0.41	0.668	24	1.08	0.356	36	1.00	0.378
Herbicide * trait	33	0.91	0.414	24	0.90	0.421	24	8.23	0.002	36	1.60	0.216
Trait*row spacing	33	0.64	0.428	9	1.81	0.212	12	3.67	0.079	36	1.00	0.324
Herbicide * trait*row spacing	33	0.64	0.532	24	0.53	0.596	24	4.18	0.028	36	1.00	0.378

[a] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021

Table 2.16 Dry weed biomass as a percent of the non-treated check at R7 growth stage in soybean at Ashland Bottoms in 2021.

Herbicide treatment [a]	Row spacing	Trait	AB21[b]	
	cm		% of nontreated check	
PRE	38	LLGT27	67.3	a
POST	38	LLGT27	1.6	b
POR	38	LLGT27	0.1	b
PRE	76	LLGT27	31.0	b
POST	76	LLGT27	2.8	b
POR	76	LLGT27	0.7	b
PRE	38	Enlist E3	6.3	b
POST	38	Enlist E3	0.0	b
POR	38	Enlist E3	0.0	b
PRE	76	Enlist E3	18.6	b
POST	76	Enlist E3	0.2	b
POR	76	Enlist E3	0.0	b
SE			7.01	

[a] Herbicide treatments: PRE (LLGT27), pyroxasulfone + isoxaflutole; POST (LLGT27), PRE fb glufosinate + ammonium sulfate; POR (LLGT27), PRE fb glufosinate + ammonium sulfate + *S*-metolachlor; PRE(Enlist E3), pyroxasulfone + sulfentrazone; POST (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline; POR (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline + *S*-metolachlor

[b] Means separated with Tukey's pairwise comparisons. Similar letters within a column are not different ($p \leq 0.05$).

Table 2.17 Analysis of variance of fixed effects and all treatment interactions for canopy cover measured with Canopeo eight weeks after planting soybean for each location.

	OT20[a]			OT21			AB21			SC21		
Fixed effects	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value
Row spacing	9	5.55	0.043	9	2.00	0.191	12	56.22	< 0.001	3	29.89	0.012
Trait	9	0.49	0.503	9	4.10	0.074	12	2.33	0.153	6	0.01	0.932
Trait*row spacing	9	0.00	0.967	9	2.29	0.165	12	0.79	0.393	6	1.40	0.282

[a] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021

Table 2.18 Canopy cover measured with Canopeo eight weeks after planting soybeans in Ottawa, KS in 2020 and 2021, Ashland Bottoms in 2021, and Scandia, KS in 2021 pooled across soybean trait.

Row spacing	OT20 [ab]		OT21[c]		AB21		SC21	
cm	-------------------- % canopy ----------------------							
38	92	a	52	a	94	a	90	a
76	86	a	41	a	91	b	79	b
SE	5.62		5.74		0.255		5.98	

[a] Means separated with Tukey's pairwise comparisons. Similar letters within a column are not different ($p \leq 0.05$).

[b] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021; SE, standard error

[c] Not significant

Table 2.19 Analysis of variance of fixed effects and all treatment interactions for 100 seed weight.

	OT20[a]			OT21			AB21			SC21		
Fixed effects	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value
Herbicide	58	0.46	0.768	48	1.12	0.360	47.2	0.29	0.882	46.3	1.26	0.298
Row spacing	58	9.78	0.003	9	7.13	0.026	8.8	0.00	0.996	12.1	0.10	0.756
Trait	58	14.11	< 0.001	9	4.38	0.066	9.1	3.33	0.101	12.1	0.01	0.907
Herbicide * row spacing	58	0.21	0.931	48	0.53	0.713	47.0	0.78	0.541	46.3	1.17	0.336
Herbicide * trait	58	1.24	0.304	48	0.67	0.618	47.2	0.90	0.474	46.3	0.99	0.421
Trait*row spacing	58	0.67	0.416	9	0.85	0.381	8.8	1.30	0.285	12.1	0.12	0.740
Herbicide * trait*row spacing	58	0.52	0.722	48	0.30	0.880	47.0	1.30	0.285	46.3	0.86	0.495

[a] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021

Table 2.20 Row spacing differences in 100 seed weight for Ottawa, KS in 2020 and 2021 as well as trait difference for Ottawa, KS in 2020.

Row spacing	OT20[abc]		OT21[a]	
cm	---------------- g 100 seed^{-1}-----------			
38	12.5	b	15.7	b
76	12.9	a	16.0	a
SE	0.08		0.21	

Trait	OT20[de]	
	g 100 seed^{-1}	
LLGT27	12.1	b
Enlist E3	13.2	a
SE	0.08	

[a] Pooled across soybean trait and herbicide treatment

[b] Means separated with Tukey's pairwise comparisons. Similar letters within a column are not different ($p \leq 0.05$).

[c] Abbreviations: OT20, Ottawa, KS in 2020; OT21, Ottawa, KS in 2021; SE, standard error

[d] Pooled across herbicide treatment and row spacing.

[e] Soybean trait is confounded with soybean variety.

Table 2.21 Analysis of variance of fixed effects and all treatment interactions for yield pooled across Ottawa, KS during 2020 and 2021, Ashland bottoms in 2021, and Scandia, KS in 2021.

	Yield		
Fixed effects	df	F- value	P- value
Herbicide	191.8	2.50	0.044
Row spacing	45.3	6.85	0.012
Trait	45.4	19.72	< 0.001
Site year [b]	45.4	53.02	< 0.001
Herbicide* row spacing	191.6	0.20	0.938
Herbicide* trait	191.8	0.30	0.878
Row spacing* trait	45.3	9.77	0.003
Herbicide* site year [a]	191.8	1.85	0.043
Row spacing* site year	45.3	7.23	< 0.001
Trait*site year	45.4	17.00	< 0.001
Herbicide* row spacing* trait	191.6	0.36	0.840
Herbicide* row spacing * site year	191.6	1.23	0.265
Herbicide* trait*site year	191.8	0.71	0.738
Row spacing* trait*site year	45.3	8.48	< 0.001
Herbicide* row spacing* trait*site year	191.6	0.60	0.838

[a] Site year interaction is significant. Yield results will be analyzed separately.

Table 2.22 Analysis of variance of fixed effects and all treatment interactions for yield in Ottawa, KS during 2020 and 2021, Ashland bottoms in 2021, and Scandia, KS in 2021, ran separately.

	Yield											
	OT20[a]			OT21			AB21			SC21		
Fixed effects	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value
Herbicide	57	0.57	0.689	56	3.80	0.008	48	3.36	0.017	57	0.23	0.921
Row spacing	57	0.76	0.388	56	8.35	0.005	9	17.01	0.003	57	25.74	< 0.001
Trait	57	3.87	0.054	56	4.69	0.035	9	92.36	< 0.001	57	7.90	0.007
Herbicide * row spacing	57	0.63	0.646	56	1.27	0.294	48	1.90	0.126	57	0.15	0.960
Herbicide * trait	57	0.12	0.976	56	1.18	0.327	48	0.95	0.445	57	0.12	0.973
Trait*row spacing	57	3.23	0.078	56	4.02	0.050	9	37.06	0.000	57	9.90	0.003
Herbicide * trait*row spacing	57	0.23	0.921	56	0.94	0.450	48	0.76	0.554	57	0.16	0.959

[a] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021

Table 2.23 Yield results for herbicide treatment in Ottawa, KS in 2021 and Ashland Bottoms in 2021 pooled across row spacing and soybean trait.

	Yield [b]			
Herbicide [a]	OT21[c]		AB21	
PRE	2832	a	1850	b
POST	2844	a	2366	a
POR	2771	a	2525	a
Weed free check	2849	a	2328	a
Non-treated	1696	b	990	c
SE	186		139	

[a] Herbicide treatments: PRE (LLGT27), pyroxasulfone + isoxaflutole; POST (LLGT27), PRE fb glufosinate + ammonium sulfate; POR (LLGT27), PRE fb glufosinate + ammonium sulfate + *S*-metolachlor; PRE(Enlist E3), pyroxasulfone + sulfentrazone; POST (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline; POR (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline + *S*-metolachlor; Weed free check, POR + hoeing as needed; Non-treated, no herbicide applied

[b] Means separated with Tukey’s pairwise comparisons. Similar letters within a column are not different ($p \leq 0.05$).

[c] Abbreviations: OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SE, standard error

Table 2.24 Yield results for Ottawa, KS in 2020 and 2021, Ashland bottoms in 2021, and Scandia, KS in 2021 pooled across herbicide treatments.

		Yield [a]							
Trait	Row spacing	OT20[bc]		OT21		AB21		SC21	
		kg ha^{-1}							
LLGT27	38	2463	a	2597	ab	1099	c	3957	ab
LLGT27	76	2806	a	2702	ab	1934	b	3862	bc
Enlist E3	38	2800	a	2258	b	2588	a	4085	a
Enlist E3	76	2681	a	2837	a	2427	a	3681	c
SE		144		180		134		61.5	

[a] Means separated with Tukey's pairwise comparisons. Similar letters within a column are not different ($p \leq 0.05$).

[b] The interaction between row spacing and soybean trait was not significant for OT20.

[c] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021; SE, standard error

Table 2.25 Partial budget comparing the soybean trait, row spacing, and herbicide treatment to the nontreated control in the Enlist E3 trait in 76 cm rows.

			OT20			OT21			AB21			Average for rainfed[c]	SC21		
Trait	Row spacing	Treatment [a, b]	Added income	Added costs	Net income change	Added income	Added costs	Net income change	Added income	Added costs	Net income change	Net income change	Added income	Added costs	Net income change
	cm		US $ /ha												
LLGT27	38	NT	-37	25	-61	-370	25	-395	-219	25	-244	-233	193	25	168
		PRE	-34	132	-166	574	133	441	-174	132	-307	-10	238	133	105
		POST	154	183	-29	357	212	145	292	211	81	66	159	212	-53
		POR	227	211	17	244	240	4	375	211	164	62	133	240	-107
LLGT27	76	NT	43	4	40	-83	4	-87	73	4	69	7	145	4	140
		PRE	248	111	137	374	112	262	522	112	410	270	174	112	63
		POST	395	162	233	522	191	331	606	162	443	336	145	191	-46
		POR	291	190	101	520	219	301	766	190	576	326	58	219	-161
Enlist E3	38	NT	27	21	6	-317	21	-338	297	21	276	-19	272	21	251
		PRE	316	126	190	249	126	123	860	126	734	349	287	126	161
		POST	319	209	111	134	237	-103	1133	209	924	311	211	237	-26
		POR	300	237	64	277	265	12	1138	237	901	326	259	265	-6
Enlist E3	76	PRE	482	105	377	438	105	333	765	105	660	457	122	105	17
		POST	105	188	-83	647	221	426	1033	188	845	396	6	217	-211
		POR	51	216	-165	465	217	249	1121	216	906	330	30	244	-215

[a] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021

[b] Herbicide treatments: NT, nontreated; PRE (LLGT27), pyroxasulfone + isoxaflutole; POST (LLGT27), PRE fb glufosinate + ammonium sulfate; POR (LLGT27), PRE fb glufosinate + ammonium sulfate + *S*-metolachlor; PRE(Enlist E3), pyroxasulfone + sulfentrazone; POST (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline; POR (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline + *S*-metolachlor

[c] Rainfed: OT20, OT21, and AB21; Irrigated: SC21

Chapter 3 - Effect of carrier volume and weed size on Palmer amaranth (*Amaranthus palmeri* S. Watson) and large crabgrass (*Digitaria sanguinalis* L.) control by co-applications used in 2,4-d resistant soybeans.

Abstract

Herbicide co-application increases farm efficiency and facilitates control of a broader spectrum of weed species. However, application requirements may conflict or weed control may be reduced when herbicides are co-applied. Enlist E3 soybeans (*Glycine max* (L.) Merr) are resistant to postemergence applications of 2,4-D, glyphosate, and glufosinate, making co-application of these products during the soybean growing season possible. However, reduced efficacy has been documented when some combinations of these products are applied to grasses. Greenhouse experiments were conducted to determine Palmer amaranth (*Amaranthus palmeri* S. Watson) and large crabgrass (*Digitaria sanguinalis* L.) control by 2- and 3-way combinations of 2,4-D (1064 g ai ha^{-1}), glufosinate (655 g ai ha^{-1}), and glyphosate (862 g ae ha^{-1}). Each treatment included ammonium sulfate (3,351 g ai ha^{-1}) and was applied with carrier volumes of 93-, 140-, and 187 L ha^{-1} to 5-, 10-, and 20-cm Palmer amaranth and large crabgrass. Treatments were randomized in a split-split plot design with plant size as the main plot and replication as sub-plots. Water-sensitive paper was also sprayed with each treatment to determine the number of droplets and percent area covered. Four weeks after treatment, visual ratings of weed control and above ground biomass were collected. Data were subjected to analysis of variance and means separation ($\alpha = 0.05$). Control of 5-, 10-, and 20-cm Palmer amaranth was 100%, > 91%, and 7 to 79% for the herbicide combinations, respectively. 2,4-D + glyphosate provided the greatest

Palmer amaranth control. Palmer amaranth control was similar for all carrier volumes. Large crabgrass control was $\geq$ 82% when treatments were applied to 5-cm large crabgrass, but control of 10- or 20-cm large crabgrass was reduced to 51 to 56%. Large crabgrass control was similar for all carrier volumes. There was a carrier volume by herbicide combination interaction for the number of droplets deposited and percent area covered on water-sensitive paper. Treatments containing glufosinate had more droplets than those not containing glufosinate. The percent area covered by 2,4-D + glyphosate was less than other herbicide combinations. These data suggest that under ideal conditions, carrier volume has a limited effect on control of Palmer amaranth and large crabgrass and control was not related to spray deposition.

Introduction

Palmer amaranth (*Amaranthus palmeri* S. Watson) is among the most common and troublesome weeds in Kansas soybean production (Van Wychen 2019). The dioecious summer annual plant ranges from 1.5 to 2.0 m in height and produces 200,000 to 600,000 seeds per plant (Keeley et al. 1987, Meyers et al. 2010, Sellers et al. 2003, Webster and Grey 2015). Klingaman and Oliver (1994) reported a 60% reduction in soybean yield by three Palmer amaranth plants m^{-1} of row. Others reported soybean yield loss that ranged from 37% (Basinger et al. 2019) to 79% (Bensch et al. 2003) by Palmer amaranth at a density of eight plants m^{-2}.

Large crabgrass (*Digitaria sanguinalis* L.) is also a common weed in soybean production. The summer annual grass plant can produce 900 to 3,100 seeds, depending on plant density (Aguyoh and Masiunas 2003) and reaches 0.35 m tall in 42 days (Travlos 2018). Basinger et al. (2019) reported 37% yield loss in soybean with sixteen large crabgrass plants m^{-2}.

Control of a diverse weed population that includes weeds like Palmer amaranth and large crabgrass can be improved by co-applying herbicides (Aulakh and Jhala 2015, Craigmyle et al.

2013). Transgenic crops have increased the number of herbicides that can be co-applied in soybeans. For example, Enlist E3 varieties allow application of 2,4-D, glyphosate, and glufosinate to control emerged weeds. 2,4-D is a synthetic auxin herbicide, glyphosate is a non-selective herbicide targeting the EPSP synthase enzyme, and glufosinate is also a non-selective herbicide but it targets the glutamate synthase pathway. Using multiple modes of action, including those made possible by the Enlist E3, is a best practice to manage herbicide resistant weeds (Norsworthy et al. 2012).

Numerous published studies have evaluated Palmer amaranth control with co-applied herbicides. Lawrence et al. (2018) observed 46, 84, and 59% control of five- to ten-cm Palmer amaranth 14 days after glyphosate, glufosinate and 2,4-D were applied alone, respectively. Control improved to $\geq$ 92% for glufosinate + 2,4-D or glyphosate + glufosinate + 2,4-D. Similarly, when Palmer amaranth size increased to 15 to 20 cm glyphosate, glufosinate and 2,4-D applied alone provided 40, 53, and 89% control, respectively. Co-applications at this weed size for glufosinate + 2,4-D and glufosinate + 2,4-D + glyphosate improved control to > 94%. Merchant et al. (2013) observed similar results, with 2,4-D alone at rates of 532 to 1064 g ha^{-1} providing 68 to 80% Palmer amaranth control, but control by 2,4-D + glufosinate increased to 90% or greater.

However, antagonism has been documented when combinations of 2,4-D, glufosinate, and glyphosate are applied to grass species (Bethke et al. 2013, Craigmyle et al. 2013, Flint and Barrett 1989). Control of 15-cm large crabgrass by glufosinate was decreased 10 to 20% by the addition of 2,4-D at rates of 0.84 to 1.12 kg ha^{-1} and glufosinate rates of 0.59 to 0.73 kg ha^{-1} (Craigmyle et al. 2013). Meyer et al. (2021) observed antagonism when glufosinate and glyphosate were co-applied to 18-cm large crabgrass, although control was $\geq$ 95% for all rates evaluated.

Application parameters such as carrier volume and weed size at application affect control. The herbicide labels for glyphosate, glufosinate and 2,4-D recommend different carrier volumes ranging from 93 to 187 L ha^{-1} (Arneson and Werle 2020, BASF Ag Products 2019, Bayer Ag Products 2017). Multiple researchers have reported greater weed control when herbicides were applied at greater carrier volumes (Butts et al. 2018, Creech et al. 2015b, Knoche 1994).

Knoche (1994) reported increased weed control with smaller droplets (< 150 µm) in 79% of published experiments, while the other 21% observed no change. Butts et al. (2018) reported that weed control by glufosinate is maximized with 300-µm droplets while control with dicamba is greater with < 600-µm droplets. Droplet size is affected by active ingredients, nozzle type, orifice size, spray pressure and carrier volume (Creech et al. 2015a). Glyphosate + glufosinate co-applications increase droplet size compared glufosinate alone (Meyer et al. 2021), hypothetically reducing control.

There is limited published research investigation the interactions of herbicide co-application, carrier volume, and weed size on Palmer amaranth and large crabgrass control. Therefore, objectives of this study were to determine the effect of carrier volume, herbicide co-application, and weed size on Palmer amaranth and large crabgrass control and spray deposition. We hypothesize that Palmer amaranth and large crabgrass control will be greater when herbicide combinations that include 2,4-D are applied to smaller weed size at greater carrier volumes.

Materials and methods

Glyphosate susceptible Palmer amaranth collected from Riley County, KS and large crabgrass seed (Azlin Seed Services, Leland, MS) were used for these greenhouse experiments, which were repeated in time. Both Palmer amaranth and one large crabgrass runs were conducted in the spring of 2021 in a greenhouse set to have 16 hours of supplemental light with day and nighttime temperatures of 31.7 and 22.7 C. The second large crabgrass run was conducted during the fall of 2020 and had 14 hours of supplemental light with day and nighttime temperatures of 28.9 and 22.2 C, respectively. Palmer amaranth was treated with Captan 50W Fungicide before planting. Then multiple Palmer amaranth or large crabgrass seeds were planted into 10-cm square pots filled with Miracle-Gro® Moisture Control® Potting Mix (Table 3.1). After emergence, seedlings were thinned to 1 plant per pot. Plants were subirrigated until herbicide applications were made and then watered from the top as needed.

Plants were sprayed when the upper-most fully expanded leaf reached 5-, 10-, and 20-cm tall with the herbicide combinations listed in Table 3.2. The carrier volumes were 93, 140, and 187 L ha^{-1} and were achieved with AIXR 110015 (Teejet Technologies, Spraying Systems Co., Springfield, IL) at 91.4 kPa, AIXR 110025 at 118.9 kPa, and AIXR 11003 at 148 kPa, respectively with the Generation III Research Spray Booth track sprayer at 4.8 kph. Additionally, water-sensitive paper (WSP; Syngenta, Greensboro, NC) was sprayed with the same herbicide combinations and carrier volumes immediately after weeds were treated.

Visual ratings of control were taken one, two, and four weeks after treatment (WAT) and above ground biomass was harvested four WAT. WSP was processed as outlined by Haramoto et al. (2020). Briefly, cards were scanned using a 200-dpi scanner and ImageJ (Schneider et al. 2012) was used to quantify the number of droplets, average droplet size, and percent area covered.

Fixed factors for the Palmer amaranth and large crabgrass experiments were herbicide combination, carrier volume, and weed size. Run, replication within run, and height within replication within run were considered random for the Palmer amaranth experiment. Replication and replication within height were considered random for the large crabgrass experiment. Data were subjected to analysis of variance ($\alpha = 0.05$), and means were separated with Tukey's HSD ($P = 0.05$). The following R packages are listed with their uses: lmerTest, helps to make mixed effect models; car, is a companion to applied regression; emmeans, helps to estimate marginal means; multcompView, helps to summarize multiple paired comparisons; multcomp, allows comparisons of groups of data; and tidyverse, helps to organize data (Fox et al. 2021, Graves and Dorai-Raj 2019, Hothorn et al. 2022, Kuznetsova et al. 2017, Length 2020, R Core Team 2020, Wickham et al. 2019).

Results and discussions

Palmer amaranth experiments

Palmer amaranth data will be presented pooled over both runs. This was done to allow interpretation of the data across all replicates from run one and run two, which were conducted in similar environments (Table 3.1). The analysis of variance showed a significant interaction between herbicide combination and weed size ($p < 0.001$) for both visual ratings four WAT and dry biomass (Table 3.3). Spraying 5- and 10-cm Palmer amaranth resulted in > 91% control (Table 3.4). Similar to the current study, Shyam et al. (2021) reported that 2,4-D + glufosinate combinations controlled 10- to 15-cm Palmer amaranth ≥ 96%. Lawrence et al. (2018) reported that 5- to 10-cm glyphosate-resistant Palmer amaranth control by 2,4-D co-applied with glyphosate resulted in 81% four WAT compared to 89% when co-applied with glufosinate.

However, Palmer amaranth control was more variable when herbicide combinations were applied to 20-cm Palmer amaranth (Table 3.4). 2,4-D + glyphosate controlled 20-cm Palmer amaranth 79%, compared to 2,4-D + glufosinate or 2,4-D + glufosinate + glyphosate combinations, which provided 26 to 28% control and glyphosate + glufosinate, which provided 7% control. Reed et al. (2014) reported antagonism between glyphosate and glufosinate herbicide combinations in Palmer amaranth because glyphosate alone provided 98% control compared to glyphosate + glufosinate with < 70% control two WAT.

Four WAT visual ratings of weed control were similar to dry biomass. All herbicide combinations applied to 5- and 10-cm Palmer amaranth resulted in $\leq$ 1.11 g. Results were more variable for 20-cm Palmer amaranth. 2,4-D + glyphosate resulted in 5.07 g and combinations containing both 2,4-D and glufosinate resulted in 9.76 to 9.90 g compared to glufosinate treatments without 2,4-D resulting in 13.02 g.

Palmer amaranth response four WAT was similar for all carrier volumes when both visual ratings of weed control ($p = 0.265$) and biomass ($p = 0.942$) were evaluated (Table 3.3). Likewise, Creech et al. (2015b) reported similar weed control by glufosinate for carrier volumes ranging from 94 to 187 L ha^{-1} for five out of seven species evaluated. In both the current experiment and Creech et al. (2015b) one plant was sprayed at a time in a very controlled setting, meaning coverage was ideal. In a field experiment, Berger et al. (2014) reported that control of 15- to 20-cm Palmer amaranth in densities of 10 to 40 plants m^{-2} by lactofen increased 6% for the carrier volume of 187 L ha^{-1} compared to 94 L ha^{-1}.

Large crabgrass experiments

Large crabgrass data will be presented separately for run 1 and 2, as run and interactions with run were significant and plants were grown at different times (Table 3.1). Large crabgrass plants grown in the second run grew faster and larger than plants in the first run at the end of the experiment. For example, biomass of the non-treated control in second run averaged 33.5 g compared to the first run which averaged 3.5 g (data not shown) and plants in the second run took 20 days to grow 20 cm tall, while the first run required 37 days to obtain the same height (Table 3.1). This is likely due to differences in the temperature and light conditions between the two runs.

In the first run, there was an interaction between herbicide combination and weed size at application four WAT for both visual ratings of weed control ($p < 0.001$) and biomass ($p = 0.017$; Table 3.5). For the first large crabgrass run, all treatments sprayed with 2,4-D + glyphosate had 100% control, and all treatments applied to 5-cm large crabgrass had $\geq$ 86% control 4 WAT (Table 3.6). Herbicide combinations containing glufosinate applied to 10- and 20-cm weeds were controlled 53 to 65% and 48 to 78%, respectively. Meyer and Norsworthy (2019) reported a 7 to 12% reduction in barnyardgrass control when weed size was increased from 10-cm to 30-cm with similar herbicide combinations. Then in a field experiment Meyer et al. (2021) reported that the combination of glufosinate + glyphosate was antagonistic, but with control ranged from 95 to 98%. Similarly, Bethke et al. (2013) reported antagonism between co-applications of glufosinate + glyphosate in giant foxtail. Takano and Dayan (2020) reviewed glufosinate and reported that glufosinate is hydrophilic which impedes translocation and often results in poorer control of grasses. Large crabgrass biomass collected four WAT was $\leq$ 0.13 g for 5- and 10-cm plants, compared to 0.22 to 0.39 g when 20-cm plants were sprayed. 2,4-D + glyphosate provided the greatest large crabgrass control, regardless of weed size. In Meyer et al. (2021) glyphosate alone provided 98% to 100% control of 17 to 18-cm large crabgrass. However, Merritt et al. (2021) sprayed 10-cm broadleaf signalgrass, giant foxtail, and barnyardgrass with glyphosate plus 2,4-D and reported 27% control four WAT.

In the second large crabgrass experiment, interactions between herbicide combination and weed size were observed four WAT for both weed control ($p < 0.001$) and biomass (p <

0.001; Table 3.5). 2,4-D + glyphosate resulted in $\geq$ 97% control, regardless of the large crabgrass size at application (Table 3.6). All large crabgrass sprayed at 5-cm size had $\geq$ 74% control. The least control at every carrier volume resulted from application of 2,4-D + glufosinate and ranged from 0 to 29%.

Carrier volume had minimal effects on control in large crabgrass. In run one, carrier volume was not significant, however in run two a carrier volume by size interaction was observed (Table 3.5). In run two all carrier volumes within a weed size had similar control, except for 187 L ha^{-1} applied to 5-cm large crabgrass resulting in 87% control when pooled over herbicide treatments (Table 3.7). Control of 5-cm large crabgrass with 93 and 140 L ha^{-1} carrier volumes was 62%. Visual ratings of control for 10- and 20-cm weeds were similar regardless of carrier volume, ranging from 31 to 52%. Biomass from run two confirmed there were no differences among carrier volumes within a weed size. Mahoney et al. (2019) reported significant effects of carrier volume ranging from 70 to 561 L ha^{-1} on Palmer amaranth and large crabgrass, however differences in control were less than 6%.

Water-sensitive paper

Water-sensitive paper (WSP) data will be presented pooled for both runs of the experiment. There was as significant interaction between herbicide combination and carrier volume ($p < 0.001$) for droplet number, droplet size, and area covered (Table 3.8). The greatest number of droplets was observed with glyphosate + glufosinate sprayed at 140 L ha^{-1} (Table 3.9). The fewest droplets for each carrier volume was obtained with 2,4-D + glyphosate.

The largest droplets were observed at 187 L ha^{-1} with all herbicide combinations ranging from 0.86 to 1.08mm compared to water alone 0.52 mm. Creech et al. (2015a) reported that increasing the carrier volume from 47 to 187 L ha^{-1} increased droplet size 5%. However, nozzle operating pressure, herbicide, and nozzle orifice size are also important in determining droplet size. Lower operating pressures and larger orifice sizes result in larger droplets (Creech et al. 2015a). In order to apply the 187 L ha^{-1}, a 11003 orifice was used, compared to the 93 and 140 L ha^{-1}, which used a 110015 and a 110025 orifice, respectively. Creech et al. (2015b) also changed orifice size from XR11001 to XR11002 to adjust the carrier volume from 94 to 187 L ha^{-1} in a study looking at droplet size and weed control.

The area covered ranged from 13 to 44% (Table 3.9). Glyphosate + glufosinate had the greatest spray coverage for each carrier volume. When applied at 187 L ha^{-1}, glyphosate + glufosinate covered 44% of the area compared to a range of 32 to 37% for the remaining herbicide combinations (Table 3.9). Herbicide combinations containing 2,4-D applied at 140 L ha^{-1} ranged from 19 to 24% coverage. A previously published field experiment reported 25% coverage for 2,4-D alone at the same carrier volume (Haramoto et al. 2020).

In conclusion, farmers should pay close attention to weed size at application, as control will decrease as weed size increases. Carrier volume, however, had a limited effect on Palmer amaranth and large crabgrass control when one plant was sprayed at a time in the greenhouse. In field settings greater carrier volumes should be considered, especially with greater weed densities. The herbicide combination of 2,4-D + glyphosate would be recommended as it had the greatest control of Palmer amaranth ($\geq$ 79%) and large crabgrass ($\geq$ 97%), regardless of size at application.

References

Aguyoh JN, Masiunas JB (2003) Interference of large crabgrass (*Digitaria sanguinalis*) with snap beans. Weed Sci 51:171–176

Arneson N, Werle R (2020) Enlist E3 soybean system in 2020: what we think applicators should know. https://www.wiscweeds.info/post/enlist-e3-system-in-2020-what-we-think-applicators-should-know/. Accessed January 20, 2022

Aulakh JS, Jhala AJ (2015) Comparison of glufosinate-based herbicide programs for broad-spectrum weed control in glufosinate-resistant soybean. Weed Technol 29:419–430

BASF Ag Products (2019) Liberty 280 SL Herbicide Label. http://www.cdms.net/ldat/ldG9N000.pdf. Accessed August 8, 2020

Basinger NT, Jennings KM, Monks DW, Jordan DL, Everman WJ, Hestir EL, Bertucci MB, Brownie C (2019) Large crabgrass (*Digitaria sanguinalis*) and Palmer amaranth (*Amaranthus palmeri*) intraspecific and interspecific interference in soybean. Weed Sci 67:649–656

Bayer Ag Products (2017) Roundup Power MAX Herbicide Label. https://s3-us-west-1.amazonaws.com/agrian-cg-fs1-production/pdfs/Roundup_PowerMAX1e_Herbicide_Label.pdf. Accessed August 8, 2020

Bensch CN, Horak MJ, Peterson D (2003) Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci 51:37–43

Berger S, Dobrow M, Ferrell J, Webster T (2014) Influence of carrier volume and nozzle selection on Palmer amaranth control. Peanut Sci 41:120–123

Bethke RK, Molin WT, Sprague C, Penner D (2013) Evaluation of the interaction between glyphosate and glufosinate. Weed Sci 61:41–47

Butts TR, Samples CA, Franca LX, Dodds DM, Reynolds DB, Adams JW, Zollinger RK, Howatt KA, Fritz BK, Hoffmann WC, Kruger GR (2018) Spray droplet size and carrier volume effect on dicamba and glufosinate efficacy. Pest Manag Sci 74:2020–2029

Craigmyle BD, Ellis JM, Bradley KW (2013) Influence of weed height and glufosinate plus 2,4-D combinations on weed control in soybean with resistance to 2,4-D. Weed Technol 27:271–280

Creech CF, Henry RS, Fritz BK, Kruger GR (2015a) Influence of herbicide active ingredient, nozzle type, orifice size, spray pressure, and carrier volume rate on spray droplet size characteristics. Weed Technol 29:298–310

Creech CF, Henry RS, Werle R, Sandell LD, Hewitt AJ, Kruger GR (2015b) Performance of postemergence herbicides applied at different carrier volume rates. Weed Technol 29:611–624

Flint JL, Barrett M (1989) Antagonism of glyphosate toxicity to johnsongrass (*Sorghum halepense*) by 2,4-D and dicamba. Weed Sci 37:700–705

Fox J, Weisberg S, Price B, Adler D, Bates D, Baud-Bovy G, Bolker B, Ellison S, Firth D, Friendly M, Gorjanc G, Graves S, Heiberger R, Krivitsky P, Laboissiere R, Maechler M, Monette G, Murdoch D, Nilsson H, Ogle D, Ripley B, Venables W, Walker S, Winsemius D, Zeileis A, R-Core (2021) car: Companion to applied regression

Graves S, Dorai-Raj H-PP and LS with help from S (2019) multcompView: Visualizations of paired comparisons

Haramoto ER, Sherman AD, Green JD (2020) 2,4-D deposition is reduced and more variable immediately adjacent to cereal rye cover crop rows. Weed Technol 34:147–152

Hothorn T, Bretz F, Westfall P, Heiberger RM, Schuetzenmeister A, Scheibe S (2022) multcomp: Simultaneous inference in general parametric models

Keeley PE, Carter CH, Thullen RJ (1987) Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci 35:199–204

Klingaman TE, Oliver LR (1994) Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). Weed Sci 42:523–527

Knoche M (1994) Effect of droplet size and carrier volume on performance of foliage-applied herbicides. Crop Prot 13:163–178

Kuznetsova A, Brockhoff PB, Christensen RHB (2017) lmerTest Package: Tests in linear mixed effects models. J Stat Softw 82:1–26

Lawrence BH, Bond JA, Eubank TW, Golden BR, Cook DR, Mangialardi JP (2018) Evaluation of 2,4-D–based herbicide mixtures for control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Technol 33:263–271

Length R (2020) emmeans: Estimated marginal means, aka least-squares means. R package version 153

Mahoney DJ, Jordan DL, Hare AT, Leon RG, Vann MC, Burgos NR, Jennings KM (2019) The effect of nozzle selection and carrier volume on weed control in soybean in North Carolina. CFTM 5:1-3

Merchant RM, Sosnoskie LM, Culpepper AS, Steckel LE, York AC, Braxton LB, Ford JC (2013) Weed response to 2,4-D, 2,4-DB, and dicamba applied alone or with glufosinate J Cotton Sci 17:212-218

Merritt LH, Brown-Johnson AE, Meredith AN, Ferguson JC (2021) Comparison of efficacy and detection of clethodim and glyphosate applied with dicamba and 2,4-D through tank mixture and sequential applications. J Agric Food Chem 69:101–111

Meyer CJ, Norsworthy JK (2019) Influence of weed size on herbicide interactions for Enlist™ and Roundup Ready® Xtend® technologies. Weed Technol 33:1-9

Meyer CJ, Norsworthy JK, Kruger GR (2021) Antagonism in mixtures of glufosinate + glyphosate and glufosinate + clethodim on grasses. Weed Technol 35:12–21

Meyers SL, Jennings KM, Schultheis JR, Monks DW (2010) Interference of Palmer amaranth (*Amaranthus palmeri*) in sweet potato. Weed Sci 58:199–203

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60:31–62

R Core Team (2020) R: The R project for statistical computing. https://www.r-project.org/. Accessed February 15, 2022

Reed JD, Keeling JW, Dotray PA (2014) Palmer amaranth (*Amaranthus palmeri*) management in GlyTol® LibertyLink® Cotton. Weed Technol 28:592–600

Schneider CA, Rasband WS, Eliceiri KW (2012) NIH Image to ImageJ: 25 years of image analysis. Nat Methods 9:671–675

Sellers BA, Smeda RJ, Johnson WG, Kendig JA, Ellersieck MR (2003) Comparative growth of six Amaranthus species in Missouri. Weed Sci 51:329–333

Shyam C, Chahal PS, Jhala AJ, Jugulam M (2021) Management of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in 2,4-D–, glufosinate-, and glyphosate-resistant soybean. Weed Technol 35:136–143

Takano HK, Dayan FE (2020) Glufosinate-ammonium: a review of the current state of knowledge. Pest Manag Sci 76: 3911-3925

Travlos AD (2018) Relative contribution of physical interference and allelopathy to weed suppression by winter annual cover crop mixtures. MS Thesis. Springfield, MO: Missouri State University

Van Wychen (2019) 2019 Baseline survey of the most common and troublesome weeds in the United States and Canada. Weed Science Society of America National Weed Survey Dataset

Webster TM, Grey TL (2015) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) morphology, growth, and seed production in Georgia. Weed Sci 63:264–272

Wickham H, Averick M, Bryan J, Chang W, McGowan L, François R, Grolemund G, Hayes A, Henry L, Hester J, Kuhn M, Pedersen T, Miller E, Bache S, Müller K, Ooms J, Robinson D, Seidel D, Spinu V, Takahashi K, Vaughan D, Wilke C, Woo K, Yutani H (2019) Welcome to the Tidyverse. JOSS 4:1686

Table 3.1 Planting and spray dates for run one and two of Palmer amaranth and large crabgrass experiments.

Dates	Palmer amaranth run 1	Palmer amaranth run 2	large crabgrass run 1	large crabgrass run 2
Planting	2/5/2021	2/25/2021	10/5/2020	3/9/2021
5 cm	2/24/2021	3/10/2021	10/19/2020	3/22/2021
10 cm	2/26/2021	3/16/2021	10/26/2020	3/26/2021
20 cm	3/8/2021	3/19/2021	11/14/2020	3/29/2021

Table 3.2 Herbicide combinations, active ingredients, rates, trade name, and manufacture.

Herbicide combination [a]	Active ingredient	Rate	Trade name	Manufacture
		g ai/ae ha^{-1}		
Nontreated control	-	-	-	-
2,4-D + glyphosate	2,4-D choline	1,064	Enlist One®	Corteva[b]
	glyphosate	862	Roundup PowerMax®	Bayer[c]
2,4-D + glufosinate	2,4-D choline	1,064	Enlist One®	Corteva[b]
	glufosinate	655	Liberty® SL 280	BASF[d]
glyphosate + glufosinate	glyphosate	862	Roundup PowerMax®	Bayer[c]
	glufosinate	655	Liberty® SL 280	BASF[d]
2,4-D + glyphosate + glufosinate	2,4-D choline	1,064	Enlist One®	Corteva[b]
	glyphosate	862	Roundup PowerMax®	Bayer[c]
	glufosinate	655	Liberty® SL 280	BASF[d]

[a] All herbicide combinations also included ammonium sulfate (3351 g ai ha^{-1}).

[b] Corteva Agriscience, Wilmington, DE

[c] Bayer Crop Science, St. Louis, MO

[d] BASF Corporation, Research Triangle Park, NC

Table 3.3 Analysis of variance of fixed effects and all treatment interactions for the Palmer amaranth experiment pooled across run.

	Palmer amaranth					
	4 WAT [a]			Dry biomass		
Fixed effects	df	F-value	P-value	df	F-value	P-value
Herbicide	231	29.08	< 0.001	231	14.41	< 0.001
Volume	231	1.34	0.265	231	0.06	0.942
Size	20	260.23	< 0.001	20	94.17	< 0.001
Herbicide* volume	231	0.95	0.463	231	1.44	0.200
Herbicide* size	231	22.44	< 0.001	231	14.33	< 0.001
Volume* size	231	0.35	0.842	231	0.30	0.879
Herbicide* volume* size	231	1.27	0.240	231	1.39	0.169

[a] Abbreviations: WAT, weeks after treatment

Table 3.4 Visual estimate of control and dry biomass at four WAT on Palmer amaranth as a result of herbicide combinations applied at multiple weed sizes pooled across run and carrier volume.

		Palmer amaranth			
Herbicide combination	Size	4 WAT[ab]		Dry biomass	
	cm	%		g	
2,4-D+ glyphosate	5	100	a	0.17	d
2,4-D+ glufosinate	5	100	a	0.15	d
glyphosate+ glufosinate	5	100	a	0.12	d
2,4-D+ glyphosate + glufosinate	5	100	a	0.12	d
2,4-D+ glyphosate	10	100	a	0.99	d
2,4-D+ glufosinate	10	100	a	0.62	d
glyphosate+ glufosinate	10	91	ab	1.11	d
2,4-D+ glyphosate + glufosinate	10	96	ab	0.94	d
2,4-D+ glyphosate	20	79	b	5.07	c
2,4-D+ glufosinate	20	28	c	9.90	b
glyphosate+ glufosinate	20	7	d	13.02	a
2,4-D+ glyphosate + glufosinate	20	26	c	9.76	b
SE		4.73		1.04	

[a] Abbreviations: WAT, weeks after treatment; SE, standard error

[b] Means separated with Tukey’s pairwise comparisons. Similar letters within a column are not different ($p < 0.05$).

Table 3.5 Analysis of variance of fixed effects and all treatment interactions for run one and two of the large crabgrass experiment.

	large crabgrass (run 1)						large crabgrass (run 2)					
	4 WAT [a]			Dry biomass			4 WAT [a]			Dry biomass		
Fixed effects	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value
Herbicide	108	21.86	< 0.001	108	4.52	0.005	99	120.13	< 0.001	99	60.31	< 0.001
Volume	108	0.54	0.583	108	1.42	0.246	99	1.62	0.203	99	1.79	0.172
Size	108	23.81	< 0.001	108	85.15	< 0.001	6	38.93	< 0.001	6	59.58	< 0.001
Herbicide* volume	108	0.27	0.951	108	1.14	0.346	99	1.89	0.09	99	2.01	0.071
Herbicide* size	108	4.83	< 0.001	108	2.73	0.017	99	5.86	< 0.001	99	12.39	< 0.001
Volume* size	108	1.67	0.163	108	0.80	0.528	99	5.06	< 0.001	99	4.4	0.003
Herbicide* volume* size	108	0.9	0.548	108	0.82	0.625	99	1.25	0.262	99	0.81	0.644

[a] Abbreviations: WAT, weeks after treatment

Table 3.6 Visual estimate of control and dry biomass at four WAT on large crabgrass run one and two as a result of herbicide combinations applied at multiple weed sizes pooled across carrier volume.

		large crabgrass (run 1)				large crabgrass (run 2)			
Herbicide combination	Size	4 WAT [ab]		Dry biomass		4 WAT [ab]		Dry biomass	
	cm	%		g		%		g	
2,4-D+ glyphosate	5	100	a	0.01	d	100	a	0.06	g
2,4-D+ glufosinate	5	86	ab	0.01	d	29	bc	5.35	cdefg
glyphosate+ glufosinate	5	98	a	0.01	d	79	a	0.56	fg
2,4-D+ glyphosate + glufosinate	5	92	ab	0.01	d	74	a	1.15	efg
2,4-D+ glyphosate	10	100	a	0.02	d	99	a	0.28	g
2,4-D+ glufosinate	10	55	cd	0.13	cd	8	cd	10.62	bc
glyphosate+ glufosinate	10	53	cd	0.13	cd	44	b	7.15	cd
2,4-D+ glyphosate + glufosinate	10	65	bcd	0.09	cd	28	bcd	6.15	cdef
2,4-D+ glyphosate	20	100	a	0.22	bc	97	a	2.17	defg
2,4-D+ glufosinate	20	49	d	0.37	ab	0	d	24.04	a
glyphosate+ glufosinate	20	78	abc	0.23	bc	30	bc	6.49	cde
2,4-D+ glyphosate + glufosinate	20	48	d	0.39	a	9	cd	13.95	b
SE		6.07		0.033		6.53		1.26	

[a] Abbreviations: WAT, weeks after treatment; SE, standard error

[b] Means separated with Tukey's pairwise comparisons. Similar letters within a column are not different ($p < 0.05$).

Table 3.7 Visual estimate of control and dry biomass at four WAT on large crabgrass run two as a result of carry volumes applied at multiple weed sizes pooled across herbicide combination.

		large crabgrass (run 2)			
Volume	Size	4 WAT [ab]		Dry biomass	
L ha^{-1}	cm	%		g	
93	5	62	b	2.28	d
140	5	62	b	2.62	d
187	5	87	a	0.45	d
93	10	52	bc	4.29	cd
140	10	46	bc	5.09	cd
187	10	36	c	8.78	bc
93	20	34	c	10.40	ab
140	20	31	c	13.89	a
187	20	38	c	10.69	ab
SE		5.86		1.11	

[a] Abbreviations: WAT, weeks after treatment; SE, standard error

[b] Means separated with Tukey’s pairwise comparisons. Similar letters within a column are not different ($p < 0.05$).

Table 3.8 Analysis of variance of fixed effects and all treatment interactions for WSP[a].

Fixed effects	Number of droplets			Area covered			Average droplet size		
	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value
Herbicide	103	33.14	< 0.001	103	79.54	< 0.001	103	37.58	< 0.001
Volume	103	67.84	< 0.001	103	281.02	< 0.001	103	79.48	< 0.001
Herbicide* volume	103	8.94	< 0.001	103	7.82	< 0.001	103	3.87	< 0.001

[a] Abbreviation: WSP, water-sensitive paper

[b] P-values with * denotes significant ($P < 0.05$), ** means ($P < 0.01$), *** means ($P < 0.001$)

Table 3.9 Number of droplets, percent coverage, and average droplet size for WSP. [a]

Herbicide combination	Volume	Number of droplets [b]		Coverage		Average droplet size	
	L ha^{-1}			%		mm	
2,4-D+ glyphosate	94	767	h	15	efg	0.72	cde
2,4-D+ glufosinate	94	1152	de	15	efg	0.46	fg
glyphosate+ glufosinate	94	856	gh	21	cde	0.84	bcd
2,4-D+ glyphosate + glufosinate	94	955	fg	18	defg	0.61	defg
water	94	1078	ef	13	g	0.39	g
2,4-D+ glyphosate	140	963	fg	19	cdef	0.66	cdef
2,4-D+ glufosinate	140	1421	abc	24	c	0.55	efg
glyphosate+ glufosinate	140	1562	a	32	b	0.67	cdef
2,4-D+ glyphosate + glufosinate	140	1484	ab	23	cd	0.51	efg
water	140	1079	ef	14	fg	0.42	g
2,4-D+ glyphosate	187	978	fg	32	b	1.08	a
2,4-D+ glufosinate	187	1258	cd	37	b	0.97	ab
glyphosate+ glufosinate	187	1387	bc	44	a	1.07	a
2,4-D+ glyphosate + glufosinate	187	1380	bc	36	b	0.86	abc
water	187	1258	cd	20	cde	0.52	efg
SE		35.5		1.46		2.88	

[a] Abbreviations: WSP, Water-sensitive paper; SE, standard error

[b] Number of droplets per WSP card, which was 550 mm^2

Appendix A - Supplemental information for chapter 2

Table A.1 Soil series, slope, OM, and pH for Ottawa, KS in 2020 and 2021, Ashland Bottoms in 2021, and Scandia, KS in 2021.

	OT20[ab]	OT21[a]	AB21	SC21
Soil series	Woodson silt loam	Woodson silt loam	Reading Silt loam	Crete silt loam
Slope (%)	1 to 3	1 to 3	1 to 3	1 to 3
OM	3	3	2.6	2.8
pH	6.4	6.4	6	5.8

[a] 121 kg ha^{-1} of 18-46-0 and 93 kg ha^{-1} of 0-0-60 were applied.

[b] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021; OM, organic matter

Table A.2 Weather data at herbicide application for Ottawa, KS in 2020 and 2021, Ashland Bottoms in 2021, and Scandia, KS in 2021.

	OT20[a]		OT21		AB21		SC21	
Timing	PRE	7 to 10 cm weeds	PRE	7 to 10 cm weeds	PRE	7 to 10 cm weeds	PRE	7 to 10 cm weeds
date	6/3/20	7/1/20	6/10/21	7/13/21	6/8/21	6/28/21	6/16/21	7/22/21
start time	2:10	1:40	4:30	2:00	6:15	1:20	3:10	10:45
end time	2:30	2:55	5:40	2:50	7:00	1:50	4:10	11:40
start temperature (C)	34.4	30.8	31.7	29.4	30	29.6	38.3	26.1
end temperature (C)	33.3	32.2	32.8	30.6	30	28.3	38.3	27.8
start humidity (%)	51	68.8	38.6	65	37.7	57	27.9	63
end humidity (%)	50	69.3	45	60	37.7	62	20	32
start wind (kph)	15.8	9.7	10	4.8	6.1	5.6	16.1	8
start wind direction	SW	SE	ESE	S	ESE	NE	SSE	S
end wind (kph)	8	5.8	7.7	10.9	6.8	6.8	12.9	11.3
end wind direction	SW	SE	ESE	S	ESE	ESE	SSE	S
max wind (kph)	16.1	12.6	18	14.5	6.8	8.8	19.3	17.5
soil temp (C)	28.3	26.6	31.1	31.1	30	28.9	29.4	27.8
soil moisture	dry	adequate	sub-adequate	wet	adequate	adequate	dry	adequate
cloud cover (%)	40	90	50	10	0	70	0	0

[a] Abbreviations: OT20, Ottawa, KS 2020; OT21, Ottawa, KS 2021; AB21, Ashland Bottoms, 2021; SC21, Scandia, KS 2021; OM, organic matter

Table A.3 Visual ratings of weed control for yellow foxtail ten weeks after POST treatment (WAT) in Scandia, KS in 2021

			yellow foxtail	
Trait	Row spacing (cm)	Herbicide treatment [a]	10 WAT[b]	
LLGT27	38	PRE	99	a
LLGT27	38	POST	99	a
LLGT27	38	POR	99	a
LLGT27	76	PRE	99	a
LLGT27	76	POST	99	a
LLGT27	76	POR	99	a
Enlist E3	38	PRE	99	a
Enlist E3	38	POST	99	a
Enlist E3	38	POR	99	a
Enlist E3	76	PRE	99	a
Enlist E3	76	POST	99	a
Enlist E3	76	POR	99	a
SE[c]			< 0.001	

[a] Herbicide treatments: PRE (LLGT27), pyroxasulfone + isoxaflutole; POST (LLGT27), PRE fb glufosinate + ammonium sulfate; POR (LLGT27), PRE fb glufosinate + ammonium sulfate + S-metolachlor; PRE(Enlist E3), pyroxasulfone + sulfentrazone; POST (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline; POR (Enlist E3), PRE fb glufosinate + ammonium sulfate +2,4-D choline + S-metolachlor

[b] Means separated with Tukey's pairwise comparisons. Similar letters within a column are not different ($p \leq 0.05$).

[c] Abbreviations: SE, standard error

Appendix B - Supplemental information for chapter 3

Table B.1 Analysis of variance of fixed effects and all treatment interactions for the Palmer amaranth experiment pooled across run for one and two WAT.[a]

	Palmer amaranth					
	1 WAT [a]			2 WAT		
Fixed effects	df	F-value	P-value	df	F-value	P-value
Herbicide	252	7.58	< 0.001	231	14.10	< 0.001
Volume	252	0.42	0.656	231	1.10	0.336
Size	252	330.31	< 0.001	21	220.77	<0.001
Herbicide* volume	252	0.80	0.573	231	1.77	0.106
Herbicide* size	252	8.94	< 0.001	231	12.37	< 0.001
Volume* size	252	0.40	0.807	231	0.40	0.811
Herbicide* volume* size	252	1.03	0.425	231	1.80	0.049

[a] Abbreviations: WAT, weeks after treatment

Table B.2 Visual estimate of Palmer amaranth control as a result of herbicide combinations applied at multiple weed sizes pooled across carrier volume for one WAT. [a]

Herbicide combination	Size	Palmer amaranth 1 WAT	
	cm	%	
2,4-D+ glyphosate	5	100	a
2,4-D+ glufosinate	5	100	a
glyphosate+ glufosinate	5	100	a
2,4-D+ glyphosate + glufosinate	5	100	a
2,4-D+ glyphosate	10	95	a
2,4-D+ glufosinate	10	100	a
glyphosate+ glufosinate	10	99	a
2,4-D+ glyphosate + glufosinate	10	100	a
2,4-D+ glyphosate	20	78	b
2,4-D+ glufosinate	20	76	b
glyphosate+ glufosinate	20	60	c
2,4-D+ glyphosate + glufosinate	20	76	b
SE		1.7	

[a] Abbreviations: WAT, weeks after treatment; SE, standard error

Table B.3 Visual estimate of Palmer amaranth control as a result of herbicide combinations applied at multiple weed sizes and carrier volume for 2 WAT. [a]

			Palmer amaranth	
Size	Carrier volume	Herbicide combination	2 WAT	
cm			%	
5	94	2,4-D+ glyphosate	100	a
5	94	2,4-D+ glufosinate	100	a
5	94	glyphosate+ glufosinate	100	a
5	94	2,4-D+ glyphosate + glufosinate	100	a
5	140	2,4-D+ glyphosate	100	a
5	140	2,4-D+ glufosinate	100	a
5	140	glyphosate+ glufosinate	100	a
5	140	2,4-D+ glyphosate + glufosinate	100	a
5	187	2,4-D+ glyphosate	100	a
5	187	2,4-D+ glufosinate	100	a
5	187	glyphosate+ glufosinate	100	a
5	187	2,4-D+ glyphosate + glufosinate	100	a
10	94	2,4-D+ glyphosate	100	a
10	94	2,4-D+ glufosinate	100	a
10	94	glyphosate+ glufosinate	92	ab
10	94	2,4-D+ glyphosate + glufosinate	94	ab
10	140	2,4-D+ glyphosate	99	a
10	140	2,4-D+ glufosinate	100	a
10	140	glyphosate+ glufosinate	99	a
10	140	2,4-D+ glyphosate + glufosinate	100	a
10	187	2,4-D+ glyphosate	99	a
10	187	2,4-D+ glufosinate	100	a
10	187	glyphosate+ glufosinate	100	a
10	187	2,4-D+ glyphosate + glufosinate	100	a
20	94	2,4-D+ glyphosate	67	bc
20	94	2,4-D+ glufosinate	53	cd
20	94	glyphosate+ glufosinate	28	d
20	94	2,4-D+ glyphosate + glufosinate	46	cd
20	140	2,4-D+ glyphosate	85	ab
20	140	2,4-D+ glufosinate	30	d
20	140	glyphosate+ glufosinate	34	d
20	140	2,4-D+ glyphosate + glufosinate	54	cd
20	187	2,4-D+ glyphosate	74	abc
20	187	2,4-D+ glufosinate	67	bc
20	187	glyphosate+ glufosinate	27	d
20	187	2,4-D+ glyphosate + glufosinate	49	cd
SE			5.33	

[a] Abbreviations: WAT, weeks after treatment; SE, standard error

Table B.4 Analysis of variance of fixed effects and all treatment interactions for run one and two of the large crabgrass experiment at one and two WAT.[a]

	large crabgrass (run 1)						large crabgrass (run 2)					
	1 WAT [a]			2 WAT			1 WAT			2 WAT		
Fixed effects	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value	df	F-value	P-value
Herbicide	99	1.74	0.165	108	20.52	< 0.001	105	11.84	< 0.001	105	83.26	< 0.001
Volume	99	1.75	0.180	108	0.41	0.666	105	1.28	0.281	105	0.10	0.904
Size	9	9.49	0.006	108	12.17	< 0.001	105	281.97	< 0.001	105	85.00	< 0.001
Herbicide* volume	99	1.15	0.337	108	0.34	0.912	105	2.53	0.025	105	3.57	0.003
Herbicide* size	99	8.67	< 0.001	108	3.40	0.004	105	2.99	0.010	105	2.82	0.014
Volume* size	99	1.91	0.115	108	1.50	0.208	105	3.87	0.006	105	9.63	< 0.001
Herbicide* volume* size	99	0.56	0.869	108	0.54	0.886	105	3.13	< 0.001	105	1.78	0.061

[a] Abbreviations: WAT, weeks after treatment

Table B.5 Visual estimate of large crabgrass control as a result of herbicide combinations applied at multiple weed sizes pooled across carrier volume for one WAT in run one and two WAT for both run one and two. [ab]

		large crabgrass (run 1)		large crabgrass (run 2)
Herbicide combination	Size	1 WAT [ab]	2 WAT	2 WAT
	cm	-------------------------------%	------------------------------	
2,4-D+ glyphosate	5	86 cd	99 a	95 a
2,4-D+ glufosinate	5	95 ab	94 abc	66 cd
glyphosate+ glufosinate	5	96 a	95 ab	94 a
2,4-D+ glyphosate + glufosinate	5	93 abc	91 abcd	90 a
2,4-D+ glyphosate	10	96 a	100 a	84 ab
2,4-D+ glufosinate	10	89 abcd	79 d	60 d
glyphosate+ glufosinate	10	84 cd	79 d	85 ab
2,4-D+ glyphosate + glufosinate	10	89 abcd	84 bcd	73 bcd
2,4-D+ glyphosate	20	88 abcd	100 a	73 bcd
2,4-D+ glufosinate	20	87 bcd	82 cd	32 e
glyphosate+ glufosinate	20	88 abcd	91 abcd	74 bc
2,4-D+ glyphosate + glufosinate	20	80 d	81 d	63 cd
SE		1.85	2.66	2.87

[a] Abbreviations: WAT, weeks after treatment; SE, standard error

Table B.6 Visual estimate of large crabgrass control one WAT for the second run. [a]

			large crabgrass (run 2)	
Size	Carrier volume	Herbicide combination	1 WAT	
cm	L ha^{-1}		%	
5	94	2,4-D+ glyphosate	90	a-d
5	94	2,4-D+ glufosinate	90	a-c
5	94	glyphosate+ glufosinate	94	a
5	94	2,4-D+ glyphosate + glufosinate	91	a-c
5	140	2,4-D+ glyphosate	88	a-e
5	140	2,4-D+ glufosinate	93	a-b
5	140	glyphosate+ glufosinate	95	a
5	140	2,4-D+ glyphosate + glufosinate	89	a-d
5	187	2,4-D+ glyphosate	90	a-c
5	187	2,4-D+ glufosinate	93	ab
5	187	glyphosate+ glufosinate	92	abc
5	187	2,4-D+ glyphosate + glufosinate	94	a
10	94	2,4-D+ glyphosate	79	b-i
10	94	2,4-D+ glufosinate	83	a-g
10	94	glyphosate+ glufosinate	88	a-e
10	94	2,4-D+ glyphosate + glufosinate	81	a-h
10	140	2,4-D+ glyphosate	80	a-i
10	140	2,4-D+ glufosinate	89	a-d
10	140	glyphosate+ glufosinate	85	a-f
10	140	2,4-D+ glyphosate + glufosinate	86	a-e
10	187	2,4-D+ glyphosate	79	b-i
10	187	2,4-D+ glufosinate	81	a-h
10	187	glyphosate+ glufosinate	89	a-d
10	187	2,4-D+ glyphosate + glufosinate	83	a-g
20	94	2,4-D+ glyphosate	74	e-j
20	94	2,4-D+ glufosinate	63	j-l
20	94	glyphosate+ glufosinate	78	c-i
20	94	2,4-D+ glyphosate + glufosinate	68	h-k
20	140	2,4-D+ glyphosate	55	kl
20	140	2,4-D+ glufosinate	53	l
20	140	glyphosate+ glufosinate	75	d-j
20	140	2,4-D+ glyphosate + glufosinate	70	g-j
20	187	2,4-D+ glyphosate	61	j-l
20	187	2,4-D+ glufosinate	66	i-l
20	187	glyphosate+ glufosinate	63	j-l
20	187	2,4-D+ glyphosate + glufosinate	71	f-j
SE			2.65	

[a] Abbreviations: WAT, weeks after treatment; SE, standard error

Table B.7 Visual estimate of large crabgrass control two WAT for the second run as a result of herbicide combinations applied at multiple carrier volumes pooled across weed sizes. [a]

Herbicide combination	carrier volume	large crabgrass (run 2) 2 WAT	
	L ha^{-1}	%	
2,4-D+ glyphosate	93	88	a
2,4-D+ glyphosate	140	81	abc
2,4-D+ glyphosate	187	83	abc
2,4-D+ glufosinate	93	48	e
2,4-D+ glufosinate	140	52	e
2,4-D+ glufosinate	187	57	de
glyphosate+ glufosinate	93	87	a
glyphosate+ glufosinate	140	79	abc
glyphosate+ glufosinate	187	86	ab
2,4-D+ glyphosate + glufosinate	93	73	bc
2,4-D+ glyphosate + glufosinate	140	82	abc
2,4-D+ glyphosate + glufosinate	187	70	cd
SE		2.87	

[a] Abbreviations: WAT, weeks after treatment; SE, standard error

Table B.8 Visual estimate of large crabgrass control two WAT for the second run as a result of multiple carrier volumes and weed sizes pooled over herbicide combinations. [a]

		large crabgrass (run 2)	
Volume	Size	2 WAT	
L ha^{-1}	cm	%	
93	5	79	bc
140	5	85	ab
187	5	95	a
93	10	77	bcd
140	10	79	bc
187	10	70	cd
93	20	66	de
140	20	57	e
187	20	58	e
SE		2.5	

[a] Abbreviations: WAT, weeks after treatment; SE, standard error