Spring 5-2020

Control of Volunteer Corn in Enlist Corn and Economics of Herbicide Programs for Weed Control in Conventional and Multiple Herbicide-Resistant Soybean Across Nebraska

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Striegel, Adam M., "Control of Volunteer Corn in Enlist Corn and Economics of Herbicide Programs for Weed Control in Conventional and Multiple Herbicide-Resistant Soybean Across Nebraska" (2020). *Department of Agronomy and Horticulture: Dissertations, Theses, and Student Research*. 191.
https://digitalcommons.unl.edu/agronhortdiss/191

CONTROL OF VOLUNTEER CORN IN ENLIST CORN AND ECONOMICS OF HERBICIDE PROGRAMS IN CONVENTIONAL AND MULTIPLE HERBICIDE-RESISTANT SOYBEAN SYSTEMS ACROSS NEBRASKA

by

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A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Agronomy

Under the Supervision of Professor Amit J. Jhala

Lincoln, Nebraska

May, 2020

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With commercialization of multiple herbicide-resistant corn and soybean cultivars, producers have new management options for controlling herbicide-resistant weeds and volunteer corn. Corn-on-corn production systems are common in irrigated fields in southcentral Nebraska which can create issues with volunteer corn management in corn fields. Enlist corn contains a new multiple herbicide-resistant trait providing resistance to 2,4-D choline, glyphosate, and the aryloxyphenoxypropionate (FOPs). Field experiments were conducted in 2018 and 2019 at South Central Agricultural Laboratory near Clay Center, Nebraska with the objective to evaluate ACCase-inhibiting herbicides and herbicide application timing on volunteer corn control, Enlist corn injury, and yield. Glyphosate/glufosinate-resistant corn harvested the year prior was cross-planted at 49,000 seeds ha^{-1} to mimic volunteer corn in Enlist corn. Application timing of FOP herbicides had no effect on Enlist corn injury or yield, and provided 97-99% control of volunteer corn at 28 d after treatment (DAT). Clethodim and sethoxydim and pinoxaden provided 84-98% and 65-71% control of volunteer corn at 28 DAT, respectively;

however, resulting in 62-96% Enlist corn injury and 69-98% yield reduction. While all FOP herbicides evaluated did not cause crop injury or yield loss, quizalofop is the only labeled product as of 2020 for control of volunteer corn in Enlist corn.

Despite widespread adoption of dicamba/glyphosate-resistant soybean by producers in the United States, economic information comparing herbicide programs in glufosinate-resistant and conventional soybean is not available. Field experiments were conducted in 2018 and 2019 at five locations across Nebraska to evaluate weed control, crop safety, gross profit margin, and benefit-cost ratios of herbicide programs with three unique sites of action in multiple herbicide-resistant and conventional soybean. Herbicides applied pre-emergence (PRE) that included provided 85-99% control for all weed species, and 72-96% weed biomass reductions at all locations. Herbicides applied POST provided 93-99% control for all weed species, and 89-98% weed biomass reduction 28 DAT. For individual site-years, yield was similar for many herbicide programs in herbicide-resistant and conventional systems. Gross profit margins and benefit-cost ratios were higher in herbicide-resistant systems than conventional systems, although price premiums for conventional soybean can help compensate increased herbicide costs.

DEDICATION

This thesis is dedicated to Dr. Russell E. Mullen, Dr. Erik J. Christian, and Dennis Miller for helping me discover and ignite my life-long passion for agronomy at Iowa State University.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor Dr. Amit Jhala who has provided me with the utmost support and guidance throughout my degree program. His continued belief in me and my ability as a researcher is something I do not take for granted. I would also like to acknowledge my committee members, Dr. Gary Hein, Dr. Stevan Knezevic, and Dr. Nevin Lawrence for the helpful input and advice they have provided for my research. Additionally, I would like to acknowledge Dr. Kent Eskridge for the significant contributions he provided in the statistical analysis of this research.

I would like to specially thank Dr. Rodrigo Werle and Liberty Butts for igniting my passion for weed science research. The additional assistance from Irvin Schleufer, Jeff Golus, Dr. Jon Scott, Mike Schlick, and Whitney Schultz proved invaluable, and support from Dr. Chris Proctor, Dr. Greg Kruger, and the Pesticide Application Technology (PAT) lab helped make this research feasible. I would like to extend a special thanks to the countless graduate and undergraduate students who assisted along the way including: Adam Leise, Alexandre Rosa, Dr. Bruno Víeira, Débora Latorre, Jacob Krings, Jesaelen Moraes, Jared Stander, Josh Wehrbein, Kaity Wilmes, Kolby Grint, Milos Zaric, Samantha Issacson and Dr. Tommy Butts. Likewise, I would like to recognize the assistance from my fellow lab members Clint Beiermann, Dr. Ethann Barnes, Jasmine Mausbach, Dr. Parminder Chahal, Shawn McDonald and Will Neels.

Finally, I want to thank my close friends Amy Hauver and Mary Happ, my parents Mike and Suzette Striegel, and my siblings Megan and Sarah for their encouragement, overall enthusiasm, and much needed moral support they have provided me throughout this endeavor.

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CHAPTER 1: INTRODUCTION AND OBJECTIVES

Introduction

Corn and Soybean Production. Corn [*Zea mays* L.] is a is a critically important food crop which, combined with rice [*Oryza sativa* L.] and wheat [*Triticum aestivum* L.] produce 30% of the food calories for more than 4.5 billion people around the globe (Shiferaw et al. 2011). With 37.5 million ha planted in 2019, the United States is the world's largest producer of corn USDA-NASS 2019a). Nebraska is the third largest producer of corn in the United States, planting 3.8 to 3.9 million ha each year (USDA-NASS 2017). Corn is used for animal feed or processed into a variety of food products or ethanol, and it was the second highest U.S. agricultural export with a value of $9.1 billion in 2017 USDA-FAS 2017). Predominantly, corn grown in the United States is hybrid corn which boasts superior yields and more vigorous growth in comparison to open-pollinated varieties. In 2018, 95% of the United States' corn hectares were planted with hybrid seed (USDA-ARS 2018). With advancements in transgenic breeding programs, traits conferring resistance or enhanced tolerance to plant-stressors (e.g. drought, insects, plant pathogens) as well as resistance to commonly used herbicides have further augmented the management of important insects, diseases, and weeds.

Soybean [*Glycine max* L.] is a monoecious, annual C3 legume crop that is a globally important oilseed crop with 30.9 million ha planted in 2019 (USDA-NASS 2019b). The United States is the largest producer of soybean in the world (Masuda and Goldsmith 2009). With 2.31 million ha planted in 2017, Nebraska was the fifth largest producer of soybean in the United States (USDA-NASS 2017). Soybean was introduced to the United States in 1765 from eastern Asia (Hymowitz and Shurtleff 2005), and it is grown primarily for livestock feed, human consumption, biofuel production, and industrial products. As in the case with corn, the incorporation of genetic engineered traits into soybean breeding programs has provided resistance to several commonly used herbicides.

Herbicide-Resistant (HR) Crops. With commercialization of glyphosate-resistant corn in 1998 and soybean in 1996, there has been a rapid, widespread adoption of glyphosate-resistant crops across the United States, and in many other countries (Dill et al. 2008). Crops with glyphosate resistant varieties or cultivars include corn, soybean, cotton (*Gossypium hirsutum* L.), canola (*Brassica napus* L.), sugar beets (*Beta vulgaris* L.) and alfalfa (*Medicago sativa* L.).With additional genetic engineering, crops resistant to multiple herbicides have been developed and are popular in many crops, including corn (Green et al. 2008). For example, corn resistant to both glyphosate and glufosinate is popular amongst growers across the Midwestern United States. This trend is similar in soybean, with soybean cultivars resistant to multiple herbicide sites of action (SOAs) such as dicamba/glyphosate is popular amongst growers (Beckie et al. 2019; Werle et al. 2018). Overall, in 2018 HR corn and soybean comprised 90% and 94% of total hectares planted in the United States, with a vast majority of these acres containing glyphosate-resistant traits (USDA-ERS 2018). HR crops have provided great flexibility in weed management; however, overreliance on a single herbicide or herbicide(s) with the same site of action has led to shifts in weed species composition and concerns with HR crops overwintering in the field and acting as a weedy species in the following year (Davis et al. 2008; Heap 2014; Marquardt et al. 2012; Owen 2008).

Dicamba/Glyphosate-Resistant Soybeans. In 2005, researchers at the University of Nebraska-Lincoln discovered genetic tolerance which provided resistance to the popular growth regulator herbicide dicamba (Behrens et al. 2007). In partnership with researchers at Monsanto, this HR trait was integrated into soybean and cotton (Anonymous 2020a). Referred to as Roundup Ready 2 Xtend (RR2X) soybean, it was approved by the United States Environmental Protection Agency (USEPA) in 2016. Soybean cultivars with this HR trait were quickly adopted in Nebraska with 8.7% of producers planting RR2X cultivars in 2017 (Werle et al. 2018). RR2X soybeans have increased substantially with total market share set to exceed 50% by the end of 2019 (Beckie et al. 2019).

Glufosinate-Resistant Crops. Glufosinate and glufosinate-resistant (LibertyLink) traits were divested by Bayer to BASF in the recent Bayer/Monsanto merger. This included the LibertyLink soybean system released in 2009 (Beckie et al. 2019). Adoption of this technology has been estimated at 20% total market share in the United States, adoption in Nebraska has been low with roughly 5.2% of soybeans planted (Werle et al. 2018). Total market share of the LibertyLink system has increased dramatically in the last five years due to a growing need for effective POST management options to control glyphosate-resistant weeds (Beckie et al. 2019). Combinations of the LibertyLink trait with other HR traits (dicamba/glyphosate-resistant, glyphosate/resistant, and glyphosate/isoxaflutole) are now currently commercially available in soybean (Beckie et al. 2019).

2,4-D Choline-Resistant Crops and Enlist™ Corn. With approval from the United States EPA in 2017, Corteva Agriscience commercially released cultivars of soybean and cotton which contained a new HR trait with resistance to 2,4-D choline, glufosinate, and glyphosate in the United States. (Anonymous 2020b). Likewise, Enlist corn was also developed as part of the Enlist weed control system, which confers resistance to 2,4-D choline, glyphosate, and the aryloxyphenoxypropionate (FOP) chemical family (an A carboxylase (ACCase) inhibiting herbicide). Enlist is the first commercialized HR trait to provide resistance to FOP herbicides in corn and is commonly integrated into glufosinate-resistant corn cultivars. Enlist corn provides POST herbicide options to producers with continuous corn-on-corn cropping systems in Nebraska and the Midwest who currently have no selective POST herbicide options to effectively control glyphosate/glufosinate-resistant volunteer corn through the use of FOP chemistries (Chahal et al. 2016; Soltani et al. 2015).

Volunteer Corn. Volunteer corn is a problematic weed species which can act as a competitive weed species in rotated crops (Chahal et al. 2016). Adverse weather conditions preceding or during harvest can increase the prevalence of volunteer corn due to additional harvest losses (Rees and Jhala 2018). Since volunteer corn retains the HR traits of planted hybrid parents, HR volunteer corn require additional herbicides to manage whenever tillage is not an option (Steckel et al. 2009).

Impact of Volunteer Corn on Rotated Crop Yield. Competition with volunteer corn has been experimentally shown to reduce the yields of rotated crops. Kniss et al. (2012) reported volunteer corn densities of 1 to 1.7 plants m^{-2} resulted in sucrose yield reduction of 19% in sugar beets, and Clewis et al. (2008) reported cotton lint yield was reduced by 4 to 8% for each 500 g of volunteer corn biomass per meter of crop row in cotton. In soybeans, Beckett and Stoller (1988) reported a single clump of 5 to 10 plants m^{-2}resulted in a 6% yield reduction. Andersen et al. (1982) reported uncontrolled volunteer corn densities of one clump per 2.4 m of row reduced yield 31%. Research conducted in Nebraska has shown similar results. Volunteer corn densities of 8,750 and 17,500 plants ha^{-1} reduced soybean yields 10 to 27% (Wilson et al. 2010), and densities of 35,000 plants ha^{-1} resulted in an average soybean yield reduction of 87% (Chahal and Jhala 2015).

Management of Volunteer Corn and ACCase-Inhibiting Herbicides. A majority of producers have implemented no-till or reduced tillage cropping systems in Nebraska (Sarangi and Jhala 2019). This has resulted in management of volunteer corn relying heavily on POST herbicides (Chahal and Jhala 2015). Prior to the commercialization of GR crops, glyphosate was commonly used with rope-wick applicator to selectively control volunteer corn in soybean fields (Andersen et al., 1982; Beckett and Stoller, 1988; Dale, 1981). Widespread adoption of glyphosate/glufosinate-resistant corn made this control practice fall out of favor. The use of planned rotations between GR and glufosinate-resistant cultivars proved to be effective in rotated soybean fields. However, the release of stacked glyphosate and glufosinate-resistant corn in 2012 make both herbicides ineffective at controlling volunteer corn (Chahal and Jhala 2015).

With PRE soybean herbicides often only providing partial control of volunteer corn (Chahal and Jhala 2015), the need for selective POST herbicides to control volunteer corn and grass weeds has led to the use of acetyl-coenzyme A carboxylase (ACCase) inhibiting herbicides. Previous research has shown active ingredients in the FOP (diclofop, fluazifop, quizalofop) chemical family and the cyclohexanedione (DIM) (clethodim, sethoxydim) are effective for controlling volunteer corn in soybean (Andersen et al. 1982; Beckett et al. 1992; Beckett and Stoller 1988; Marquardt and

Johnson 2013; Soltani et al. 2006; Young and Hart 1997), and in sethoxydim-resistant corn (Vangessel et al. 1997). The study of herbicide programs for controlling volunteer corn in soybean has been amply explored; however, many aspects about volunteer corn control in corn has not been adequately addressed (Shauck 2011).

Glufosinate. Glufosinate is a non-selective, contact POST herbicide which inhibits glutamine synthase. It results in an increased concentration of cellular ammonium (Wendler et al. 1990) causing necrotic injury symptoms within three to five days (Everman et al. 2009; Steckel et al. 1997) and eventual plant death. Like glyphosate, glufosinate is known as a broad-spectrum herbicide, providing control of 37 grass species and 105 broadleaf weed species when applied at label recommended rates and weed growth stages. Previous research has shown glufosinate applied alone or in tank-mixture is effective for controlling glyphosate-resistant weeds such as waterhemp (Jhala et al. 2017), common and giant ragweed (Barnes et al. 2017; Ganie and Jhala 2017), and Palmer amaranth (Butts et al. 2016). Likewise, glufosinate can also provide effective control of glyphosate-resistant volunteer corn (Chahal and Jhala 2015; Schultz et al. 2015; Shauck and Smeda 2012).

Lactofen & PPO-Inhibitor Herbicides. Lactofen is a protoporphyrinogen oxidase-(PPO) inhibitor herbicide in the diphenylether chemical family. PPO-inhibiting herbicides are commonly used to control weeds in a variety of crops, including soybean (Rangani et al. 2019) due to their broad-spectrum weed control. With limited translocation in plants, PPO-inhibiting herbicides are considered selective, contact herbicides which disrupt plant cell membranes. In soybean, POST applications result in necrotic patches (also referred to as bronzing) on soybean leaves although rarely cause significant yield reductions (Graham 2005; Wichert and Talbert 1993). PPO-inhibiting herbicides can be applied pre-plant (PP), pre-emergent (PRE) as well as POST in many crops. They are the only effective POST chemical control option in conventional and glyphosate-resistant soybean to control glyphosate and acetolactate synthase (ALS)-inhibitor resistant weeds (Gizotti de Moraes 2018).

Adoption of PRE Herbicide Programs in Soybean. Largely in response to manage the six GR weed species reported in Nebraska, 59% of surveyed producers utilize soil-applied residual herbicides in soybean (Sarangi and Jhala 2018). Soil-applied residual herbicides applied at pre-plant (PP) or PRE has increased from 25% to 70% of the total domestic hectares planted in the United States from 2000 to 2015 (Peterson et al. 2018). Integration of pre-emergent (PRE) herbicides use by soybean producers in Nebraska are similar to national trends. Surveyed producers in Nebraska utilizing PRE herbicides in soybean relied primarily on PPO-inhibitors and ALS-inhibitors. Cloransulam plus sulfentrazone and flumioxazin alone, or in tank mixture with chlorimuron and thifensulfuron ranked as the most commonly used (Sarangi and Jhala 2018).

Objectives

1. Evaluate ACCase-inhibiting herbicides for glyphosate/glufosinate-resistant volunteer corn control in Enlist corn.
2. Evaluate effect of ACCase-inhibiting herbicide application timing (early POST versus late POST) on volunteer corn control, Enlist corn injury, and yield.
3. Evaluate pre-emergence (PRE) followed by (fb) post-emergence (POST) herbicide programs with multiple sites of action in dicamba/glyphosate-resistant, glufosinate-resistant, and conventional soybean systems for weed control efficacy, crop safety, gross profit margin, and benefit-cost ratio at five locations across Nebraska.

Literature Cited

Andersen RN, Ford JH, Lueschen WE (1982) Controlling volunteer corn (*Zea mays*) in soybeans (*Glycine max*) with diclofop and glyphosate. Weed Sci 30:132–136

Anonymous (2016) Liberty® Herbicide Label. http://www.cdms.net/ldat/ldUA5013.pdf. Accessed February 28, 2020

Anonymous (2020a) History | Roundup Ready Xtend Crop System. https://www.roundupreadyxtend.com/About/History/Pages/default.aspx. Accessed February 28, 2020

Anonymous (2020b) Welcome to Enlist.com | Enlist^{TM} weed control system. https://www.enlist.com/en.html. Accessed February 28, 2020

Barnes ER, Knezevic SZ, Sikkema PH, Lindquist JL, Jhala AJ (2017) Control of glyphosate-resistant common ragweed (*Ambrosia artemisiifolia* L.) in glufosinate-resistant soybean [*Glycine max* (L.) Merr]. Front Plant Sci 8:1455

Beckett TH, Stoller EW (1988) Volunteer corn (*Zea mays*) interference in soybeans (*Glycine max*). Weed Sci 36:159–166

Beckett TH, Stoller EW, Bode LE (1992) Quizalofop and sethoxydim activity as affected by adjuvants and ammonium fertilizers. Weed Sci 40:12–19

Beckie HJ, Ashworth MB, Flower KC (2019) Herbicide resistance management: recent developments and trends. Plants 8:161

Behrens MR, Mutlu N, Chakraborty S, Dumitru R, Jiang WZ, Lavallee BJ, Herman PL, Clemente TE, Weeks DP (2007) Dicamba resistance: enlarging and preserving biotechnology-based weed management strategies. Science 316:1185–1188

Butts TR, Norsworthy JK, Kruger GR, Sandell LD, Young BG, Steckel LE, Loux MM, Bradley KW, Conley SP, Stoltenberg DE, Arriaga FJ, Davis VM (2016) Management of pigweed (*Amaranthus* spp.) in glufosinate-resistant soybean in the Midwest and Mid-South. Weed Technol 30:355–365

Chahal PS, Jha P, Jackson-Ziems T, Wright R, Jhala AJ (2016) Glyphosate-resistant volunteer maize (*Zea Mays* L.): impact and management. Page *in* IS Travlos, D Bilalis, D Chachalis, eds. Weed and pest control: molecular biology, practices and environmental impact. Hauppauge, New York: Nova Science Publishers

Chahal PS, Jhala AJ (2015) Herbicide programs for control of glyphosate-resistant volunteer corn in glufosinate-resistant soybean. Weed Technol 29:431–443

Clewis S, Thomas W, Everman W, Wilcut J (2008) Glufosinate-resistant corn interference in glufosinate-resistant cotton. Weed Technol 22:211–216

Dale JE (1981) Control of johnsongrass (*Sorghum halepense*) and volunteer corn (*Zea mays*) in soybeans (*Glycine max*). Weed Sci 29:708–711

Davis VM, Marquardt PT, Johnson WG (2008) Volunteer corn in northern Indiana soybean correlates to glyphosate-resistant corn adoption. Crop Manag 7:0

Dill GM, CaJacob CA, Padgette SR (2008) Glyphosate-resistant crops: adoption, use and future considerations. Pest Manag Sci 64:326–331

Everman WJ, Mayhew CR, Burton JD, York AC, Wilcut JW (2009) Absorption, translocation, and metabolism of ^{14}C-glufosinate in glufosinate-resistant corn, goosegrass (*Eleusine indica*), large crabgrass (*Digitaria sanguinalis*), and sicklepod (*Senna obtusifolia*). Weed Sci 57:1–5

Ganie ZA, Jhala AJ (2017) Interaction of 2,4-D or dicamba with glufosinate for control of glyphosate-resistant giant ragweed (*Ambrosia trifida* L.) in glufosinate-resistant maize (*Zea mays* L.). Front Plant Sci 8:1207

Gizotti de Moraes J (2018) Evaluation of glyphosate and PPO-inhibiting herbicide tank-mixtures to manage glyphosate resistance in soybean. M.Sc thesis. Lincoln, NE: University of Nebraska-Lincoln. 93 p

Graham MY (2005) The diphenylether herbicide lactofen induces cell death and expression of defense-related genes in soybean. Plant Physiol 139:1784–1794

Green JM, Hazel CB, Forney DR, Pugh LM (2008) New multiple-herbicide crop resistance and formulation technology to augment the utility of glyphosate. Pest Manag Sci 64:332–339

Heap I (2014) Global perspective of herbicide-resistant weeds. Pest Manag Sci 70:1306–1315

Hymowitz T, Shurtleff WR (2005) Debunking soybean myths and legends in the historical and popular literature. Crop Sci 45:473

Jhala AJ, Sandell LD, Sarangi D, Kruger GR, Knezevic SZ (2017) Control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in glufosinate-resistant soybean. Weed Technol 31:32–45

Kniss AR, Sbatella GM, Wilson RG (2012) Volunteer glyphosate-resistant corn interference and control in glyphosate-resistant sugarbeet. Weed Technol 26:348–355

Marquardt PT, Johnson WG (2013) Influence of clethodim application timing on control of volunteer corn in soybean. Weed Technol 27:645–648

Marquardt PT, Terry R, Krupke CH, Johnson WG (2012) Competitive effects of volunteer corn on hybrid corn growth and yield. Weed Sci 60:537–541

Masuda T, Goldsmith P (2009) World soybean production: area harvested, yield, and long-term projections. Int Food Agribus Man 12

Owen MD (2008) Weed species shifts in glyphosate-resistant crops. Pest Manag Sci 64:377–387

Peterson MA, Collavo A, Ovejero R, Shivrain V, Walsh MJ (2018) The challenge of herbicide resistance around the world: a current summary: Herbicide resistance around the world. Pest Manag Sci 74:2246–2259

Rangani G, Salas-Perez RA, Aponte RA, Knapp M, Craig IR, Mietzner T, Langaro AC, Noguera MM, Porri A, Roma-Burgos N (2019) A novel single-site mutation in the catalytic domain of protoporphyrinogen oxidase IX (PPO) confers resistance to PPO-inhibiting herbicides. Front Plant Sci 10:568

Rees J, Jhala A (2018) Impacts of Volunteer Corn on Crop Yields. CropWatch. https://cropwatch.unl.edu/2018/impacts-volunteer-corn-crop-yields. Accessed January 16, 2020

Sarangi D, Jhala AJ (2018) A statewide survey of stakeholders to assess the problem weeds and weed management practices in Nebraska. Weed Technol 32:642–655

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

Schultz JL, Myers DB, Bradley KW (2015) Influence of soybean seeding rate, row spacing, and herbicide programs on the control of resistant waterhemp in glufosinate-resistant soybean. Weed Technol 29:169–176

Shauck TC (2011) Competition and management of volunteer corn in corn. M.Sc thesis. Columbia, MO: University of Missouri. 106 p

Shauck TC, Smeda RJ (2012) Control of glyphosate-resistant corn (*Zea mays*) with glufosinate or imazethapyr plus imazapyr in a replant situation. Weed Technol 26:417–421

Shiferaw B, Prasanna BM, Hellin J, Bänziger M (2011) Crops that feed the world 6 past successes and future challenges to the role played by maize in global food security. Food Sec 3:307

Soltani N, Shropshire C, Sikkema PH (2006) Control of volunteer glyphosate-tolerant maize (*Zea mays*) in glyphosate-tolerant soybean (*Glycine max*). J. Crop Prot 25:178–181

Soltani N, Shropshire C, Sikkema PH (2015) Control of volunteer corn with the AAD-1 (aryloxyalkanoate dioxygenase-1) transgene in soybean. Weed Technol 29:374–379

Steckel GJ, Hart SE, Wax LM (1997) Absorption and translocation of glufosinate on four weed species. Weed Sci 45:378–381

Steckel LE, Thompson MA, Hayes RM (2009) Herbicide options for controlling glyphosate-tolerant corn in a corn replant situation. Weed Technol 23:243–246

[USDA-FAS] United States Department of Agriculture- Foreign Agricultural Service (2017) Top U.S. Agricultural Exports in 2017. https://www.fas.usda.gov/data/top-us-agricultural-exports-2017. Accessed May 24, 2019

[USDA-ARS] United States Department of Agriculture-Agricultural Research Service (2018) Timeline: Improving Corn. https://www.ars.usda.gov/oc/timeline/corn/. Accessed May 28, 2019

[USDA-ERS] United States Department of Agriculture-Economic Research Service (2018) Recent Trends in GE Adoption. https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us/recent-trends-in-ge-adoption.aspx. Accessed May 23, 2019

[USDA-NASS] United States Department of Agriculture-National Agricultural Statistics Service (2017) 2017 State Agriculture Overview for Nebraska. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NEBRASKA. Accessed November 30, 2018

[USDA-NASS] United States Department of Agriculture-National Agricultural Statistics Service (2019a) National Statistics for Corn- Acres Planted. https://www.nass.usda.gov/Statistics_by_Subject/result.php?008ACF17-46BA-3647-9657-C915182D5D30&sector=CROPS&group=FIELD%20CROPS&comm=CORN. Accessed May 24, 2019

[USDA-NASS] United States Department of Agriculture-National Agricultural Statistics Service (2019b) National Statistics for Soybeans – Acres Planted. https://www.nass.usda.gov/Statistics_by_Subject/result.php?AC6583D7-1E57-

32B6-89EF-37419FD44B15&sector=CROPS&group=FIELD%20CROPS&comm=SOYBEANS. Accessed October 14, 2019

Vangessel MJ, Johnson Q, Isaacs M (1997) Response of sethoxydim-resistant corn (*Zea mays*) hybrids to postemergence graminicides. Weed Technol 11:598–601

Wendler C, Barniske M, Wild A (1990) Effect of phosphinothricin (glufosinate) on photosynthesis and photorespiration of C3 and C4 plants. Photosynth Res 24:55–61

Werle R, Oliveira MC, Jhala AJ, Proctor CA, Rees J, Klein R (2018) Survey of Nebraska farmers' adoption of dicamba-resistant soybean technology and dicamba off-target movement. Weed Technol 32:754–761

Wichert RA, Talbert RE (1993) Soybean [*Glycine max* (L.)] response to lactofen. Weed Sci 41:23–27

Wilson R, Sandell L, Robert K, Mark B (2010) Volunteer corn control. Pages 212–215 *in* Proceedings of the 2010 Crop Production Clinic. Lincoln, NE: University of Nebraska-Lincoln Extension

Young BG, Hart SE (1997) Control of volunteer sethoxydim-resistant corn (*Zea mays*) in soybean (*Glycine max*). Weed Technol 11:649–655

CHAPTER 2:

CONTROL OF GLYPHOSATE/GLUFOSINATE-RESISTANT VOLUNTEER CORN IN CORN RESISTANT TO ARYLOXYPHENOXYPROPIONATES

Striegel AM, Lawrence, NC, Knezevic SZ, Krumm JT, Hein GL, Jhala AJ (2020) Control of Glyphosate/Glufosinate-Resistant Volunteer Corn in Corn Resistant to Aryloxyphenoxypropionates. Weed Technol (*Accepted*)

Abstract

Corn-on-corn production systems are common in highly productive irrigated fields in southcentral Nebraska which can create issues with volunteer corn management in corn fields. Enlist corn is a new multiple herbicide-resistant trait providing resistance to 2,4-D choline, glyphosate, and the aryloxyphenoxypropionate (FOPs) which is commonly integrated in glufosinate-resistant germplasm. The objectives of this study were to (1) evaluate ACCase-inhibiting herbicides for glyphosate/glufosinate-resistant volunteer corn control in Enlist corn and (2) evaluate effect of ACCase-inhibiting herbicide application timing (early POST versus late POST) on volunteer corn control, Enlist corn injury, and yield. Field experiments were conducted in 2018 and 2019 at South Central Agricultural Laboratory near Clay Center, Nebraska. Glyphosate/glufosinate-resistant corn harvested the year prior was cross-planted at 49,000 seeds ha^{-1} to mimic volunteer corn in this study. Seven to ten days later, Enlist corn was planted at 91,000 seeds ha^{-1}. Application timing of aryloxyphenoxypropionates (fluazifop, quizalofop, and fluazifop/fenoxaprop) had no effect on Enlist corn injury or yield, and provided 97 to 99% control of glyphosate/glufosinate-resistant volunteer corn at 28 d after treatment (DAT). Cyclohexanediones (clethodim and sethoxydim) and phenylpyrazolin (pinoxaden) provided 84 to 98% and 65 to 71% control of volunteer corn at 28 DAT, respectively; however, resulting in 62 to 96% Enlist corn injury and 69 to 98% yield reduction. Orthogonal contrasts comparing early POST (30 cm tall volunteer corn) and late-POST (50 cm tall volunteer corn) applications of aryloxyphenoxypropionates (fluazifop, quizalofop, and fluazifop/fenoxaprop) were not significant for volunteer corn control, Enlist corn injury and yield. Fluazifop, quizalofop, and fluazifop/fenoxaprop resulted in 94 to 99% control of glyphosate/glufosinate-resistant volunteer corn with no associated Enlist corn injury or yield loss; however, quizalofop is the only labeled product as of 2020 for control of volunteer corn in Enlist corn.

Introduction

With commercialization of glyphosate-resistant (GR) corn in 1998 and soybean (*Glycine max* (L.) Merr.) in 1996, there has been a widespread adoption of GR crops across the United States, and in many other countries (Dill et al. 2008). Further advancements in genetic engineering has led to the commercialization of crops with multiple herbicide-resistant (HR) traits, such as glufosinate and glyphosate resistant corn (Green et al. 2008) and soybean (Beckie et al. 2019). In 2018, HR corn and soybean comprised 90 and 94% of total corn and soybean production in the United States, respectively (USDA-ERS 2018). Herbicide-resistant crops have provide flexibility in weed management to producers; however, overreliance on a single herbicide or herbicide(s) with the same site of action have led to shifts in weed species composition (Owen 2008) and the evolution of HR weed biotypes (Heap 2014, 2020; Johnson et al. 2009).

With widespread adoption of GR corn in the United States, correlative increases in the presence of GR volunteer corn in rotated crops have been identified (Davis et al. 2008), creating management concerns (Marquardt et al. 2012a) as well as new challenges for insect-resistance management (Krupke et al. 2009). Derived from dropped ears or kernels and lodged plants in the field, volunteer corn overwinters in the field and emerge the following year (Chahal and Jhala 2015). While grain loss due to mechanized harvest can be reduced to below 5% (Shauck 2011; Shay et al. 1993), adverse weather conditions (wind storms) prior to harvest can increase plant lodging and dropped corn ears resulting in additional harvest loss, and management problems with volunteer corn the following year (Rees and Jhala 2018). Managing volunteer corn requires additional selective herbicides when tillage is not an option due to the retention of the HR traits from the initially planted hybrid parent (Steckel et al. 2009). Acting as a very competitive weed, volunteer corn depending on density can cause yield reductions in rotated crops. Kniss et al. (2012) reported volunteer corn densities of 1 to 1.7 plants m^{-2} reduced sugar beet (*Beta vulgaris* L.) sucrose yield by 19%. Likewise, Clewis et al. (2008) reported cotton (*Gossypium hirsutum* L.) lint yield was reduced by 4 to 8% for each 500 g of volunteer corn biomass per meter of crop row. In soybean, Beckett and Stoller (1988) reported a single clump of 5 to 10 plants m^{-2} resulted in a 6% yield reduction. Similarly, Andersen et al. (1982) reported uncontrolled volunteer corn densities of one clump per 2.4 m of row resulted in 31% soybean yield reduction. Research conducted in Nebraska has shown similar results with volunteer corn densities of 8,750, 17,500 and 35,000 plants ha^{-1} reduced soybean yields by 10, 27, and 97%, respectively (Chahal and Jhala 2016; Wilson et al. 2010).

In addition to research focused on the effects of volunteer corn in rotated agronomic crops, studies examining yield effects of volunteer corn on hybrid corn and the control of failed hybrid corn stands in replant situations have also been conducted. For example, Shauck and Smeda (2014) reported 0.5 to 8 hybrid corn plants m^{-2} resulted in 7 to 81% corn yield reductions under a replant situation. Likewise, Steckel et al. (2009) reported 27,000 hybrid corn plants ha^{-1} reduced corn yield by 1,000 kg ha^{-1}, with a yield loss threshold of two plants m^{-2}. In a multi-state study examining corn yield reduction from low densities of volunteer corn, 1,250, 2,500, and 5,000 plants ha^{-1} resulted in 0.4, 0.7 and 1.5% yield loss, respectively (Jeschke and Doerge 2008). Yield effects of high volunteer corn densities were studied by Alms (2015) and Marquardt et al. (2012b) and reported 8 and 9 volunteer corn plants m^{-2} resulted in 0-41% and 22 to 23% corn yield reductions, respectively.

Nebraska is the third largest corn producing state in the United States (Nebraska Corn Board 2017) with approximately 3.8 to 3.9 million ha of corn planted each year compared to 2.3 million ha of soybean (USDA-NASS 2017). This discrepancy indicates many producers are rotating corn into a non-soybean crop or more commonly, utilizing a corn-on-corn production system. In southcentral Nebraska especially, highly productive soils and easy access to irrigation have promoted adoption of corn-on-corn cropping systems. With a majority of Nebraska producers implementing no-till or reduced tillage cropping systems (Sarangi and Jhala 2019), management of volunteer corn has relied on POST herbicides in soybean production (Chahal and Jhala 2015). Prior to the commercialization of GR crops, glyphosate was commonly used with rope-wick applicator to selectively control volunteer corn in soybean fields (Andersen et al. 1982;

Beckett and Stoller 1988; Dale 1981); however, widespread adoption of GR corn has made this control practice ineffective. With commercialization of stacked glyphosate and glufosinate-resistant corn in 2012, planned rotations between GR and glufosinate-resistant hybrids have also become challenging for producers to implement successfully due to the prevalence of stacked glyphosate and glufosinate-resistance traits in many elite hybrids. With widespread adoption in the United States, glyphosate/glufosinate-resistant hybrids make both glyphosate and glufosinate ineffective for controlling volunteer corn in the following year (Chahal and Jhala 2015).

In rotated field, the need for selective POST herbicides to control volunteer corn and grass weed species has led to the use of acetyl-coenzyme A carboxylase (ACCase) inhibiting herbicides. Comprised of the aryloxyphenoxypropionate (FOPs), cyclohexanedione (DIMs) and phenylpyrazolin chemical families, previous research has indicated diclofop, clethodim, fluazifop, quizalofop, and sethoxydim are effective for controlling volunteer corn in soybean (Andersen et al. 1982; Beckett et al. 1992; Beckett and Stoller 1988; Marquardt and Johnson 2013; Soltani et al. 2006; Young and Hart 1997), and in sethoxydim-resistant corn (Vangessel et al. 1997). However, studies examining control of glyphosate/glufosinate-resistant volunteer corn in corn has not been previously addressed due to lack of selective herbicides (Shauck 2011).

Enlist is a new multiple HR corn trait developed by Corteva Agriscience inferring resistance to 2,4-D choline, glyphosate, and FOP herbicides. Commonly integrated in glufosinate-resistant germplasm, Enlist is the first commercialized HR trait provided resistance to FOPs herbicides in corn, and provides an opportunity for selective in-season management of glyphosate/glufosinate-resistant volunteer corn through the use of FOP herbicides. Before recommending this technology to growers, Enlist corn needs to be assessed for volunteer corn control and Enlist corn safety. The objectives of this project were (1) to evaluate ACCase-inhibiting herbicides for glyphosate/glufosinate-resistant volunteer corn control in Enlist corn and (2) to evaluate effect of timing of applying ACCase-inhibiting herbicides (early POST versus late POST) on volunteer corn control, Enlist corn injury, and yield.

Materials and Methods

Site Description. Field experiments were conducted at the South Central Agricultural Laboratory (SCAL), University of Nebraska–Lincoln, near Clay Center, NE. Fields were irrigated by center pivot and followed a corn-soybean crop rotation with soybean preceding the field experiment in both years. The soil texture at the research site consisted of a Hastings silt loam (montmorillonitic, mesic, Pachic Argiustolls) with a pH of 6.5, 17% sand, 58% silt, and 25% clay and 3.0% organic matter.

Treatments were arranged in a randomized complete block design with four replications. Plot size was 3 m wide (four corn rows spaced 0.75 m wide) by 9 m in length. Herbicide treatments comprised of six ACCase inhibitors (fluazifop, quizalofop, fluazifop/fenoxaprop, clethodim, sethoxydim, and pinoxaden) applied at two application timings based on the height of volunteer corn. For comparison, a No-POST herbicide control and weed-free control treatment were included. Due to recent commercialization of Enlist corn, supplementary labels for ACCase-inhibiting herbicides were not available; thus, application rates were selected based on labeled rates for control of volunteer corn in soybean and included all label-recommended adjuvants, excluding pinoxaden which was applied at labeled rates for grass weed control in wheat (*Triticum aestivum* L.) (Table 2-1). Labeled rates for volunteer corn control in soybean were selected for all other treatments due to the prevalence of corn/soybean cropping rotations in the Midwest, and local use of many of these herbicides in soybean production fields.

Treatments were applied with a CO_2-pressurized backpack sprayer consisting of a five-nozzle boom fitted with AIXR 110015 flat-fan nozzles (TeeJet Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60189) calibrated to deliver 140 L ha^{-1} at 276 kPa. Early-POST (EPOST) herbicides were applied on June 12, 2018 and June 13, 2019 when volunteer corn was 30 cm (V5) and 28 cm (V5) in height, respectively with Enlist corn at 36 cm (V7). Late-POST (LPOST) herbicides were applied June 18, 2018 and June 24, 2019 when volunteer corn was 50 cm (V7) in height with Enlist corn at 70 and 73 cm (V8), respectively.

To simulate uniform infestations of volunteer corn, glyphosate/glufosinate-resistant corn harvested from the field (F2 populations) in 2017 (Pioneer P1197 AM) and 2018 (Channel 210-26 STX) were planted in no-tillage conditions at a population of 49,000 seeds ha^{-1} at a depth of 4.5 cm on April 26, 2018 and April 23, 2019 across the entire plot for a total of twelve rows per plot spaced 0.75 m apart. Enlist corn hybrids were planted perpendicular to the volunteer corn rows at a density of 91,000 seeds ha^{-1} in rows spaced 0.75 m apart at a depth of 4.5 cm on May 7, 2018 and May 1, 2019, respectively. Enlist corn hybrid Mycogen MY10V09 was used in 2018, but due to end-of-season stalk strength concerns, was replaced with Enlist corn hybrid Mycogen MY11V17 in 2019.

To control broadleaf and grass weed species without effecting cross-planted volunteer corn in all experimental plots, a pre-mix of *S*-metolachlor, atrazine, mesotrione, bicyclopyrone (Acuron, Syngenta Crop Protection, LLC, Greensboro, North Carolina 27419) was applied PRE at 2,410 g ai ha^{-1} to the entire experimental area on May 10, 2018 and May 3, 2019. A general maintenance application of glyphosate (Roundup PowerMAX, Monsanto Company, 800 North Lindberg Ave., St. Louis, MO) at 1.50 kg ae ha^{-1} was applied on June 20, 2018 to whole experimental area excluding the No-POST herbicide control plots to provide POST control of all other broadleaf and grass weeds. Due to the presence of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) at the experimental location in 2019, general maintenance application of glyphosate was replaced with glufosinate (Liberty 280 SL, Bayer Crop Science, 2 T.W. Alexander Drive, Research Triangle Park, NC, 27709) at 0.90 kg ai ha^{-1} plus acetochlor (Warrant, Monsanto Company, 800 North Lindberg Ave., St. Louis, MO) at 1.26 kg ai ha^{-1} which were applied on June 17, 2019 to the experimental area excluding the No-POST herbicide control plots.

Data Collection. Crop and volunteer corn stands were assessed at 28 days after PRE (DAPRE) herbicide applications by counting the number of crop and volunteer corn plants in a 1 m^2 quadrat placed across the middle two Enlist corn rows. Visual estimates of volunteer corn control were recorded at 14 and 28 d after early POST (DAEPOST) and late POST (DALPOST) herbicide applications based on 0-100% scale, where 0% equals no control and 100% equals volunteer corn plant death. A similar scale was also utilized to assess crop injury at 14 and 28 DAEPOST/LPOST. At 21 DAEPOST/LPOST, a 1 m^2 quadrat was placed over the middle two rows in each plot and volunteer corn density and total volunteer corn biomass (living and dead) were collected. Within each quadrat, a representative sample of total crop biomass (living and dead) were collected from 0.5 m from either the left or right row. Collected aboveground biomass was oven dried at 70 C for 10 d and dry weight was recorded. Corn was harvested from the center two rows in each plot at maturity using a small-plot combine with grain weight and moisture content recorded and adjusted to 15.5%. Percent biomass reduction and percent yield loss were calculated using the equation (Wortman 2014):

$$Y = [(C\text{-}B)/C] \times 100$$

where C represents the volunteer corn biomass from the No-POST herbicide plots or yield from the weed-free control, or crop biomass from weed-free control and B represents the volunteer corn biomass or crop biomass, or grain yield from the treated plots.

Statistical Analysis. Data were subjected to ANOVA using R 3.6.1, utilizing the base packages in the Stats Package “stats” version 3.6.1 (R Core Team 2018), the Statistical Procedures for Agricultural Research Package “agricolae” version 1.3-1 (Mendiburu 2019), and Various R Programming Tools for Model Fitting Package “gmodels” version 2.18.1 (Warnes et al. 2018). One-way ANOVA was performed using the *aov* function with treatment and year as fixed effect. Replication nested within years were considered as random effect in the model. If year-by-treatment interactions were significant, data were analyzed separately among years.

ANOVA assumptions of normality was tested using Shapiro-Wilk tests with the *shapiro.test* function, and homogeneity of variance was tested using Bartlett, Fligner-Killen, and Levene’s tests (Wang et al. 2017) with the *bartlett.test*, *fligner.test* (Kniss and

Streibig 2018) and *leveneTest* functions, respectively. Square root and logit transformation of data did not improve normality; therefore, data which failed ANOVA assumptions of normality and homogeneity of variance (crop and volunteer corn biomass reductions, ratings for volunteer corn control, crop injury) were subjected to non-parametric Kruskal-Wallis tests (McDonald 2014; Ostertagová et al. 2014) using the *kruskal* function. Treatment means were separated at $P \leq 0.05$ using Fisher's protected LSD tests with the *LSD.test* function and the *kruskal* function with Bejamini-Hochberg and Bonferroni *P*-value adjustments respectively to correct for multiple comparisons (Mendiburu 2019). Following treatment means separation, *a priori* orthogonal contrasts were performed with the *fit.contrast* function (Warnes et al. 2018).

Results and Discussion

Average daily temperature in 2018 (14.5ºC) was lower than the 30-yr average (19.0ºC) for the experiment location, but similar in 2019 (Figure 2-1). Cumulative precipitation received in both years exceeded the 30-yr average, with 714 mm in 2018 and 756 mm in 2019 from May to November (Figure 2-1). Year-by-treatment interactions were not significant for most experimental variables excluding crop yield, yield reduction and 28 DAPOST crop injury; therefore, data from 2018 and 2019 were separated on a per variable basis. Data from pinoxaden applied EPOST in 2019 were removed from analysis of the current study due to the mistaken substitution of pinoxaden with an unknown FOP herbicide.

Crop and Volunteer Corn Stand. Enlist corn and volunteer corn stands did not differ from 2018 or 2019 at 28 DAPRE, nor across treatments ($P = 0.83$, $P = 0.70$) with overall study means of 79,000 Enlist corn plants ha^{-1}, and 41,000 volunteer corn plants ha^{-1} (Table 2-2).

Volunteer Corn Control. ACCase-inhibiting herbicides evaluated in this study provided 94 to 99% control of volunteer corn at 14 DAEPOST and LPOST, except for pinoxaden applied LPOST (85%) (Table 2-2). Similarly, at 28 DAEPOST and LPOST, fluazifop, quizalofop, and fluazifop/fenoxaprop provided 97 to 99% control of volunteer corn whereas clethodim and sethoxydim, provided 90 and 84% control 28 DAEPOST and 98 and 94% control at 28 DALPOST, respectively. Pinoxaden provided 65% control of volunteer corn 28 DAEPOST in 2018, and 71% control 28 DALPOST in 2018 and 2019 (Table 2-2). Application timing was significant for clethodim and sethoxydim with 87% and 97% control of volunteer corn at 28 DAEPOST and LPOST, respectively. Previous studies have demonstrated ACCase-inhibiting herbicides provide effective control of volunteer corn. In a two-year study in Nebraska, Chahal and Jhala (2015) reported 76 to 93% volunteer corn control at 15 d after application of ACCase-inhibiting herbicides in soybean. Similarly, Underwood et al. (2016) reported quizalofop and clethodim provided 95% control of glyphosate-resistant volunteer corn at 4 weeks after application in dicamba-resistant soybean. While application time was significant ($P < 0.001$) for DIM herbicides in this study at 28 DAPOST, overall efficacy of clethodim was comparable to a two-year, two-location study conducted in Indiana in which early (30 cm) and late (90 cm) applications of clethodim provided 95-99% control of volunteer corn at 28 d after application in soybean (Marquardt and Johnson 2013).

Prior to harvest near the end of the growing season, fluazifop, quizalofop, and fluazifop/fenoxaprop provided 94 to 99% control of volunteer corn in both years regardless of volunteer corn height at the time of application. Orthogonal contrasts comparing volunteer corn control by application time in clethodim and sethoxydim were significant ($P < 0.001$), with 89% and 96% control of volunteer corn for EPOST and LPOST applications, respectively. Reduced volunteer corn control for EPOST (28-30 cm, V5) applications of clethodim and sethoxydim was primarily due to the production of axillary tillers by volunteer corn in response to herbicide applications which persisted throughout the growing season (Figure 2-3). This physiological response was not observed in plots which received FOPs, but was also present in a lesser extent for EPOST application of pinoxaden.

At the end of the season, pinoxaden provided 60 and 85% control of volunteer corn for EPOST and LPOST applications, respectively, with volunteer corn and Enlist corn growing out of the injury symptoms and persisting to the end of the growing season. This could be attributed to the rate of pinoxaden applied in the current study (44 and 60 g ai ha^{-1}), but is unsurprising as pinoxaden is labeled in wheat and barley (*Hordeum vulgare* L.) for POST control of grass weeds and has not previously been studied for volunteer corn control as it is not labeled for volunteer corn control (Anonymous 2014).

Volunteer Corn Biomass Reduction. Compared to the no-POST herbicide control at EPOST (129 g m^2) and LPOST (211 g m^2), ACCase-inhibiting herbicides evaluated in this study provided 43 to 74% reduction of volunteer corn biomass except pinoxaden (25%) at 21 DALPOST. EPOST applications resulted in high biomass reductions compared to LPOST applications (Table 2-2). In contrast, Soltani et al. (2006) reported 89 to 99% GR volunteer corn biomass reduction at 70 d after application of clethodim, fluazifop, and quizalofop in GR soybean. Similarly, Underwood et al. (2016) reported 90 to 99% volunteer corn biomass reduction at 42 d after application of quizalofop and clethodim. The relatively lower biomass reduction observed in the current study could be due to the timing of volunteer biomass collection at 21 d after applying ACCase inhibiting herbicides compared with more than 40 d after application in previous studies (Chahal and Jhala 2015; Soltani et al. 2006; Underwood et al. 2016).

Crop Biomass Reduction. Reduction in Enlist corn biomass was not different from the weed free control at EPOST (316 g m^{-2}) or LPOST (407 g m^{-2}) applications of fluazifop, quizalofop, and fluazifop/fenoxaprop. In contrast, clethodim and sethoxydim reduced crop biomass by 64 to 69% regardless of application time while pinoxaden resulted in 28 and 37% crop biomass reduction at 21 DAEPOST and LPOST, respectively. A 17% reduction to Enlist corn biomass in the No-POST herbicide control was also observed. Results from the current study are similar to reductions in Enlist corn biomass by clethodim and sethoxydim reported by Soltani et al. (2015) with 97 and 99% reduction for sethoxydim and clethodim at 42 DAT, respectively. Likewise, crop biomass reduction in the no-POST herbicide control is consistent with the findings of Marquardt et al. (2012b) in which volunteer corn competition reduced hybrid corn leaf area and biomass.

Crop Injury. Enlist corn injury was not observed for fluazifop, quizalofop, or fluazifop/fenoxaprop applied EPOST or LPOST at any observation time (Table 2-3). In contrast, high levels of crop injury were observed with clethodim and sethoxydim (Figure 2-3) with 66 to 88% injury at 28 DAEPOST, and 88 to 89% injury at 28 DALPOST in 2018 and 2019 (Table 2-3). Similarly, pinoxaden resulted in 25% and 59 to 61% crop injury at 28 DAEPOST and LPOST, respectively. Clethodim and sethoxydim have been previously shown to injure Enlist corn by Soltani et al. (2015) reporting 92 to 97% and 84 to 96% control of volunteer Enlist corn in soybean, respectively. The same study also demonstrated volunteer Enlist corn tolerance of fluazifop, fenoxaprop, and quizalofop. Prior to harvest, clethodim and sethoxydim applied LPOST resulted in higher crop injury (97%) compared to EPOST applications (77%) (Table 2-3). Lower crop injury ratings of EPOST applications of clethodim and sethoxydim were due in part to axillary tillers produced by the Enlist corn which was 36 cm tall (V7) at the time of application. Enlist corn tillers persisted through the growing season and produced harvestable grain (Table 2-4).

Crop Yield. Due to wind and hail storms in 2019, end of season crop stand was reduced compared to 2018; therefore, Enlist corn yield was analyzed separately by year. Plots receiving EPOST and LPOST applications of fluazifop, quizalofop, and fluazifop/fenoxaprop resulted in comparable Enlist corn yield to the weed free control in 2018 (13,601 kg ha^{-1}) and in 2019 (8,150 kg ha^{-1}). Likewise, percent yield reduction calculated in comparison of the weed free control ranged from 0 to 7% without statistical difference among FOPs (Table 2-4). In contrast, clethodim and sethoxydim with EPOST applications resulted in 57-88% and LPOST applications resulted in 93-98% Enlist corn yield reduction in both years (Table 2-4). Pinoxaden yield loss varied from 21 to 69% in 2018 for EPOST and LPOST application, respectively, with comparable yield losses to clethodim and sethoxydim in 2019 (86%) for LPOST application. Absence of Enlist corn yield reductions from FOP chemistries and subsequent Enlist corn yield reductions from DIM and DEN chemistries presented in this study are comparable to results reported by Soltani et al. (2015). Despite volunteer corn densities of 41,000 plants ha^{-1} in 2018 and 2019, no significant reduction in crop yield was observed in the no-POST herbicide control compared with the weed free control (Table 2-4). In both years, the entire experimental area including no-POST herbicide control received a premix of atrazine, bicyclopyrone, mesotrione, *S*-metolachlor applied PRE at labeled rate which provided excellent early season weed control. As such, no-POST herbicide control plots were essentially weed free for most of the growing season, excluding competition from cross-planted volunteer corn. Lack of Enlist corn yield loss from volunteer corn competition in the current study are consistent with Marquardt et al. (2012b) in which 22 to 23% hybrid corn yield loss associated with spike-planted volunteer corn at 8 plants m^{-2} were removed when volunteer corn grain was included with hybrid corn grain yield. Likewise, in a two-year study conducted in South Dakota by Alms (2015), season-long competition from scattered volunteer corn kernels incorporated by cultipacker at densities ranging from 0.2 to 8.5 plants m^{-2} resulted in hybrid corn yield losses ranging from 0-41% when volunteer corn was hand-removed prior to harvest. Further analysis of hand-harvested volunteer corn grain from the study indicate even at low densities volunteer corn can contribute to grain production, with 5,700 kg ha^{-1} at 1.6 plants m^{-2} and 4,800 kg ha^{-1} at 3.4 plants m^{-2} (Alms 2015). All referenced studies examining the competitive effects of volunteer corn on hybrid corn established volunteer corn populations via planting individual corn kernels, which were similar to the cross-planting method used in the current study and by Chahal and Jhala (2015) in glufosinate-resistant soybean. While literature indicates yield loss associated with volunteer corn competition in hybrid corn can be compensated by the grain produced by volunteer corn, the unpredictable nature of volunteer corn distribution (dropped ears vs. loose kernels), density and location within the field and crop rows warrants additional study.

Practical Implications. Control of glyphosate/glufosinate-resistant volunteer corn has been achieved primarily through the use of ACCase-inhibiting herbicides applied POST in soybean, but no selective herbicide providing effective control of glyphosate/glufosinate-resistant volunteer corn in non-Enlist corn is available. Integration of aryloxyphenoxypropionate-resistant Enlist corn into corn-on-corn production systems will enable control of glyphosate/glufosinate-resistant volunteer corn in a corn-on-corn production system. Results of this study indicate fluazifop, quizalofop, and fluazifop/fenoxaprop provided 94 to 99% control of glyphosate/glufosinate-resistant volunteer corn with no associated Enlist corn injury or yield loss. Although Enlist corn is resistant to all FOP herbicides, quizalofop is the only product currently labeled for control of volunteer corn in Enlist corn; therefore, other FOPs cannot be applied. Results also indicate sensitivity of Enlist corn to cyclohexanediones (clethodim and sethoxydim) and phenylpyrazolin (pinoxaden); therefore, they cannot be applied. It must be noted FOP herbicides will not be effective for control of volunteer Enlist corn because Enlist corn is resistant to FOPs; therefore, rotation of Enlist corn with soybean or other broadleaf crops where DIMs are labeled is required (Soltani et al. 2015). If corn is planted the year following Enlist corn, no selective herbicide is available to control volunteer Enlist corn in corn.

Literature Cited

Alms J (2015) Volunteer glyphosate-resistant corn and soybean competition and control. M.Sc thesis. Brookings, SD: South Dakota State University. 85 p

Andersen RN, Ford JH, Lueschen WE (1982) Controlling volunteer corn (*Zea mays*) in soybeans (*Glycine max*) with diclofop and glyphosate. Weed Sci 30:132–136

Anonymous (2014) Axial XL - Herbicide Product & Label Information | Syngenta US. http://www.syngenta-us.com/herbicides/axial-xl. Accessed January 16, 2020

Beckett TH, Stoller EW (1988) Volunteer corn (*Zea mays*) interference in soybeans (*Glycine max*). Weed Sci 36:159–166

Beckett TH, Stoller EW, Bode LE (1992) Quizalofop and sethoxydim activity as affected by adjuvants and ammonium fertilizers. Weed Sci 40:12–19

Beckie HJ, Ashworth MB, Flower KC (2019) Herbicide resistance management: recent developments and trends. Plants 8:161

Chahal P, Jhala AJ (2016) Effect of glyphosate-resistant volunteer corn density, control timing, and late season emergence on soybean yield. Crop Prot 81:38–42

Chahal PS, Jhala AJ (2015) Herbicide programs for control of glyphosate-resistant volunteer corn in glufosinate-resistant soybean. Weed Technol 29:431–443

Clewis S, Thomas W, Everman W, Wilcut J (2008) Glufosinate-resistant corn interference in glufosinate-resistant cotton. Weed Technol 22:211–216

Dale JE (1981) Control of johnsongrass (*Sorghum halepense*) and volunteer corn (*Zea mays*) in soybeans (*Glycine max*). Weed Sci 29:708–711

Davis VM, Marquardt PT, Johnson WG (2008) Volunteer corn in northern Indiana soybean correlates to glyphosate-resistant corn adoption. Crop Manag 7:0

Dill GM, CaJacob CA, Padgette SR (2008) Glyphosate-resistant crops: adoption, use and future considerations. Pest Manag Sci 64:326–331

Green JM, Hazel CB, Forney DR, Pugh LM (2008) New multiple-herbicide crop resistance and formulation technology to augment the utility of glyphosate. Pest Manag Sci 64:332–339

Heap I (2014) Global perspective of herbicide-resistant weeds. Pest Manag Sci 70:1306–1315

Heap I (2020) The International Survey of Herbicide Resistant Weeds. Weeds Resistant to EPSP Synthase Inhibitors. http://www.weedscience.org/Summary/MOA.aspx?MOAID=12. Accessed February 21, 2020

Jeschke M, Doerge T (2008) Managing volunteer corn in corn fields. Pioneer Agronomy Sciences 18:1–4

Johnson WG, Davis VM, Kruger GR, Weller SC (2009) Influence of glyphosate-resistant cropping systems on weed species shifts and glyphosate-resistant weed populations. Eur J Agron 31:162–172

Kniss AR, Sbatella GM, Wilson RG (2012) Volunteer glyphosate-resistant corn interference and control in glyphosate-resistant sugarbeet. Weed Technol 26:348–355

Kniss AR, Streibig JC (2018) Statistical Analysis of Agricultural Experiments using R. https://rstats4ag.org/. Accessed September 23, 2019

Krupke C, Marquardt P, Johnson W, Weller S, Conley SP (2009) Volunteer corn presents new challenges for insect resistance management. Agron J 101:797–799

Marquardt P, Krupke C, Johnson WG (2012a) Competition of transgenic volunteer corn with soybean and the effect on western corn rootworm emergence. Weed Sci 60:193–198

Marquardt PT, Johnson WG (2013) Influence of clethodim application timing on control of volunteer corn in soybean. Weed Technol 27:645–648

Marquardt PT, Terry R, Krupke CH, Johnson WG (2012b) Competitive effects of volunteer corn on hybrid corn growth and yield. Weed Sci 60:537–541

McDonald JH (2014) Handbook of Biological Statistics. 3rd ed. Baltimore, Maryland: Sparky House Publishing. 291 p

Mendiburu F de (2019) agricolae: Statistical Procedures for Agricultural Research. https://CRAN.R-project.org/package=agricolae

McGinnis SE (2016) Equivalency of near infrared transmission instruments for grain analyzers. M.Sc thesis. Ames, IA: Iowa State University. 32 p

Nebraska Corn Board (2017) Corn 101 | Nebraska Corn Board. https://nebraskacorn.gov/corn-101/. Accessed October 8, 2019

Ostertagová E, Ostertag O, Kováč J (2014) Methodology and application of the kruskal-wallis test. Appl Mech Mater 611:115–120

Owen MD (2008) Weed species shifts in glyphosate-resistant crops. Pest Manag Sci 64:377–387

R Core Team (2018) R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. http://www.R-project.org/.

Rees J, Jhala A (2018) Impacts of volunteer corn on crop yields. CropWatch. https://cropwatch.unl.edu/2018/impacts-volunteer-corn-crop-yields. Accessed January 16, 2020

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

Shauck T, Smeda R (2014) Competitive effects of hybrid corn on replanted corn. Weed Technol 28:685–693

Shauck TC (2011) Competition and management of volunteer corn in corn. M.Sc thesis. Columbia, MO: University of Missouri. 106 p

Shay CW, Ellis L, Hires W (1993) Measuring and reducing soybean harvesting losses. University of Missouri Extension Agricultural Publication G01280. p1-4 http://extension.missouri.edu/p/G1280. Accessed March 18, 2020

Soltani N, Shropshire C, Sikkema P (2015) Control of volunteer corn with the AAD-1 (aryloxyalkanoate dioxygenase-1) transgene in soybean. Weed Technol 29:374–379

Soltani N, Shropshire C, Sikkema PH (2006) Control of volunteer glyphosate-tolerant maize (*Zea mays*) in glyphosate-tolerant soybean (*Glycine max*). Crop Prot 25:178–181

Steckel LE, Thompson MA, Hayes RM (2009) Herbicide options for controlling glyphosate-tolerant corn in a corn replant situation. Weed Technol 23:243–246

Underwood MG, Soltani N, Hooker DC, Robinson DE, Vink JP, Swanton CJ, Sikkema PH (2016) The addition of dicamba to POST applications of quizalofop-p-ethyl or clethodim antagonizes volunteer glyphosate-Resistant corn control in dicamba-resistant soybean. Weed Technol 30:639–647

[USDA-ERS] United States Department of Agriculture-Economic Research Service (2018) Recent Trends in GE Adoption. https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us/recent-trends-in-ge-adoption.aspx. Accessed May 23, 2019

[USDA-NASS] United States Department of Agriculture-National Agricultural Statistics Service (2017) 2017 State Agriculture Overview for Nebraska. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NEBRASKA. Accessed November 30, 2018

U.S. Grains Council (2019) 2019/2020 Corn Harvest Quality Report. Page 84. Washington, DC, USA: U.S. Grain Council https://grains.org/wp-content/uploads/2019/12/USGC-Corn-Harvest-Quality-Report-2019-2020.pdf

Vangessel MJ, Johnson Q, Isaacs M (1997) Response of sethoxydim-resistant corn (*Zea mays*) hybrids to postemergence graminicides. Weed Technol 11:598–601

Wang Y, Rodríguez de Gil P, Chen Y-H, Kromrey JD, Kim ES, Pham T, Nguyen D, Romano JL (2017) Comparing the performance of approaches for testing the homogeneity of variance assumption in one-factor ANOVA models. Educ. Psychol. Meas. 77:305–329

Warnes GR, Bolker B, Lumley T (2018) gmodels: Various R Programming Tools for Model Fitting. https://CRAN.R-project.org/package=gmodels

Wilson R, Sandell L, Robert K, Mark B (2010) Volunteer corn control. Pages 212–215 *in* Proceedings of the 2010 Crop Production Clinic. Lincoln, NE: University of Nebraska-Lincoln Extension

Wortman SE (2014) Integrating weed and vegetable crop management with multifunctional air-propelled abrasive grits. Weed Technol 28:243–252

Young BG, Hart SE (1997) Control of volunteer sethoxydim-resistant corn (*Zea mays*) in soybean (*Glycine max*). Weed Technol 11:649–655

Table 2-1. Acetyl CoA carboxylase (ACCase)-inhibiting herbicides, their application timings, rates, and products used for control of volunteer corn in aryloxyphenoxypropionate-resistant corn in field experiments conducted at South Central Agricultural Lab near Clay Center, NE in 2018 and 2019.[a]

Herbicide Program[b]	Timing	Rate	Trade Name	Manufacturer	Adjuvants[c]
		g ai ha^{-1}			
No-POST herbicide					
Weed Free Control					
Fluazifop	EPOST	70	Fusilade® DX	Syngenta Crop Protection, LLC., Greensboro, NC, 27419	COC
Quizalofop	EPOST	31	Assure® II	Corteva AgriScience, Wilmington, DE 19880	AMS^1 + COC
Fluazifop/fenoxaprop	EPOST	133	Fusion®	Syngenta Crop Protection	AMS^2 + COC
Clethodim	EPOST	68	Select Max®	Valent USA Corporation, Walnut Creek, CA 94596	NIS
Sethoxydim	EPOST	158	Poast Plus®	BASF Corporation, Research Triangle Park, NC 27709	AMS^3 + COC
Pinoxaden	EPOST	44	Axial® XL	Syngenta Crop Protection	COC
Fluazifop	LPOST	105	Fusilade® DX	Syngenta Crop Protection	COC
Quizalofop	LPOST	39	Assure® II	Corteva AgriScience	AMS^1 + COC
Fluazifop/fenoxaprop	LPOST	133	Fusion®	Syngenta Crop Protection	AMS^2 + COC
Clethodim	LPOST	119	Select Max®	Valent USA Corporation	NIS
Sethoxydim	LPOST	210	Poast Plus®	BASF Corporation	AMS^3 + COC
Pinoxaden	LPOST	60	Axial® XL	Syngenta Crop Protection	COC

[a] Abbreviations: AMS, Ammonium sulfate (N-Pak AMS Liquid, Winfield United, LLC., St. Paul, MN 55164); COC, crop oil concentrate (Agri-Dex, Helena Chemical Company, Collierville, TN 38017); EPOST, early POST; LPOST, late POST; NIS, nonionic surfactant (Induce, Helena Chemical Co.).

[b] A pre-mix of *S*-metolachlor, atrazine, mesotrione, bicyclopyrone (Acuron, Syngenta Crop Protection, LLC, Greensboro, North Carolina 27419) was applied PRE at 2,410 g ai ha^{-1} to the entire experimental area on May 10, 2018 and May 3, 2019.

[c] AMS^1 at 4% v/v, AMS^2 at 3% v/v, AMS^3 at 5% v/v, COC at 1% v/v, and NIS at 0.25% v/v were mixed with POST herbicide treatments based on label recommendations.

Table 2-2. Effects of Acetyl CoA carboxylase (ACCase)-inhibiting herbicides on control of glyphosate/glufosinate-resistant volunteer corn at 14 DAPOST, 28 DAPOST and pre-harvest, with 21 DAPOST biomass reduction and 28 DAPRE stand for field experiments conducted at South Central Agricultural Lab near Clay Center, NE in 2018 and 2019. [a,b]

			Crop stand 28 DAPRE		Volunteer Corn Control			Volunteer Corn Biomass Reduction
Herbicide Program	Timing	Rate	Enlist corn	Vol. Corn	14 DAPOST	28 DAPOST	Pre-Harvest	21 DAPOST
		g ai ha^{-1}	———plants ha^{-1}———		——————————————%——————————————			
No-POST herbicide			79,500	43,000	0	0	0	0.0 f
Weed Free Control			78,000	--	99	99	99	100 a
Fluazifop	EPOST	70	79,750	42,000	99 a	97 a	94 ab	71.7 bc
Quizalofop	EPOST	31	75,500	34,750	98 a	99 a	99 a	65.7 bcd
Fluazifop/fenoxaprop	EPOST	133	79,000	37,250	99 a	99 a	99 a	73.8 b
Clethodim	EPOST	68	80,000	44,000	94 a	90 bc	90 cd	72.3 bc
Sethoxydim	EPOST	158	77,000	50,000	98 a	84 c	88 cd	64.0 bcd
Pinoxaden	EPOST	44	77,000	47,000	99 a	65 d	60 d	49.6 bcde
Fluazifop	LPOST	105	79,500	41,500	99 a	99 a	99 a	60.3 bcd
Quizalofop	LPOST	39	81,500	37,500	99 a	99 a	99 a	50.9 bcde
Fluazifop/fenoxaprop	LPOST	133	77,750	35,000	99 a	99 a	99 a	57.0 bcd
Clethodim	LPOST	119	78,250	43,500	97 a	98 a	99 a	43.3 de
Sethoxydim	LPOST	210	85,000	39,750	97 a	94 ab	94 bc	47.8 cde
Pinoxaden	LPOST	60	78,000	39,750	85 b	71 d	85 de	25.3 ef
***LSD*-value**					6.4	7.1	6.8	25.7
***P*-value**			**0.830**	**0.700**	**0.001**	**<0.001**	**<0.001**	**<0.001**
Contrasts[c]								
FOP: EPOST vs. LPOST			NS	NS	98 vs. 99 NS	98 vs. 99 NS	97 vs. 99 NS	73.7 vs. 52.0 ***
DIM: EPOST vs. LPOST			NS	NS	96 vs. 97 NS	87 vs. 97 ***	89 vs. 96 ***	68.1 vs. 45.5 ***

[a] Abbreviations: DAPRE, days after PRE herbicide application; DAPOST, days after POST; DIM, herbicides in the cyclohexanedione family; EPOST, early POST, LPOST, late POST; FOP, herbicides in the aryloxyphenoxypropionate family

[b] Means presented within this table with no common letters are significantly difference according to Fisher's protected LSD with Bonferroni correction for multiple comparison, where α= 0.05.

[c] *a priori* orthogonal contrasts; * = significant ($P < 0.05$); **= significant ($P < 0.01$); ***= significant ($P < 0.001$); NS, non-significant ($P \geq 0.05$).

Table 2-3. Effects of Acetyl CoA carboxylase (ACCase)-inhibiting herbicides on Enlist corn injury at 14 DAPOST, 28 DAPOST and pre-harvest, with 21 DAPOST aboveground crop biomass reduction for field experiments conducted at South Central Agricultural Lab near Clay Center, NE in 2018 and 2019.[a,b,c]

			Enlist corn injury				Enlist corn Biomass Reduction
				28 DAPOST			
Herbicide Program	Timing	Rate	14 DAPOST	2018	2019	Pre-Harvest	21 DAPOST
		g ai ha^{-1}	%				
No-POST herbicide			0	0	0	0	17.2 bc
Weed Free Control			0	0	0	0	0.0 a
Fluazifop	EPOST	70	0 a	0 a	0 a	0 a	1.3 a
Quizalofop	EPOST	31	0 a	0 a	0 a	0 a	6.7 a
Fluazifop/fenoxaprop	EPOST	133	0 a	0 a	0 a	0 a	2.5 a
Clethodim	EPOST	68	94 cd	64 c	88 d	77 c	67.8 d
Sethoxydim	EPOST	158	96 cd	76 cd	66 c	78 c	69.5 d
Pinoxaden	EPOST	44	89 cd	25 b	--	62 b	27.9 c
Fluazifop	LPOST	105	0 a	0 a	0 a	0 a	0.0 a
Quizalofop	LPOST	39	0 a	0 a	0 a	0 a	0.0 a
Fluazifop/fenoxaprop	LPOST	133	0 a	0 a	0 a	0 a	0.7 a
Clethodim	LPOST	119	99 d	98 d	89 d	90 d	64.3 d
Sethoxydim	LPOST	210	97 cd	96 d	88 d	96 d	63.7 d
Pinoxaden	LPOST	60	85 b	56 bc	61 c	84 c	36.7 c
***LSD*-value**			12.9	23.2	5.4	7.9	16.7
***P*-value**			**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Contrasts[d]							
FOP: EPOST vs. LPOST			0 vs. 0 NS	0 vs. 0 NS	0 vs. 0 NS	0 vs. 0 NS	2.2 vs. 0.0 NS
DIM: EPOST vs. LPOST			95 vs. 98 NS	70 vs. 97 ***	77 vs. 88 **	77 vs. 97 ***	61.9 vs. 61.2 NS

[a] Abbreviations: DAPOST, days after POST; EPOST, early POST, LPOST, late POST

[b] Means presented within this table with no common letters are significantly difference according to Fisher's protected LSD with Bonferroni correction for multiple comparison, where $\alpha = 0.05$.

[c] Data presented in these columns were pooled across both years (2018 and 2019) unless otherwise indicated

[d] *a priori* orthogonal contrasts; * = significant ($P < 0.05$); **= significant ($P < 0.01$); ***= significant ($P < 0.001$); NS, non-significant ($P \geq 0.05$).

Table 2-4. Effect of Acetyl CoA carboxylase (ACCase)-inhibiting herbicides on Enlist corn yield and percent yield reduction in field experiments conducted in 2018 and 2019 at the South Central Agricultural Lab near Clay Center, NE.[a,b,c]

			Enlist Corn Yield		Yield Reduction	
Herbicide Program	Timing	Rate	2018	2019	2018	2019
		g ai ha^{-1}	kg ha^{-1}		%	
No-POST herbicide			14,262 a	8,846 abc	0.0 a	0.0 a
Weed Free Control			13,601 a	8,150 bc	0.0 a	0.0 a
Fluazifop	EPOST	70	13,202 a	8,888 abc	2.9 a	0.0 a
Quizalofop	EPOST	31	12,581 ab	8,651 abc	7.5 a	0.0 a
Fluazifop/fenoxaprop	EPOST	133	12,817 ab	9,488 ab	5.8 a	0.0 a
Clethodim	EPOST	68	1,621 d	1,127 e	88.1 d	85.2 c
Sethoxydim	EPOST	158	1,954 d	3,506 d	85.6 d	57.0 b
Pinoxaden	EPOST	44	10,673 b	--	21.5 b	--
Fluazifop	LPOST	105	13,795 a	9,530 ab	0.0 d	0.0 a
Quizalofop	LPOST	39	14,491 a	8,590 abc	0.0 d	0.0 a
Fluazifop/fenoxaprop	LPOST	133	13,342 a	9,738 a	1.9 d	0.0 a
Clethodim	LPOST	119	178 d	556 e	98.7 d	93.2 c
Sethoxydim	LPOST	210	465 d	532 e	96.6 d	93.4 c
Pinoxaden	LPOST	60	4,291 c	1,123 e	68.5 c	86.2 c
***LSD*-value**			2,087	1,356	14.6	12.8
***P*-value**			**<0.001**	**<0.001**	**<0.001**	**<0.001**
Contrasts[d]						
FOP: EPOST vs. LPOST			12,867 vs. 13,876 *	9,009 vs. 9,286 NS		
DIM: EPOST vs. LPOST			1,788 vs. 321 ***	2,316 vs. 544 **		

[a] Abbreviations: EPOST, early POST, LPOST, late POST

[b] Means presented within this table with no common letters are significantly difference according to Fisher's protected LSD with Bejamini-Hochberg correction for multiple comparison, where $\alpha = 0.05$.

[c] Data presented in this table were separated by year (2018 vs. 2019) due to significant yield reduction from hail and wind storms in August.

[d] *a priori* orthogonal contrasts; * = significant ($P < 0.05$); **= significant ($P < 0.01$); ***= significant ($P < 0.001$); NS, non-significant ($P \geq 0.05$).

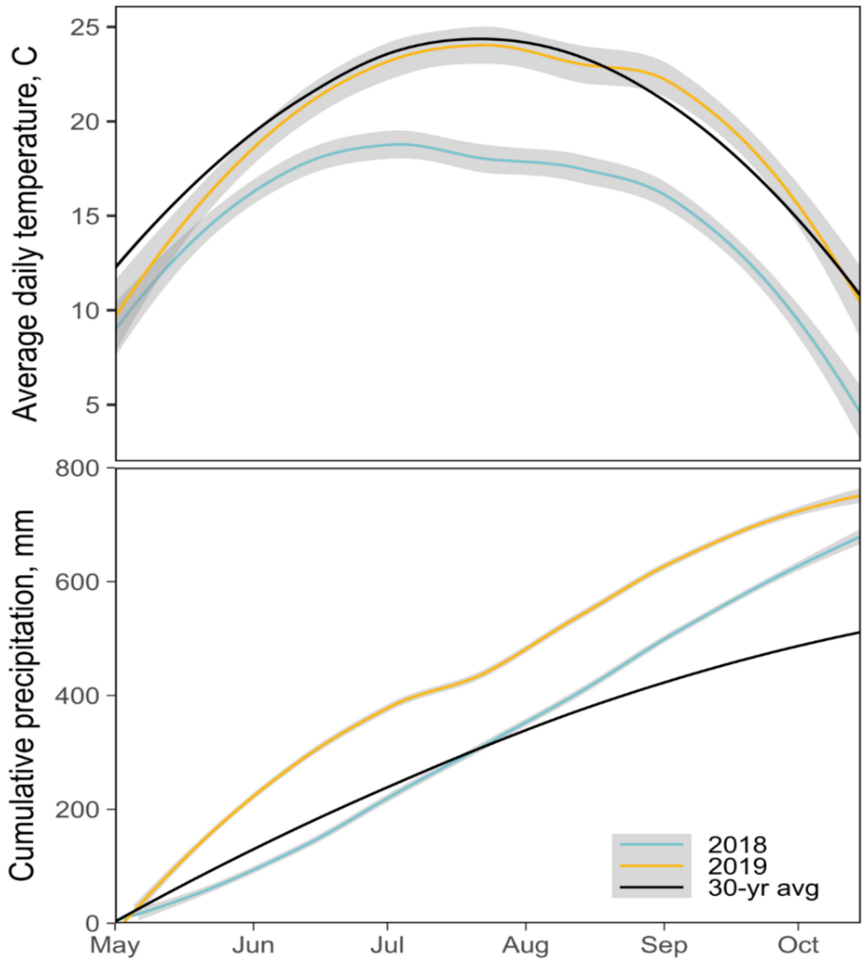

Figure 2-1. Average daily air temperature (ºC) and total cumulative precipitation (mm) received during the 2018 and 2019 growing seasons compared to the 30-year average at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, NE.

Figure 2-2. Axillary tiller production depicted 28 DAEPOST in Enlist corn treated with sethoxydim in experiment conducted at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, NE.

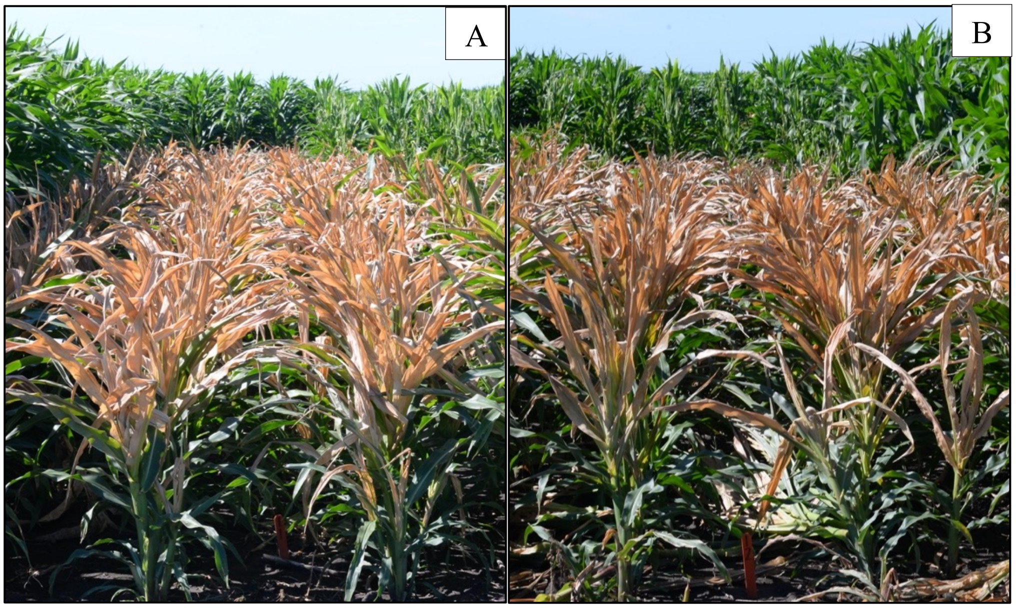

Figure 2-3A and 2-3B. Enlist corn injury depicted 14 d after late-POST for (A) sethoxydim applied at 210 g ai ha^{-1} and (B) clethodim applied at 119 g ai ha^{-1} for control of glyphosate/glufosinate-resistant volunteer corn in Enlist corn in experiments conducted at the University of Nebraska-Lincoln, South Central Agricultural Laboratory near Clay Center, Nebraska.

APPENDIX A: VOLUNTEER CORN GRAIN PRODUCTION

After observing no yield loss in the no-POST herbicide control despite season-long competition with planted volunteer corn, an additional no-POST herbicide control plot was added to the field experiment in 2019 with hand removal of volunteer corn seven days prior to harvest in order to estimate volunteer corn production and grain quality. Grain from hand-harvested volunteer corn was dried at 65 C for five days, with hundred kernel weight, number of ears plot, average ear length, grain weight and moisture content recorded and adjusted to 15.5% moisture. Grain quality measurements (percent protein, oil, starch and density) was conducted with a FOSS Infratec 1241 (Foss North America, Eden Prairie, MN, USA) near-infrared (NIR) grain analyzer, which is an approved model for USDA grain quality testing (McGinnis 2016).

Grain quality measurements for hand harvested volunteer corn was 8.8% protein, 3.8% oil, and 71.8% starch with a seed density of 1.29 g cm^{-3} (Table A-1), which are similar to published yellow commodity corn benchmarks (U.S. Grains Council 2019). Similarly, orthogonal contrasts for harvest test weight comparing no-POST herbicide control harvested without hand removal prior to harvest and weed free control plots were not significant in 2018 (P= 0.869) or in 2019 (P= 0.427) indicating grain from volunteer corn did not reduce test weight (data not shown). For grain production, orthogonal contrasts comparing No-POST herbicide control grain yield in 2019 with and without hand removal of volunteer corn prior to harvest were not statistically significant (P = 0.169) in 2019 with 8,945 kg ha^{-1} for no hand removal, and 7,864 kg ha^{-1} for hand-removed plots. While the overall yield difference of ≈ 1,000 kg ha^{-1} is practically significant, grain produced by the hand harvested volunteer corn in 2019 equated to 234.3 kg ha^{-1} (Table A-1), which is in stark contrast of Alms (2015) findings with volunteer corn densities of 16,000 and 34,000 plants ha^{-1} producing 5,700 and 4,800 kg ha^{-1}, respectively. It is possible some of the corn ears produced by volunteer corn were missed during hand harvest, or the substantial wind storms and hail storms in 2019 reduced the volunteer corn grain production as it did the Enlist corn (Table 2-4). The insignificant effect of volunteer corn hand removal on crop yield observed in the current study has not been observed previously (Alms 2015; Marquardt et al. 2012). Considering aforementioned factors, this data was not submitted for publication to avoid conflict with the literature based on a single treatment.

Table A-1. Grain yield components and grain quality measurements for hand-harvested volunteer corn in field experiments conducted in 2019 at the South Central Agricultural Lab near Clay Center, NE.[a]

Hand-harvested Volunteer Corn	Values	SE	Lower 95% CI	Upper 95% CI	Unit[b]
Quantitative Measurements					
Ears	12.5	3.6	5.3	19.6	plot^{-1}
Ear length	10.3	0.3	10.2	10.4	cm
Kernels	242	21	201	284	ear^{-1}
100-kernel weight	18.7	0.6	17.6	19.9	g
Grain production	234.3	78.5	80.4	388.3	kg ha^{-1}
Qualitative Measurements					
Protein Content	8.8	0.4	8.0	9.5	%
Oil Content	3.8	0.1	3.6	4.0	%
Starch Content	71.8	0.1	71.6	72.1	%
Seed Density	1.29	0.0	1.28	1.29	g cm^{-1}

[a] Abbreviations: CI, confidence interval; SE, standard error

[b] Plot size was 3-m wide by 9-m long.

CHAPTER 3: ECONOMICS OF HERBICIDE PROGRAMS FOR WEED CONTROL IN CONVENTIONAL, GLUFOSINATE, AND DICAMBA/GLYPHOSATE-RESISTANT SOYBEAN ACROSS FIVE LOCATIONS IN NEBRASKA

Abstract

Despite widespread adoption of dicamba/glyphosate-resistant (DGR) soybean by producers in Nebraska and across the United States, economic information comparing herbicide programs with glufosinate-resistant and conventional soybean is not available. The objectives of this study were to evaluate weed control efficacy, crop safety, gross profit margin, and benefit-cost ratios of herbicide programs with multiple sites of action in DGR soybean, glufosinate-resistant, and conventional soybean. Field experiments were conducted in 2018 and 2019 at three irrigated and two rain-fed locations across Nebraska. Herbicides applied pre-emergence (PRE) that included herbicides with three sites of action provided 85-99% control of common lambsquarters (*Chenopodium album* L.), kochia [*Bassia scoparia* (L.) A. J. Scott], Palmer amaranth (*Amaranthus palmeri* S. Watson), velvetleaf (*Abutilon theophrasti* Medik.), and a mixture of foxtail (*Seteria* spp.) and *Poaceae* species. PRE herbicides evaluated in this study provided 72 to 96% weed biomass reduction and 61 to 79% weed density reductions compared to the nontreated control at all locations. Herbicides applied postemergence (POST; dicamba plus glyphosate, glyphosate, glufosinate, and acetochlor plus clethodim plus lactofen) provided 93-99% control of all weed species except kochia 28 days after POST (DAPOST). POST herbicide programs provided 89 to 98% weed biomass reduction and 86 to 96% density reduction at 28 DAPOST. For individual site years, yield was often similar for PRE followed by POST herbicide programs in HR and conventional soybean.

Gross profit margins and benefit-cost ratios were higher in HR soybean than conventional soybean, although price premiums for conventional soybean can help compensate increased herbicide costs.

Introduction

Over the last few decades, commercialization of herbicide-resistant (HR) crops has led to changes in weed management strategies deployed in agronomic crop production systems in the United States. These crops provide flexibility to apply non-selective, postemergence (POST) herbicides for broad-spectrum weed control, and their adoption rates in the United States have remained consistently high since 2014 with 90 and 94% of domestic corn and soybean production, respectively (USDA-ERS, 2018). In recent years, soybean varieties resistant to multiple herbicide sites of action (SOA) have been commercialized. These cultivars stack existing glyphosate or glufosinate resistant traits with synthetic auxin herbicides 2,4-D (2,4-dichlorophenoxyacetic acid), dicamba (3,6-dichloro-2-methoxybenzoic acid) or isoxaflutole, an hydroxyphenyl-pyruvate-dioxygenase (HPPD)-inhibiting herbicide (Beckie et al., 2019). Use of multiple HR soybean cultivars provide producers additional weed management options. However, prevalence of glyphosate-resistant (GR) weed species both globally (48) and nationally (17) (Heap, 2020), serve as reminders of poor stewardship and over-reliance on a single herbicide SOA can have for the evolution of HR weeds. Additionally, it also emphasizes the critical role herbicide stewardship will continue to play in preserving the utility of new multiple HR-trait technologies particularly in no-till corn-soybean cropping systems (Gage et al., 2019).

About 60% of Nebraska producers surveyed report using soil applied residual herbicides in soybean to manage the six GR weed species reported in Nebraska consisting of common ragweed (*Ambrosia artemisiifolia* L.), waterhemp (*Amaranthus tuberculatus* (Moq.) J. D. Sauer), giant ragweed (*Ambrosia trifida* L.), kochia (*Bassia scoparia* (L.) A. J. Scott), horseweed (*Erigeron canadensis* L.), and Palmer amaranth (*Amaranthus palmeri* S. Watson) (Knezevic et al. 2020; Sarangi and Jhala, 2018). Integration of pre-emergence (PRE) herbicide use by soybean producers in Nebraska is similar to trends nationally, which has seen PRE herbicide use increase from 25% to 70% of soybean production in the United States from 2000 to 2015 (Peterson et al., 2018). A 2015 survey in Nebraska revealed producers relied primarily on PPO-inhibiting and ALS-inhibiting herbicides for PRE herbicides in soybean. The most commonly used were cloransulam plus sulfentrazone and flumioxazin alone, or in tank mixture with chlorimuron and thifensulfuron (Sarangi and Jhala, 2018). As more producers adopt soil-applied residual herbicides, there are opportunities to improve herbicide stewardship through the use of robust herbicide rotations used in combination with tank-mixtures of herbicides with multiple effective SOAs (Beckie and Reboud, 2009; Busi et al., 2019).

Previous research has indicated the combination of herbicide rotation and tank-mixtures can effectively delay the evolution of new HR weed biotypes (Beckie et al., 2019; Busi et al., 2019; Gage et al., 2019), and these are endorsed as best management practices in both non-integrated and integrated weed management (IWM) programs (Knezevic and Cassman, 2003; Norsworthy et al., 2012). Research in HR weed populations has also shown tank-mixtures with multiple effective SOAs can effectively control GR weed biotypes, such as common ragweed (Barnes et al., 2017; Byker et al., 2018), waterhemp (Jhala et al., 2017), horseweed (Chahal and Jhala, 2019), and kochia (Sbatella et al., 2019). Similarly, tank-mixtures with multiple effective SOAs have also been shown to control other HR weed biotypes such as PPO-inhibitor resistant Palmer amaranth (Schwartz-Lazaro et al., 2017) or atrazine/HPPD-inhibitor-resistant Palmer amaranth (Chahal et al., 2019).

In response to concerns about herbicide resistance to soil-applied residual herbicides, pesticide manufacturers have commercialized "ready-to-use" pre-mixture formulations of soil-applied residual herbicides with multiple SOAs for use in many agronomic crops, including soybean (Norsworthy et al., 2012). Although stewardship risks associated with application of pre-mixture products below labeled rates exist (Beckie and Harker, 2017; Owen, 2016), widespread adoption and frequent use of pre-mixture products warrants further study and comparison particularly in soybeans with multiple HR-traits.

Assessments of economic benefits of incorporating PRE herbicide programs in conventional, GR, and glufosinate-resistant (LibertyLink) soybean systems were examined in a multi-year study conducted in Missouri comparing combinations of PRE and/or POST herbicide programs (Rosenbaum et al., 2013). Results from this study indicated the use of PRE herbicide programs provided the best opportunities for season-long weed control and higher net returns. However, PRE fb POST programs provided the highest control of waterhemp regardless of soybean HR-trait (Rosenbaum et al., 2013). Likewise, a multi-year study in Nebraska compared pre-plant (PP), PRE, and/or POST herbicide programs for control of GR common ragweed, and they reported that PP fb

POST and PRE fb POST herbicide programs provided the highest effective and economic control of GR common ragweed in glufosinate-resistant soybean (Barnes et al., 2017).

As producers struggle to manage GR weeds particularly using POST herbicides, many producers have considered rotation to non-GR crops such as dicamba or glufosinate-resistant cultivars, with 34% of surveyed row crop producers responding positively towards rotation (Sarangi and Jhala, 2018). Glufosinate-resistant cultivars currently make up about 20% of soybean grown in United States. This has increased substantially over the last five years due to growing need to control GR weed biotypes and troublesome pigweed (*Amaranthus* spp.) species (Beckie et al., 2019). However, adoption of glufosinate-resistant soybean in Nebraska has historically been 5.2% or less of total soybean production (Sarangi and Jhala, 2018). Glufosinate applied alone or in tank-mixture has been shown to be effective for controlling GR weeds such as waterhemp, Palmer amaranth, or common ragweed and remains a viable POST options for producers (Barnes et al., 2017; Butts et al., 2016; Jhala et al., 2017; Schultz et al., 2015).

Dicamba/glyphosate-resistant (DGR; Roundup Ready 2 Xtend) soybean received approval in 2017 by the United States Environmental Protection Agency. A statewide survey of Nebraska soybean producers indicated 8.7% of total soybean planted was DGR soybean in 2017 (Werle et al., 2018b). Popularity of DGR soybean cultivars both in Nebraska and the United States has increased since their introduction with DGR soybeans currently estimated to be the most commonly planted soybean HR trait in the United States (Anonymous, 2020). Beckie et al. (2019) estimated DGR soybean has at least 50% market share in the United States.

Producers are continually under pressure to reduce production costs. Studies comparing weed control, crop yield, and economic return in conventional and HR soybean have been conducted previously (Owen et al., 2010; Peterson et al., 2017; Rosenbaum et al., 2013). However, these studies have not focused on commercially available pre-mixture PRE herbicide products with three SOAs, nor the economic analysis of DGR, glufosinate-resistant, and conventional soybean systems. The objectives of this study were to evaluate PRE fb POST herbicide programs with multiple sites of action in DGR, glufosinate-resistant, and conventional soybean for weed control efficacy, crop safety, gross profit margin, and benefit-cost ratio at five locations across Nebraska, United States.

Materials and Methods

Study Locations. Field experiments were conducted in 2018 and 2019 in northeastern (Concord, NE), eastern (Lincoln, NE), south-central (Clay Center, NE), west-central (North Platte, NE), and western Nebraska (Scottsbluff, NE) at University of Nebraska-Lincoln Research and Extension Centers and Agricultural Laboratories under irrigated (Clay Center, North Platte, and Scottsbluff) and rain-fed (Concord and Lincoln) conditions (Figure 3-1). In both years for all studies, field experiments were established in corn-soybean rotations with corn preceding the field experiment. All locations were conservational-tilled or received an early spring pre-plant herbicide application to control winter annual weeds. Experimental sites were primarily infested with common lambsquarters (*Chenopodium album* L.), kochia, Palmer amaranth, velvetleaf (*Abutilon theophrasti* Medik.), and a mixture of bristly foxtail [*Setaria verticillata* (L.) Beauv.], giant foxtail (*Setaria faberi* Herrm.), green foxtail [*Setaria viridis* (L.) P. Beauv.], yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and field sandbur (*Cenchrus spinifex* Cav.).

Experimental Design. Field experiments were arranged in a split-block design with four replications (Federer and King, 2006a; Federer and King, 2006b). PRE herbicide program (Table 3-2) was the whole plot factor in a randomized complete block, and soybean-cultivar/trait [Roundup Ready 2 Xtend (RR2X)], LibertyLink, conventional] with subsequent POST herbicide program (Table 3-2) was the subplot factor. This resulted in seven non-standard incomplete "column" blocks each containing only four of the seven PRE herbicide treatments across all four replications. This was done to accommodate experimental locations without access to research plot/packet planters and to simplify field operations. Plot size was 3-m wide (four soybean rows spaced 0.75 m wide) by 9-m in length. To protect dicamba-sensitive cultivars from direct spray drift, DGR soybean was planted flanking either side of plots receiving POST herbicide applications of dicamba and treated with POST applications of glyphosate, resulting in a 3-m buffer between dicamba applications and dicamba-sensitive cultivars. In addition to providing a 3-m buffer, the glyphosate POST program applied to DGR soybean was included to represent the production practice of planting DGR soybeans but not applying dicamba POST. Soybean cultivars were selected based on maturity group requirements for each location (1.8-2.3 with and iron chlorosis resistance for Scottsbluff; and 2.6-3.2 cultivar for Clay Center, Concord, Lincoln, and North Platte). Soybean cultivars were planted at 296,500 seeds ha^{-1} at Scottsbluff, NE and 333,500 seeds ha^{-1} (De Bruin and Pedersen, 2008; Specht, 2016) at other locations (Table 3-1). Seed was planted untreated or pre-treated, with seed treatments consisting of the insecticide thiamethoxam, or thiamethoxam in combination with mefenoxam/fludioxonil or mefenoxam/fludioxonil/sedaxane fungicides.

Herbicide Treatments. PRE herbicides (Table 3-2) were applied at or following soybean planting (Table 3-1) at each experimental location with a CO_2-pressurized backpack sprayer consisting of a four or five nozzle boom fitted with AIXR 110015 flat-fan nozzles (TeeJet Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60189) calibrated to deliver 140 L ha^{-1} at 276 kPa. For comparison, a nontreated (weedy) control and a weed-free control were included with weed-free control plots maintained by using herbicides and hand-weeding as needed. POST herbicide programs (Table 3-2) were applied between 28 and 45 days after soybean planting depending on site-specific weed pressure. POST Herbicides were applied with CO_2-pressurized backpack sprayer consisting of four or five-nozzle boom fitted with AIXR, TTI and XR 110015 flat-fan nozzles (depending on POST herbicide sprayed) calibrated to deliver 140 L ha^{-1} and 187 L ha^{-1} at 276 kPa, respectively.

Data Collection. Visual estimates of control of Palmer amaranth and waterhemp, common lambsquarters, velvetleaf, and combined grass weed species and other present weed species were recorded at 14 and 28 d after PRE and POST herbicide applications based on 0-100% scale, where 0% equaled no control and 100% equaled plant death. Likewise, a similar scale from 0-100% was utilized to assess soybean injury at 14 and 28 d after PRE and POST herbicide applied, where 0% equaled no injury and 100% equaled plant death. Weed density of individual weed species was recorded by counting the number of weeds present in two 0.5 m^2 quadrats which were placed randomly in the center two soybean rows in each plot at 14 and 28 d after PRE and POST herbicide application, and adjusted to plants m^{-2}. Aboveground weed biomass was collected a day prior to POST herbicide applications and 28 d after POST herbicide applications by randomly sampled two 0.5 m^2 quadrants from the center two soybean rows of each plot in which weeds present were cut at the soil surface and recorded the weed species present in the biomass sample. Weed biomass samples were oven-dried until constant weight, and adjusted to grams weed biomass m^{-2}. Percent of aboveground weed biomass and density reductions were calculated by using the equation (Wortman, 2014):

$$Y = [(C\text{-}B)/C] \times 100$$

where C represents the weed biomass or density from the nontreated control plots, and B represents the weed biomass or density from the treated plots. Crop stand was assessed at 28 days after PRE (DAPRE) herbicide application by counting the number of soybean plants present in 1 or 3 m of the center two rows, depending on study location. Weather data for each study location were collected by on-farm or High Plains Regional Climate Center Automated Weather Data Network (AWDN) weather stations, with cumulative precipitation received and average daily temperature recorded from May 1st to October 31st in 2018 and 2019. Plots were harvested from the center two rows in each plot at maturity using a small-plot combine with grain weight and moisture content recorded and adjusted to 13%.

Economic Analysis. Gross profit margins and benefit-cost ratio were performed to assess the profitability for each weed management program (combination of the herbicide program with the cost for herbicide-resistant or conventional soybean seed). Gross profit margin was calculated for each weed management program utilizing the equation (Sarangi and Jhala, 2019):

$$\text{Gross profit margin (US \$)} = (R\text{-}W)$$

where R is the gross revenue calculated by multiplying soybean yield for each treatment by the average price received for genetically modified (GM) HR-soybean (US \$0.30 kg^{-1}) or non-GM soybean (US \$0.35 kg^{-1}), and W is the total weed management program cost comprised of the average cost of herbicides and spray adjuvants for each treatment with custom application and the weighted average seed cost for the soybean cultivar/trait planted.

Average market price for GM-soybean was derived from the cash prices received in Nebraska from September to December in 2018 and 2019 (USDA-NASS, 2019). The price for non-GM soybeans was calculated with and without estimated price premiums for non-GMO feed-grade soybean derived from twenty United States Department of Agriculture-Agricultural Marketing Service (USDA-AMS) National Weekly Non-GMO/GE Grain Reports from September to December in 2018 and 2019 (USDA-AMS, 2020).

Price estimates for herbicides and spray adjuvants were obtained from three independent commercial sources in Nebraska (Central Valley Ag Cooperative, Frontier Cooperative, Nutrien Ag Solutions) and averaged prior to economic analysis. Custom application price estimates from the previously listed sources were also obtained, with an average cost of US \$17.30 ha^{-1} application^{-1} for PRE herbicide programs, US \$18.94 ha^{-1} application^{-1} for non-dicamba POST herbicide programs, and US \$31.71 ha^{-1} application^{-1} for POST herbicide programs containing dicamba.

For each treatment, W included the weighted average seed costs for soybean cultivar/trait used in this study which were adjusted based on planting density. Seed costs included associated technology fees for HR-traits and commercially available discounts for volume and cash/prepay, but did not include potential herbicide rebate programs. In addition to the gross profit margin, the benefit-cost ratios were calculated for each herbicide program using the equation (Sarangi and Jhala, 2019):

$$\text{Benefit–cost ratio for a program (US \$ / US \$)} = (R_T - R_C) / W$$

Where R_T is the overall gross revenue of each weed management program, R_C is the gross revenue for the nontreated control, and W is equal to the cost for each weed management program including the cost of herbicides, spray adjuvants, custom application, and seed.

Statistical Analysis. Statistical analysis was performed in R statistical software using the base packages v. 3.6.1 (R Core Team, 2018), “lme4” package v. 1.1-21 (Bates et al., 2015), and “glmmTMB” package v. 1.0.0 (Brooks et al., 2017). Experimental data from study locations in 2018 and 2019 were analyzed with a combined analysis, with the exception of crop yield which was analyzed separately by site year (combination of study location and year). In the combined model, the interaction of PRE herbicide program, POST herbicide program, and site year were considered fixed effects whereas the interaction of site year with replication, replication by PRE, column, and finally column by POST herbicide were considered random effects. In the separated model, the interaction of site year was removed from fixed and random effects.

Total aboveground weed biomass reduction, total weed density reduction, visual estimates of weed control and crop injury ratings were log(x+1), square root, or logit-transformed and fit to generalized linear mixed-effect models using *glmmTMB* functions with gaussian (link=“identity”) and beta (link=“logit”) error distributions (Stroup, 2015).

GlmmTMB models were fit using the restricted maximum likelihood (REML) approach with the default nlminb model optimizer, and final glmmTMB models were selected based on a comparison of dispersion parameter estimates and Akaike information criterion (AIC) values, with log(x+1) or square root transformation with gaussian error distribution selected for most response variables.

Crop yield, stand, and weed density data were log(x+1) or square root transformed and fit to linear mixed-effect models using the *lmer* function with the REML approach (Kniss and Streibig, 2018). Model convergence and optimization were tested for lmer models using the *allFit* function to compare the default nloptwrap optimizer with all other available optimizers for lmer fitted models, which is standard by lme4 package authors (Bates et al., 2015). Final lmer models were selected based on a comparison of REML criterion at convergence values, with the default nlminb or Nelder Mead model optimizers used for most response variables.

Prior to conducting ANOVA, assumptions of homogeneity of variance were tested by using Levene's tests (Wang et al., 2017) with the *leveneTest* function at $\alpha = 0.05$. Variables which failed variance assumptions were log(x+1) and square root transformed, fit to glmmTMB and lmer models, and visually assessed for outliers and heterogeneity of variance by plotting residual values (Knezevic et al., 2002; Ritz et al., 2015). Assumptions of normality were tested using Shapiro-Wilk tests with the *shapiro.test* function (Kniss and Streibig, 2018).

ANOVA was performed with "car" package v. 3.0-6 (Fox and Weisberg, 2019) using the *Anova* function. For glmmTMB models, ANOVA was conducted with Type III Wald Chi-Square Tests whereas lmer models used Type III Wald F Tests with Kenward-

Rodger degrees of freedom approximation. Treatment estimated marginal means for logit, log(x+1) and square root transformed data were separated with the “emmeans” package v. 1.4.3 (Lenth, 2019) and “multcomp” package v. 1.4-11 (Hothorn et al., 2008) using the *emmeans* and *cld* functions (Kniss and Streibig, 2018) at $\alpha = 0.05$, with Kenward-Rodger degrees of freedom approximation, Sidak method confidence-level adjustment, and Post-hoc Tukey *P*-value adjustments. Following treatment means separation, data were back-transformed for the presentation of results.

Results presented in this study exclude data from North Platte, NE in 2018 and Lincoln, NE in 2019 due to a study-wide planter malfunction and flooding 10 DAPRE, respectively. Likewise, due to an 80% defoliation hail event 29 DAPOST at Scottsbluff, NE, and a 60% defoliation hail event 51 DAPOST (August 5, 2019) during the R5 soybean growth stage in Clay Center, NE in 2019, results presented in this study for crop yield, gross profit margin, and benefit-cost ratio excluded data from these site years.

Results

Average Daily Temperature and Precipitation. Average daily temperatures during the 2018 and 2019 growing seasons for most study locations were similar to the 30-year average (Figure 3-2), with the exception of Clay Center, NE which were slightly cooler with an average temperature of 14.5 C. Cumulative precipitation recorded in 2018 and 2019 at each study location were similar or exceeded 30-year average (Figure 3-2).

Crop Stand. Soybean plant stand for locations at 28 DAPRE did not differ across PRE herbicide program (*P* =0.994), soybean cultivar and subsequent POST herbicide program (*P* =0.948), PRE by site year (*P* =0.900), PRE by POST (*P* =0.676) or PRE by POST by site year (*P* =0.889) with a study wide average of 234,250 plants ha^{-1} (data not shown).

PRE Herbicide: Weed Control, Density, Density Reduction and Biomass Reduction. Across site years, PRE herbicide programs provided 93 to 99% control of Palmer amaranth, 92 to 99% control of common lambsquarters, 87 to 94% control of velvetleaf, and 81 to 97% control of grass weed species (bristly foxtail, giant foxtail, green foxtail, yellow foxtail, large crabgrass and field sandbur) at 28 DAPRE (Table 3). Kochia infestation was only at North Platte, NE research site where sulfentrazone/*S*-metolachlor plus metribuzin, and flumioxazin/pyroxasulfone plus metribuzin provided 89 to 95% control at 14 and 28 DAPRE. Reduced control of kochia was observed for other PRE herbicides with chlorimuron/flumioxazin/thifensulfuron providing 69 and 63% control, chlorimuron/flumioxazin/metribuzin providing 88 and 84% control, and imazethapyr/pyroxasulfone/saflufenacil with 77 and 71% control at 14 and 28 DAPRE, respectively (Table 3-3). Aboveground weed biomass reduction at 28-45 DAPRE ($P < 0.001$) showed PRE herbicide programs offered similar weed biomass reduction compared to the nontreated control (258 g m^{-2}) compared to weed-free control (82%) prior to hand removal where sulfentrazone/*S*-metolachlor plus metribuzin providing 96% weed biomass reduction, and imazethapyr/pyroxasulfone/saflufenacil and chlorimuron/flumioxazin/thifensulfuron provided 77 and 72% weed biomass reduction, respectively (Table 3-3). Weed density varied for Palmer amaranth, common lambsquarters, velvetleaf, aforementioned grass weed species, and kochia for PRE herbicide at 14 and 28 DAPRE, with most PRE herbicide programs providing similar total weed density reduction to the weed-free control (73%), excluding chlorimuron/flumioxazin/thifensulfuron (61%) (Table 3-4).

POST Herbicide: Weed Control, Density, Density Reduction, and Biomass Reduction. At 14 and 28 DAPOST, most POST herbicide programs provided ≥ 87% control of Palmer amaranth, common lambsquarters, velvetleaf, and aforementioned grass weed species (Table 3-5). At North Platte, NE, dicamba plus glyphosate provided 95 to 94% control of kochia at 14 and 28 DAPOST, whereas glyphosate and glufosinate provided 89 to 82% and 71 to 70% control of kochia, respectively (Table 3-5). Acetochlor plus clethodim plus lactofen provided 57% control of kochia at 14 DAPOST, which was reduced to 38% at 28 DAPOST in conventional soybean, which is likely due to variability in height (3-30 cm) at the study location which exceeded label-recommended height (5 cm) for control of kochia with lactofen (Anonymous, 2015). Aboveground biomass reduction at 28 DAPOST was significant ($P < 0.001$) with dicamba plus glyphosate, glyphosate, and glufosinate resulting in ≥ 97% reduction of total weed biomass compared to the nontreated control (1,178 g m^{-2}). Weed biomass reduction was lower for acetochlor plus clethodim plus lactofen, with 89% (Table 3-5).

Density of Palmer amaranth, common lambsquarters, grass weed species, and kochia were similar across POST herbicide programs 28 DAPOST, whereas density of velvetleaf at 14 and 28 DAPOST and common lambsquarters 14 DAPOST was significant ($P < 0.001$), although only equal to 1 plant m^{-2} for acetochlor plus clethodim plus lactofen. The density of grass weed species at 14 DAPOST was not different (Table 3-6), and POST herbicide program was not significant for total weed density reduction at 28 DAPOST ($P = 0.832$) with POST herbicide programs reducing total weed density 86 to 94% from densities present in the nontreated control (85 plants m^{-2}).

Crop Injury. PRE herbicide programs evaluated in this study displayed high margin of crop safety, with ≤ 4% soybean injury at 14 or 28 DAPRE across site-years (Table B-1). No visual injury was observed in DGR soybean at 14 or 28 DAPOST, whereas off-target movement of dicamba in glufosinate-resistant and conventional soybean resulted in phytotoxic deformities of 12-13% at 14 DAPOST, and 11-12% at 28 DAPOST (Table B-2). Across all site-years, crop injury from dicamba in dicamba-sensitive cultivars did not exceed the threshold of 30% visible injury required to cause greater than 5% soybean yield loss, as reported in a meta-analysis conducted by Kniss (2018). Lactofen applied POST in conventional soybean resulted in 12 and 9% phytotoxic necrosis at 14 and 28 DAPOST, with lactofen injury fading as the growing season progressed. It has been previously reported lactofen can cause low to moderate level of soybean injury 7-14 d after application but usually do not result in yield loss (Sarangi et al., 2015; Wichert and Talbert, 1993).

Crop Yield. For individual site years presented in this study, the main effect of PRE herbicide program was significant for six of six site years whereas the main effect of POST herbicide program was significant for four of six site years (data not shown). Due to a significant site year effect ($P = 0.002$), locations were analyzed seperately by site year. The interaction of PRE by POST herbicide program was significant at all study locations (Table 3-7) excluding North Platte, NE in 2019 ($P = 0.132$); therefore analysis of soybean yield and economics were conducted on PRE fb POST herbicide programs. Across site years, soybean yield for PRE fb POST herbicide programs in DGR, glufosinate-resistant and conventional soybean systems was similar to the weed-free control for the respective system for nearly all PRE fb POST programs. In Clay Center, NE, conventional soybean receiving chlorimuron/flumioxazin/thifensulfuron or imazethapyr/pyroxasulfone/saflufenacil produced 2,000 to 2,360 kg ha^{-1} less than the weed free control (3,771 kg ha^{-1}) in 2019 (Table 3-7). Conventional soybean yield was similar to HR-cultivars for all PRE fb POST herbicide programs at Lincoln and Concord in 2018 and 2019, respectively. In contrast, conventional soybean yield was significantly lower than HR-cultivars in Clay Center, Concord and Scottsbluff in 2018 (Table 3-7), although poor field emergence of conventional soybean cultivar U11-917032 (95,000 plants ha^{-1}) at Scottsbluff, NE in 2018 likely contributed to low yield potential for that specific site year. Soybean yield in glufosinate-resistant soybean was similar to DGR-soybean for all site years (Table 3-7).

Economic Analysis. PRE herbicide program with custom application cost ranged from \$58.30 to \$135.25 ha^{-1}, with the cost of POST herbicide programs with custom application ranging from \$33.46 to \$148.74 ha^{-1} (Table 3-2). Herbicide program costs were added to the cost of conventional and HR-cultivar seed, with weighted study wide averages of \$132.96 ha^{-1} for DGR soybean, \$109.33 ha^{-1} for glufosinate-resistant, and \$108.58 ha^{-1} for commercially available conventional soybean cultivars (Table 3-8). Low demand at most locations for conventional soybean seed resulted in higher than expected seed costs.

Gross profit margins for most weed management programs in DGR cultivars were similar within most site years, with a study-wide average gross profit margin of \$976.56 and \$1023.56 ha^{-1} for dicamba/glyphosate and glyphosate POST programs, respectively (Table 3-8). In glufosinate-resistant cultivars, gross profit margin was comparable to DGR cultivars with a study-wide average of \$928.24 ha^{-1} (Table 3-8), while in conventional weed management programs, gross profit margin was lower than in HR cultivars with a study-wide average of \$722.02 ha^{-1} for grain marketed without price premiums (data not shown). However, lower gross profit margins in conventional soybean could be partially compensated by including a price premium for non-GM soybean, with a study-wide average of \$814.12 ha^{-1} for grain marketed with a \$0.05 kg^{1} price premium (Table 3-8). At Lincoln and Scottsbluff in 2018 and 2019, gross profit margins for conventional soybean marketed with a price premium were similar or exceeded the gross profit margin for many HR-soybean programs. (Table 3-8).

Benefit-cost ratios in this study ranged both by site year and by soybean cultivar. In HR and conventional soybean, PRE fb POST herbicide provided similar or higher benefit-cost ratios to the weed-free control for most site years (Table 3-9). Across all site years excluding North Platte in 2019, study-wide averages for DGR soybean receiving dicamba plus glyphosate or glyphosate was 3.64 and 4.42, respectively. In glufosinate-resistant soybean, the average benefit-cost ratio was 3.91, whereas in conventional soybean the average benefit-cost ratio was lower, at 2.25 (Table 3-9). At North Platte in 2019, benefit-cost ratio for all PRE fb POST herbicide programs was reduced to < 2.0 primarily due to late-season competition with kochia that emerged after POST herbicide application (Table 3-9).

Discussion

Results of this study support the use of PRE herbicide with multiple effective sites of action in DGR, glufosinate-resistant, and conventional soybean and are consistent with the scientific literature for the control of broadleaf and grass weed species evaluated. It has been reported that pre-mixtures of sulfentrazone and metribuzin provided 92 to 99% control of common lambsquarters, waterhemp and velvetleaf 15 DAPRE and 98% control of Palmer amaranth 28 DAPRE in Nebraska (Aulakh and Jhala, 2015; Sarangi and Jhala, 2019). Similarly, Belfry et al. (2016) reported *S*-metolachlor plus metribuzin provided 92 to 100% control of common ragweed, green foxtail, and common lambsquarters 14 DAPRE. Sarangi et al. (2017) reported pre-mixtures of chlorimuron/flumioxazin/thifensulfuron provided 88% control of GR waterhemp 21 DAPRE in GR soybean in Nebraska. Likewise, Soltani et al. (2014) and Hedges et al. (2019) reported premixtures of flumioxazin/pyroxasulfone provided 97 to 99% control of velvetleaf, common ragweed, common lambsquarters, waterhemp, and green foxtail 28 DAPRE. In Kansas, Hay et al. (2019) reported pre-mixtures of flumioxazin/pyroxasulfone and chlorimuron/flumioxazin/metribuzin tank-mixed with paraquat provided 90% and 93% control of Palmer amaranth 56 DAPRE, respectively. Similarly, Sarangi and Jhala (2019) reported chlorimuron/flumioxazin/metribuzin provided 96% control of velvetleaf 28 DAPRE. Efficacy of various soybean herbicide pre-mixtures tank-mixed with glyphosate were studied in four, two-year studies in Ontario, Canada where imazethapyr/saflufenacil plus glyphosate provided 60 to 83% control of common ragweed 56 d after application, with 79 to 82% biomass reduction (Wely et al., 2014). Likewise, pyroxasulfone applied alone at 150 g ai ha^{-1} provided 94% control of GR waterhemp at 28 DAPRE (Hedges et al., 2019) and 95% control of GR waterhemp at 21 DAPRE herbicide applied at 208 g ai ha^{-1} (Sarangi et al., 2017).

From a weed management standpoint, all POST herbicide programs in HR soybean provided 94 to 99% control of Palmer amaranth, common lambsquarters, velvetleaf, and grass weed species. At North Platte, kochia was best controlled by dicamba plus glyphosate with 94% control 28 DAPOST which illustrates the value of dicamba for control of troublesome weed species such as kochia in DGR soybean (Sbatella et al., 2019). Competition from GR weeds in glyphosate applied POST programs was expected due to their prevalence in Nebraska (Sarangi and Jhala, 2018); however, due to relatively low frequency of GR weed species at study locations in 2018 and 2019, this was not observed in current study. Multiple herbicide-resistant soybean such as isoxaflutole/glufosinate/glyphosate-resistant soybean (LibertyLink/GT27) and dicamba/glufosinate/glyphosate-resistant soybean (XtendFlex) will be available commercially in the near future (Beckie et al., 2019). Therefore, glufosinate remains a viable POST herbicide option soybean producers should consider. In conventional soybean, an overlapping residual of acetochlor plus clethodim plus lactofen provided 87 to 95% control of broadleaf and grass weeds present excluding kochia. Producers interested in conventional soybean should take special care to select fields with weed spectrum which can be managed effectively with PRE fb POST herbicide applications of ALS and PPO-inhibiting herbicides along with residual activity of long chain fatty acid (LCFA) inhibitors, such as acetochlor/*S*-metolachlor/pyroxasulfone because POST herbicides such as 2,4-D, dicamba, glyphosate, or glufosinate cannot be used as a “rescue treatment”.

Total cost of PRE herbicide programs examined in this study were within \$10 ha^{-1} excluding chlorimuron/flumioxazin/thifensulfuron which was \$15 to \$20 ha^{-1} less expensive, and sulfentrazone/*S*-metolachlor plus metribuzin (\$134.25 ha^{-1}) which was substantially higher due to the application of metribuzin at a full-labeled rate for medium textured soils with 2-4% organic matter (700 g ai ha^{-1}). Previous research with metribuzin tank-mixed with other herbicides have shown this rate could have been reduced without compromising weed control efficacy and soybean yield potential (Hedges et al., 2019; Kaur et al., 2014; Sarangi and Jhala, 2019; Underwood et al., 2016; Wely et al., 2014; Whitaker et al., 2010).

Total cost of POST herbicide programs varied by soybean system, with substantial cost reductions in glyphosate and glufosinate. Across soybean systems, POST herbicide program in conventional soybean were the most expensive (\$148.74 ha^{-1}) primarily because it had lactofen and an overlapping residual activity of acetochlor to address concerns with season-long weed control as reported in the literature (Rosenbaum et al., 2013; Sarangi and Jhala, 2019). Sarangi and Jhala (2019) reported that the use of overlapping residual herbicides were effective at providing season-long control of Palmer amaranth and velvetleaf in conventional soybean in Nebraska. In the same study, it was reported that lactofen applied POST at 210 g ai ha^{-1} alone or tank-mixed with other herbicides provided 91% control of GR waterhemp 28 DAPOST (Sarangi and Jhala, 2019).

Reduced grain production by conventional soybean observed in the current study for three of six site years agree with results of a five location, two-year study reported by Owen et al. (2010) in which conventional soybean cultivars produced 265 and 315 kg ha^{-1} less than GR and glufosinate-resistant cultivars, respectively. Likewise, Werle et al. (2018a) reported conventional soybean cultivars produced 202 kg ha^{-1} less than GR and DGR soybean when receiving the same PRE fb POST herbicide program. However, while conventional soybean produced lower grain yields than HR-soybean at three locations, it was similar at Lincoln in 2018 and at Concord in 2019. These results are similar to a three-year, one location study conducted in Tennessee which reported similar crop yields for GR and conventional soybean (Gaban, 2013). Similar yield potential and weed control in conventional, GR and glufosinate-resistant soybean cultivars were also reported by Culpepper et al. (2000) in a three-year, six-location study in North Carolina. With variable results in the literature, the yield potential of conventional cultivars compared to HR cultivars is inconclusive. Results from this study suggest conventional soybean can produce similar yield in some locations, which is likely due in part to location-specific weed spectrum or weed pressure. Results from this study also indicate soybean yield in glufosinate-resistant soybean is similar to DGR-soybean.

Higher gross profit margin observed in HR soybean cultivars was due primarily to elevated herbicide costs in conventional soybean and reduced soybean yield when present. In this study, POST herbicide program in conventional soybean included acetochlor as an overlapping residual herbicide, which was not present in POST herbicide programs in HR soybean systems. This additional expense added to the cost of the conventional soybean system. However, in site years where conventional soybean produced similar crop yield to HR-soybean, gross profit margins were similar or slightly higher when a \$0.05 price premium for non-GM soybean was included. These results indicate price premiums for non-GM soybean can either partially or fully compensate the additional herbicide costs in conventional programs. However, after including price premium study-wide gross profit margins were on average \$114 to \$209 ha^{-1} lower in conventional soybean compared with DGR and glufosinate-resistant soybean. Results of the current study also indicate glufosinate-resistant soybean systems can provide similar economic return as DGR soybean.

Potential price savings for PRE fb POST herbicide programs evaluated in this study are possible, with herbicide rebate programs, generic formulations of specific active ingredients or pre-mixture product, and alternative products being commercially available to soybean producers. Special care should be taken when selecting herbicides for weed management programs in conventional or HR-soybean to ensure products provide multiple effective sites of action to troublesome weed species and adequately address the weed spectrum and weed pressure for the specific location.

Literature Cited

Anonymous. 2015. Cobra® herbicide. Valent U.S.A. https://www.valent.com/Products/4a28acd6-2703-4968-b34e-4afdedbdbab5/cobra-herbicide (accessed 18 February 2020).

Anonymous. 2020. Dicamba-, glyphosate- and glufosinate-resistant soybeans | clean fields and high yield potential. Roundup Ready Xtend. https://www.roundupreadyxtend.com/products/Pages/soybeans.aspx (accessed 24 February 2020).

Aulakh, J.S., and A.J. Jhala. 2015. Comparison of glufosinate-based herbicide programs for broad-spectrum weed control in glufosinate-resistant soybean. Weed Technol. 29(3): 419–430. doi: 10.1614/WT-D-15-00014.1.

Barnes, E.R., S.Z. Knezevic, P.H. Sikkema, J.L. Lindquist, and A.J. Jhala. 2017. Control of glyphosate-resistant common ragweed (*Ambrosia artemisiifolia* L.) in glufosinate-resistant soybean [*Glycine max* (L.) merr]. Front. Plant Sci. 8: 1455. doi: 10.3389/fpls.2017.01455.

Bates, D., M. Mächler, B. Bolker, and S. Walker. 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67(1): 1–48. doi: 10.18637/jss.v067.i01.

Beckie, H.J., M.B. Ashworth, and K.C. Flower. 2019. Herbicide resistance management: Recent developments and trends. Plants 8(6): 161. doi: 10.3390/plants8060161.

Beckie, H.J., and K.N. Harker. 2017. Our top 10 herbicide-resistant weed management practices. Pest Manag. Sci. 73(6): 1045–1052. doi: 10.1002/ps.4543.

Beckie, H.J., and X. Reboud. 2009. Selecting for weed resistance: herbicide rotation and mixture. Weed Technol. 23(3): 363–370. doi: 10.1614/WT-09-008.1.

Belfry, K.D., M.J. Cowbrough, F.J. Tardif, and P.H. Sikkema. 2016. Weed management options for conventional soybean. Can. J. Plant Sci. 96(5): 743–747. doi: 10.1139/cjps-2015-0353.

Brooks, M.E., K. Kristensen, K.J. van Benthem, A. Magnusson, C.W. Berg, et al. 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. The R Journal 9(2): 378–400. https://journal.r-project.org/archive/2017/RJ-2017-066/index.html.

Busi, R., S.B. Powles, H.J. Beckie, and M. Renton. 2019. Rotations and mixtures of soil-applied herbicides delay resistance. Pest Manag. Sci. 76(2): 487–496. doi: 10.1002/ps.5534.

Butts, T.R., J.K. Norsworthy, G.R. Kruger, L.D. Sandell, B.G. Young, et al. 2016. Management of pigweed (*Amaranthus* spp.) in glufosinate-resistant soybean in the Midwest and Mid-South. Weed Technol. 30(2): 355–365. doi: 10.1614/WT-D-15-00076.1.

Byker, H.P., A.C. Van Wely, A.J. Jhala, N. Soltani, D.E. Robinson, et al. 2018. Preplant followed by postemergence herbicide programs and biologically effective rate of metribuzin for control of glyphosate-resistant common ragweed (*Ambrosia artemisiifolia*) in soybean. Can. J. Plant Sci. 98(4): 809–814. doi: 10.1139/cjps-2017-0299.

Chahal, P.S., and A.J. Jhala. 2019. Integrated management of glyphosate-resistant horseweed (*Erigeron canadensis*) with tillage and herbicides in soybean. Weed Technol. 33(6): 859–866. doi: 10.1017/wet.2019.74.

Chahal PS, Jugulam M, and Jhala AJ (2019) Basis of atrazine and mesotrione synergism for controlling atrazine- and HPPD inhibitor-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson). Agron. J. 111:3265-3273

Culpepper, A.S., A.C. York, R.B. Batts, and K.M. Jennings. 2000. Weed management in glufosinate- and glyphosate-resistant soybean (*Glycine max*). Weed Technol. 14(1): 77–88. doi: 10.1614/0890-037X(2000)014[0077:WMIGAG]2.0.CO;2.

De Bruin, J.L., and P. Pedersen. 2008. Soybean seed yield response to planting date and seeding rate in the upper midwest. Agron J. 100(3): 696–703. doi: 10.2134/agronj2007.0115.

Federer, W.T., and F. King. 2006a. Standard split block experiment design. Variations on Split Plot and Split Block Experiment Designs. John Wiley & Sons, Ltd. p. 39–60

Federer, W.T., and F. King. 2006b. Variations of the split block experiment design. Variations on Split Plot and Split Block Experiment Designs. John Wiley & Sons, Ltd. p. 97–119

Fox, J., and S. Weisberg. 2019. An R companion to applied regression. Third. Sage, Thousand Oaks CA.

Gaban, B.L. 2013. Comparison of roundup ready and conventional soybean (*Glycine max* L.) weed control systems for optimizing yield and economic profitability. https://trace.tennessee.edu/utk_gradthes/1619/.

Gage, K.L., R.F. Krausz, and S.A. Walters. 2019. Emerging challenges for weed management in herbicide-resistant crops. Agriculture 9(8): 180. doi: 10.3390/agriculture9080180.

Hay, M.M., D.E. Shoup, and D.E. Peterson. 2019. Herbicide options for control of Palmer amaranth (*Amaranthus palmeri*) and common waterhemp (*Amaranthus rudis*) in double-crop soybean. Weed Technol 33(1): 106–114. doi: 10.1017/wet.2018.86.

Heap, I. 2020. The international survey of herbicide resistant weeds. weeds resistant to EPSP synthase inhibitors. http://www.weedscience.org/Summary/MOA.aspx?MOAID=12 (accessed 21 February 2020).

Hedges, B.K., N. Soltani, D.C. Hooker, D.E. Robinson, and P.H. Sikkema. 2019. Control of glyphosate-resistant waterhemp with preemergence herbicides in glyphosate- and dicamba-resistant soybean. Can. J. Plant Sci. 99(1): 34–39. doi: 10.1139/cjps-2018-0046.

Hothorn, T., F. Bretz, and P. Westfall. 2008. Simultaneous inference in general parametric models. Biometrical J. 50(3): 346–363. https://cran.r-project.org/web/packages/multcomp/multcomp.pdf.

Jhala, A.J., L.D. Sandell, D. Sarangi, G.R. Kruger, and S.Z. Knezevic. 2017. Control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in glufosinate-resistant soybean. Weed Technol. 31(1): 32–45. doi: 10.1017/wet.2016.8.

Kaur, S., L.D. Sandell, J.L. Lindquist, and A.J. Jhala. 2014. Glyphosate-resistant giant ragweed (*Ambrosia trifida*) control in glufosinate-resistant soybean. Weed technol. 28(4): 569–577. doi: 10.1614/WT-D-14-00009.1.

Knezevic, S.Z., and K.G. Cassman. 2003. Use of herbicide-tolerant crops as a component of an integrated weed management program. Crop Manag 2(1): 0. doi: 10.1094/CM-2003-0317-01-MG.

Knezevic, S.Z., C.F. Creech, A.J. Jhala, R.N. Klein, G.R. Kruger, et al. 2020. Guide for weed, disease, and insect management in Nebraska. University of Nebraska-Lincoln Extension, Lincoln, NE.

Knezevic, S.Z., S.P. Evans, E.E. Blankenship, R.C. Van Acker, and J.L. Lindquist. 2002. Critical period for weed control: the concept and data analysis. Weed Sci. 50(6): 773–786. doi: 10.1614/0043-1745(2002)050[0773:CPFWCT]2.0.CO;2.

Kniss, A.R. 2018. Soybean response to dicamba: A meta-analysis. Weed Technol. 32(5): 507–512. doi: 10.1017/wet.2018.74.

Kniss, A.R., and J.C. Streibig. 2018. Statistical analysis of agricultural experiments using R. https://rstats4ag.org/ (accessed 23 September 2019).

Lenth, R. 2019. Emmeans: Estimated marginal means, aka least-squares means. https://CRAN.R-project.org/package=emmeans.

Norsworthy, J.K., S.M. Ward, D.R. Shaw, R.S. Llewellyn, R.L. Nichols, et al. 2012. Reducing the risks of herbicide resistance: Best management practices and recommendations. Weed Sci. 60(SPEC. ISSUE 1): 31–62. doi: 10.1614/WS-D-11-00155.1.

Owen, M.D.K. 2016. Diverse approaches to herbicide-resistant weed management. Weed Sci. 64(SP1): 570–584. doi: 10.1614/WS-D-15-00117.1.

Owen, M.D.K., P. Pedersen, J.L.D. Bruin, J. Stuart, J. Lux, et al. 2010. Comparisons of genetically modified and non-genetically modified soybean cultivars and weed management systems. Crop Science 50(6): 2597–2604. doi: 10.2135/cropsci2010.01.0035.

Peterson, M.A., A. Collavo, R. Ovejero, V. Shivrain, and M.J. Walsh. 2018. The challenge of herbicide resistance around the world: a current summary: Herbicide resistance around the world. Pest Manag. Sci. 74(10): 2246–2259. doi: 10.1002/ps.4821.

Peterson, D.E., C. Thompson, and C.L. Minihan. 2017. Comparison of different weed control technology programs. Kansas Agricultural Experiment Station Research Reports 3(6). doi: 10.4148/2378-5977.7444.

R Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ritz, C., A.R. Kniss, and J.C. Streibig. 2015. Research methods in weed science: Statistics. Weed Sci. 63(SP1): 166–187. doi: 10.1614/WS-D-13-00159.1.

Rosenbaum, K.K., R.E. Massey, and K.W. Bradley. 2013. Comparison of weed control, yield, and net income in conventional, glyphosate-resistant, and glufosinate-resistant soybean. Crop Management 12(1): 0. doi: 10.1094/cm-2013-0028-rs.

Sarangi, D., and A.J. Jhala. 2018. A statewide survey of stakeholders to assess the problem weeds and weed management practices in Nebraska. Weed Technol. 32(5): 642–655. doi: 10.1017/wet.2018.35.

Sarangi, D., and A.J. Jhala. 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(1): 95–105. doi: 10.1017/wet.2018.78.

Sarangi, D., L.D. Sandell, S.Z. Knezevic, J.S. Aulakh, J.L. Lindquist, et al. 2015. Confirmation and control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in Nebraska. Weed technol. 29(1): 82–92. doi: 10.1614/WT-D-14-00090.1.

Sarangi, D., L.D. Sandell, G.R. Kruger, S.Z. Knezevic, S. Irmak, et al. 2017. Comparison of herbicide programs for season-long control of glyphosate-resistant common waterhemp (*Amaranthus rudis*) in soybean. Weed Technol. 31(1): 53–66. doi: 10.1017/wet.2016.1.

Sbatella, G.M., A.T. Adjesiwor, A.R. Kniss, P.W. Stahlman, P. Westra, et al. 2019. Herbicide options for glyphosate-resistant kochia (*Bassia scoparia*) management in the Great Plains. Weed Technol. 33(5): 658–663. doi: 10.1017/wet.2019.48.

Schultz, J.L., D.B. Myers, and K.W. Bradley. 2015. Influence of soybean seeding rate, row spacing, and herbicide programs on the control of resistant waterhemp in glufosinate-resistant soybean. Weed Technol. 29(2): 169–176. doi: 10.1614/WT-D-14-00071.1.

Schwartz-Lazaro, L.M., J.K. Norsworthy, R.C. Scott, and L.T. Barber. 2017. Resistance of two Arkansas Palmer amaranth populations to multiple herbicide sites of action. Crop Prot. 96: 158–163. doi: 10.1016/j.cropro.2017.02.022.

Soltani, N., R.E. Nurse, and P.H. Sikkema. 2014. Two-pass weed management with preemergence and postemergence herbicides in glyphosate-resistant soybean. Agr Sci 05(06): 504–512. doi: 10.4236/as.2014.56052.

Specht, J. 2016. Soybean seeding rate tips. CropWatch. University of Nebraska-Lincoln Extension. https://cropwatch.unl.edu/2016/soybean-seeding-rate-tips (accessed 9 February 2020).

Stroup, W.W. 2015. Rethinking the analysis of non-normal data in plant and soil science. Agron J. 107(2): 811–827. doi: 10.2134/agronj2013.0342.

Underwood, M.G., N. Soltani, D.C. Hooker, D.E. Robinson, J.P. Vink, et al. 2016. The addition of dicamba to post applications of quizalofop-p-ethyl or clethodim antagonizes volunteer glyphosate-resistant corn control in dicamba-resistant soybean. Weed Technol. 30(3): 639–647. doi: 10.1614/WT-D-16-00016.1.

[USDA-ERS] United States Department of Agriculture-Economic Research Service. 2018. Recent trends in GE adoption. https://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us/recent-trends-in-ge-adoption.aspx (accessed 23 May 2019).

[USDA-NASS] United States Department of Agriculture-National Agricultural Statistics Service. 2019. Nebraska agricultural statistics 2018–2019. Department of Agriculture, Washington, DC: U.S.

[USDA-AMS] United States Department of Agriculture- Agricultural Marketing Service. 2020. National weekly non-GMO/GE grain report. https://www.ams.usda.gov/mnreports/gl_gr112.txt (accessed 8 March 2020).

Wang, Y., P. Rodríguez de Gil, Y.-H. Chen, J.D. Kromrey, E.S. Kim, et al. 2017. Comparing the performance of approaches for testing the homogeneity of variance assumption in one-factor ANOVA models. Educ. Psychol. Meas. 77(2): 305–329. doi: 10.1177/0013164416645162.

Wely, A.C.V., N. Soltani, D.E. Robinson, D.C. Hooker, M.B. Lawton, et al. 2014. Control of glyphosate and acetolactate synthase resistant common ragweed (*Ambrosia artemisiifolia* L.) in soybean (*Glycine max* L.) with preplant herbicides. American J. Plant Sci. 05(26): 3934–3942. doi: 10.4236/ajps.2014.526412.

Werle, R., K. Glewen, S. Spicka, N.J. Arneson, R. Elmore, et al. 2018a. Results from 2017 Soybean Study and Insights for 2018 Planting. CropWatch. https://cropwatch.unl.edu/2018/results-2017-soybean-study-and-insights-2018-planting (accessed 2 April 2020).

Werle, R., M.C. Oliveira, A.J. Jhala, C.A. Proctor, J. Rees, et al. 2018b. Survey of Nebraska farmers' adoption of dicamba-resistant soybean technology and dicamba off-target movement. Weed Technol. 32(6): 754–761. doi: 10.1017/wet.2018.62.

Whitaker, J.R., A.C. York, D.L. Jordan, and A.S. Culpepper. 2010. Palmer amaranth (*Amaranthus palmeri*) control in soybean with glyphosate and conventional herbicide systems. Weed Technol. 24(4): 403–410. doi: 10.1614/WT-D-09-00043.1.

Wichert, R.A., and R.E. Talbert. 1993. Soybean [*Glycine max* (L.)] response to lactofen. Weed Sci. 41(1): 23–27. https://www.jstor.org/stable/4045212 (accessed 20 March 2020).

Wortman, S.E. 2014. Integrating weed and vegetable crop management with multifunctional air-propelled abrasive grits. Weed Technol 28(1): 243–252. doi: 10.1614/WT-D-13-00105.1.

Table 3-1. Soybean cultivars, planting dates, and PRE and POST herbicide application dates in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs for weed control in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.[a]

Study Location[b]	HR-trait	Cultivar	Company[c]	Planting Date	PRE Herbicide Application Date	POST Herbicide Application Date
Clay Center, NE	DGR	S29-k3x NK	Syngenta Seeds	May 07, 2018 May 15, 2019	May 07, 2018 May 15, 2019	June 04, 2018 June 13, 2019
	GLU-R	P31T02L	Corteva AgriScience			
	CON	A3253	Bayer Crop Science			
Concord, NE	DR	27MX8 NK	Syngenta Seeds	June 05, 2018 June 06, 2019	June 06, 2018 June 08, 2019	July 20, 2018 July 11, 2019
	GLU-R	CZ2601LL	BASF Corporation			
	CON	P29T50	Corteva AgriScience			
Lincoln, NE	DGR	S29-k3x NK	Syngenta Seeds	May 13, 2018 May 17, 2019	May 11, 2018 May 17, 2019	June 11, 2018 June 21, 2019
	GLU-R	P31T02L	Corteva AgriScience			
	CON	A3253	Bayer Crop Science			
North Platte, NE[d]	DGR	28XT58	Loveland Products	May 20, 2018 May 31, 2019	May 18, 2018 June 04, 2019	June 26, 2018 July 11, 2019
	GLU-R	CZ2601LL	BASF Corporation			
	CON	A3253	Bayer Crop Science			
Scottsbluff, NE[e]	DGR	AG20X7	Bayer Crop Science	May 21, 2018 June 05, 2019	May 21, 2018 June 05, 2019	July 18, 2018 July 26, 2019
	GLU-R	H20L3	Hefty Seed Company			
	CON	U11-917032 A2035	Husker Genetics Bayer Crop Science			

[a] Abbreviations: CON, conventional; DGR, dicamba/glyphosate-resistant, GLU-R, glufosinate-resistant; POST, Post-emergent herbicide; PRE, Pre-emergent herbicide.

[b] Soil tests for the study locations: Clay Center, NE (Hastings silt loam with a pH of 6.5, 17% sand, 58% silt, and 25% clay, 3.0% organic matter); Concord, NE (Silt loam with a pH of 6.4, 20% sand, 54% silt, 26% clay, 3.5% organic matter and CEC of 23.8); Lincoln, NE (silt clay loam with a pH of 5.6 , 19% sand, 54% silt, 27% clay, 3.3% organic matter); North Platte, NE (Sandy loam with a pH of 7.5, 57% sand, 32% silt, 11% clay, 2.1% organic matter and CEC of 11.7); Scottsbluff, NE (Sandy loam with a pH of 7.5, 78% sand, 8% silt, 13% clay and CEC of 7.8)

[c] BASF Corporation, Florham Park, NJ; 07932; Bayer Crop Science, Creve Coeur, MO 63141; Corteva Agriscience, Johnston, IA 50131; Hefty Seed Company, Baltic, SD 57003; Husker Genetics, Ithaca, NE 68033; Loveland Products Inc, Loveland, CO 80538; Syngenta Seeds, Hopkins, MN 55305

[d] Soybean cultivar A3253 was replanted on June 11, 2019 due to poor initial crop stand.

[e] 122 kg nitrogen and 45 kg P_2O_5 ha^{-1} were broadcasted prior to planting, with 4.7 L ha^{-1} of 6% chelated iron (Ferrilene RTU; Helena AgriEnterprises, LLC, Collierville, TN 38017) applied in-furrow to reduce iron chlorosis.

Table 3-2. PRE fb POST herbicide programs in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs for weed control in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.[a]

Herbicide Program	Rate (g ai ae ha^{-1})	Trade Name	Manufacturer[b]	Adjuvants[c]	Herbicide Program Cost[d] (\$ ha^{-1})	Nozzles, Carrier Volume (L ha^{-1})
Nontreated control						
Weed-free control	1,680 215	Warrant Zidua Pro	Bayer BASF		118.04	AIXR, 140
PRE						
Sulfentrazone/*S*-metolachlor + metribuzin	1,960 700	Authority Elite Tricor 4F	FMC UPI		134.25	AIXR, 140
Chlorimuron/flumioxazin/ thifensulfuron	94	Enlite	Corteva		58.30	AIXR, 140
Flumioxazin/pyroxasulfone + metribuzin	160 210	Fierce Tricor 4F	Valent UPI		83.66	AIXR, 140
Chlorimuron/flumioxazin/ metribuzin	374	Trivence	Corteva		73.48	AIXR, 140
Imazethapyr/pyroxasulfone/ saflufenacil	215	Zidua Pro	BASF		77.92	AIXR, 140
fb POST						
Dicamba + glyphosate	560 + 1,540	Xtendimax + Roundup Powermax	Bayer	DRA, WC	91.31	TTI, 140
Glyphosate	1,540	Roundup Powermax	Bayer	AMS	33.46	AIXR, 140
Glufosinate	656	Liberty	BASF	AMS	50.31	XR, 187
Acetochlor + Clethodim + lactofen	1,680 119 + 220	Warrant Select Max + Cobra	Bayer Valent	AMS, COC	148.74	AIXR, 140

[a] Abbreviations: ai, active ingredient; ae, acid equivalent; AMS, ammonium sulfate; COC, crop oil concentrate (Agri-Dex, Helena Chemical Company, Collierville, TN 38017); DRA, drift reducing agent (Cornbelt Vaporguard + DRA, Van Diest Supply Company, Webster City, IA, 50595 or Intact, Precision Laboratories, Waukegan, IL 60085); fb, followed by; POST, Post-emergent herbicide; PRE, Pre- for pre-emergence herbicide; WC, non-AMS water conditioner (Class Act Ridion, Winfield United, Arden Hills, MN, 55126).

[b] FMC Corporation, Philadelphia, PA 19103; United Phosphorous, Inc., King of Prussia, PA 19406; Corteva AgriScience, Wilmington, DE 19805; Valent U.S.A. Corporation, Walnut Creek, CA 94596; BASF Corporation, Research Triangle Park, NC 27709; Bayer CropScience, Research Triangle Park, NC 27709.

[c] AMS at 1 to 1.25% (wt/v), COC at 1% v/v, DRA at 0.5 to 1% v/v and WC at 1% v/v were mixed with POST herbicide treatments according to label recommendations.

[d] Herbicide costs were averaged from three independent sources in Nebraska and include custom application: PRE (\$17.30 ha^{-1} $application^{-1}$), non-dicamba containing POST (\$18.94 ha^{-1} $application^{-1}$), and dicamba-containing POST (\$31.71 ha^{-1} $application^{-1}$).

Table 3-3. Weed control at 14 & 28 DAPRE in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.[a,b,c,d]

Herbicide Program	Palmer amaranth Control		Common lambsquarters Control		Velvetleaf Control		Grass Species Control		Kochia Control[e]		Total Biomass Reduction[f]
	14 DAPRE	28 DAPRE	14 DAPRE	28 DAPRE	14 DAPRE	28 DAPRE	14 DAPRE	28 DAPRE	14 DAPRE	28 DAPRE	28-45 DAPRE
	%										%
Nontreated control	0	0	0	0	0	0	0	0	0	0	0 e
Weed-free control	99	99	99	99	99	99	99	99	99	99	82 bc
PRE											
Sulfentrazone/*S*-metolachlor + metribuzin	98 a	99 a	96 a	99 a	92 ab	92 abc	97 a	97 a	97 a	95 a	96 a
Chlorimuron/flumioxazin/ thifensulfuron	94 ab	93 b	72 bc	90 b	86 ab	88 bc	84 ab	81 c	69 d	63 d	72 d
Flumioxazin/pyroxasulfone + metribuzin	98 a	98 a	93 ab	95 ab	96 a	87 c	92 a	83 c	94 a	89 ab	88 ab
Chlorimuron/flumioxazin/ metribuzin	98 a	96 ab	85 ab	96 ab	94 a	92 ab	93 a	84 c	88 b	84 b	83 bc
Imazethapyr/pyroxasulfone/ saflufenacil	82 b	96 ab	59 bc	92 b	70 b	94 a	73 b	88 b	77 c	71 c	77 cd
***P*-value**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.041**	**0.009**	**<0.001**	**0.001**	**<0.001**	**<0.001**	**<0.001**
Site Years (n)	6 (672)	7 (784)	5 (560)	5 (560)	4 (448)	6 (672)	4 (448)	7 (784)	1 (112)	1 (112)	6 (672)

[a] Abbreviations: DAPRE, day after PRE herbicide application.

[b] Weed control data at 14 and 28 DAPRE were combined for all study locations in 2018 and 2019. Data were log(x+1) or square root transformed before analysis; however back transformed values are presented based on interpretations of transformed data.

[c] Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

[d] Mean separation for weed control at 14 and 28 DAPRE excluded comparisons to the nontreated control and weed-free control, whereas biomass reduction at 28-45 DAPRE included the comparison of PRE herbicide programs to the nontreated control and weed-free control.

[e] Significant weed pressure from kochia was only present at North Platte, NE in 2018 and 2019, thus this column only includes 14 & 28 DAPRE weed control for this study location.

[f] Total weed biomass in the nontreated control at 28-45 DAPRE was 258 g m^{-2}.

Table 3-4. Weed density at 14 & 28 DAPRE in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.[a,b,c,d]

Herbicide Program	Palmer amaranth Density		Common lambsquarters Density		Velvetleaf Density		Grass Species Density		Kochia Density[e]		Total Density Reduction[f]
	14 DAPRE	28 DAPRE	14 DAPRE	28 DAPRE	14 DAPRE	28 DAPRE	14 DAPRE	28 DAPRE	14 DAPRE	28 DAPRE	28-45 DAPRE
	no. plants m^{-2}										%
Nontreated control	5 c	30 c	21 d	44 c	5 b	8 c	16 b	18 c	58 d	60 d	0 d
Weed-free control	0 a	0 a	3 bc	6 ab	1 b	0 a	2 a	0 a	32 c	33 c	73 ab
PRE											
Sulfentrazone/*S*-metolachlor + metribuzin	0 a	1 ab	0 a	1 a	1 b	2 b	1 a	0 a	1 a	2 a	79 a
Chlorimuron/flumioxazin/ thifensulfuron	0 a	2 b	4 c	13 b	0 b	1 ab	4 a	3 b	32 c	35 c	61 c
Flumioxazin/pyroxasulfone + metribuzin	0 a	1 ab	0 a	6 ab	0 b	1 ab	2 a	1 ab	7 b	7 b	73 ab
Chlorimuron/flumioxazin/ metribuzin	0 a	1 ab	1 ab	8 b	0 b	1 ab	0 a	1 ab	14 b	13 b	71 ab
Imazethapyr/pyroxasulfone/ saflufenacil	1 b	1 ab	3 bc	11 b	1 b	0 a	2 a	0 a	28 c	26 c	68 bc
***P*-value**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Site Years (n)	5 (560)	7 (784)	5 (560)	6 (672)	4 (448)	6 (672)	5 (560)	7 (784)	1 (112)	1 (112)	8 (896)

[a] Abbreviations: DAPRE, day after PRE herbicide application.

[b] Weed density data at 14 and 28 DAPRE were combined for all study locations in 2018 and 2019. Data were log(x+1) or square-root transformed before analysis; however back transformed values are presented based on interpretations of transformed data.

[c] Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

[d] Mean separation for weed density at 14 and 28 DAPRE and total density reduction at 28 DAPRE included comparisons of PRE herbicide programs to the nontreated control and weed-free control.

[e] Significant weed pressure from kochia was only present at North Platte, NE in 2018 and 2019, thus this column only includes weed density at 14 and 28 DAPRE for this location.

[f] Total weed density in the nontreated control at 28-45 DAPRE was 160 plants m^{-2}.

Table 3-5. Weed control at 14 & 28 DAPOST in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.[a,b,c,d,e]

Herbicide Program	Palmer amaranth Control		Common lambsquarters Control		Velvetleaf Control		Grass Species Control		Kochia Control[f]		Total Biomass Reduction
	14 DAPOST	28 DAPOST	14 DAPOST	28 DAPOST	14 DAPOST	28 DAPOST	14 DAPOST	28 DAPOST	14 DAPOST	28 DAPOST	28 DAPOST
	—————————— % ——————————										——%——
Nontreated control	0	0	0	0	0	0	0	0	0	0	0
Weed-free control	99	99	99	99	99	99	99	99	99	99	97
POST											
Dicamba + glyphosate	97	95	98 a	98 a	98 a	98 a	97	98	95 a	94 a	98 a
Glyphosate	94	93	98 a	98 a	98 a	98 a	98	97	89 ab	71 b	97 a
Glufosinate	96	94	98 a	97 a	98 a	97 a	97	97	82 b	70 b	97 a
Acetochlor + clethodim + lactofen	95	94	90 b	87 b	90 b	89 b	94	95	57 c	38 c	89 b
POST *P*-value	**0.631**	**0.216**	**0.008**	**0.024**	**0.001**	**<0.001**	**0.128**	**0.501**	**<0.001**	**<0.001**	**<0.001**
PRE *P*-value	**0.999**	**0.150**	**0.999**	**0.957**	**0.999**	**0.999**	**0.986**	**0.994**	**<0.001**	**<0.001**	**0.896**
Site Years (n)	7 (784)	7 (784)	5 (560)	5 (560)	4 (448)	4 (448)	7 (784)	7 (784)	1 (112)	1 (112)	7 (784)

[a] Abbreviations: DAPOST, day after POST herbicide application.

[b] Weed control data at 14 and 28 DAPOST were combined for all study locations in 2018 and 2019. Data were log(x+1) or square root transformed before analysis; however back transformed values are presented based on interpretations of transformed data.

[c] Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

[d] Mean separation for weed control at 14 and 28 DAPOST and weed biomass reduction at 28 DAPOST excluded comparisons to the nontreated control and weed-free control.

[e] Significant weed pressure from kochia was only present at North Platte, NE in 2018 and 2019, thus this column only includes weed control at 14 and 28 DAPOST for this location.

[f] Total weed biomass for the nontreated control at 28 DAPOST was 1,178 g m^{-2}.

Table 3-6. Weed density at 14 & 28 DAPOST in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.[a,b,c,d]

Herbicide Program	Palmer amaranth Density		Common lambsquarters Density		Velvetleaf Density		Grass Species Density		Kochia Density[e]		Total Density Reduction[f]
	14 DAPOST	28 DAPOST	14 DAPOST	28 DAPOST	14 DAPOST	28 DAPOST	14 DAPOST	28 DAPOST	14 DAPOST	28 DAPOST	28 DAPOST
	no. plants m^{-2}										%
Nontreated control	9	11	24	18	4	7	13	34	12	15	0
Weed-free control	0	2	1	0	0	0	0	0	4	5	96
POST											
Dicamba + glyphosate	0	1	0 a	0	0 a	0 a	0 a	0	2	4	94
Glyphosate	1	1	0 a	0	0 a	0 a	0 a	0	4	4	94
Glufosinate	1	1	0 a	0	0 a	0 a	0 a	1	3	5	92
Acetochlor + clethodim + lactofen	0	1	1 b	2	1 b	1 b	1 a	2	13	6	86
POST *P*-value	**0.369**	**0.633**	**0.016**	**0.999**	**<0.001**	**<0.001**	**0.007**	**0.999**	**0.421**	**0.273**	**0.832**
PRE *P*-value	**0.930**	**0.651**	**0.973**	**0.999**	**0.998**	**0.997**	**0.543**	**0.999**	**0.004**	**0.067**	**0.949**
Site Years (n)	6 (672)	7 (784)	5 (560)	7 (784)	4 (448)	4 (448)	6 (672)	7 (784)	1 (112)	1 (112)	7 (784)

[a] Abbreviations: DAPOST, day after POST herbicide application.

[b] Weed density data at 14 and 28 DAPOST were combined for all study locations in 2018 and 2019. Data were log(x+1) or square root transformed before analysis; however back transformed values are presented based on interpretations of transformed data.

[c] Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

[d] Mean separation for weed density at 14 and 28 DAPOST and total density reduction excluded comparisons to the nontreated control and weed-free control.

[e] Significant weed pressure from Kochia was only present at North Platte, NE in 2018 and 2019, thus this column only includes weed density at 14 and 28 DAPOST for this location.

[f] Total weed density in the nontreated control at 28 DAPOST was 85 plants m^{-2}.

Table 3-7. Soybean yield affected by herbicide programs in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.[a,b,c,d]

HR-Trait	Herbicide Program		Program Cost[d]	Soybean Yield					
				Clay Center 2018	Concord 2018	Lincoln 2018	Scottsbluff 2018	Concord 2019	North Platte 2019
	PRE	POST	–$ ha^{-1}–	kg ha^{-1}					
DGR	Nontreated control	--	132.96	635 gh	1,854 e	622 d	406 gh	2,176 c	2,476
	Weed-free control		342.31	4,346 abc	3,662 ab	4,803 ab	4,728 abc	4,525 a	3,505
	Sulfentrazone/*S*-metolachlor + metribuzin	fb dicamba + glyphosate	358.52	4,282 abc	3,851 ab	4,812 ab	4,988 ab	4,670 a	3,698
	Chlorimuron/flumioxazin/thifensulfuron		282.57	3,925 abc	3,740 ab	4,690 ab	4,532 abc	4,685 a	3,302
	Flumioxazin/pyroxasulfone + metribuzin		307.93	4,669 a	3,768 ab	4,732 a	4,775 abc	4,878 a	3,849
	Chlorimuron/flumioxazin/metribuzin		297.75	4,343 ab	3,831 ab	4,767 ab	3,551 abcde	4,587 a	3,330
	Imazethapyr/pyroxasulfone/saflufenacil		302.19	4,154 abc	3,553 ab	4,591 ab	4,774 abc	4,598 a	3,217
DGR	Nontreated control	--	132.96	778 fgh	1,887 e	672 d	273 h	2,021 c	2,014
	Weed-free control		284.46	4,448 ab	3,803 ab	5,143 a	5,120 ab	4,719 a	2,828
	Sulfentrazone/*S*-metolachlor + metribuzin	fb glyphosate	300.67	3,925 abc	3,906 ab	4,681 ab	4,442 abc	4,674 a	3,468
	Chlorimuron/flumioxazin/thifensulfuron		224.72	4,065 abc	3,735 ab	4,554 ab	4,900 a	4,538 a	3,179
	Flumioxazin/pyroxasulfone + metribuzin		250.08	4,361 a	3,839 a	4,686 a	5,080 a	4,857 a	3,272
	Chlorimuron/flumioxazin/metribuzin		239.9	3,957 ab	3,835 ab	4,717 ab	4,726 abc	4,768 a	3,132
	Imazethapyr/pyroxasulfone/saflufenacil		244.34	3,919 abc	3,578 ab	4,290 ab	5,284 a	4,647 a	3,007
GLU-R	Nontreated control	--	109.33	562 gh	2,216 e	1,662 c	334 h	2,249 bc	2,101
	Weed-free control		277.68	4,494 ab	3,807 ab	4,995 a	3,687 bcde	4,223 a	3,230
	Sulfentrazone/*S*-metolachlor + metribuzin	fb glufosinate	293.89	3,746 abc	3,657 ab	4,870 ab	3,974 abcd	4,397 a	3,364
	Chlorimuron/flumioxazin/thifensulfuron		217.94	3,454 abc	3,427 bc	4,198 ab	4,245 abcd	4,412 a	2,771
	Flumioxazin/pyroxasulfone + metribuzin		243.3	3,812 abc	3,591 ab	4,538 ab	3,880 abcd	4,527 a	3,690
	Chlorimuron/flumioxazin/metribuzin		233.12	3,922 abc	3,631 ab	4,233 ab	3,553 bcde	4,331 a	2,966
	Imazethapyr/pyroxasulfone/saflufenacil		237.56	3,710 abc	3,524 ab	4,120 ab	3,797 abcde	4,447 a	3,269
CON	Nontreated control	--	108.58	357 h	1,752 e	1,280 c	109 h	2,551 b	2,419
	Weed-free control		375.36	3,771 abc	3,018 cd	4,788 ab	2,451 ef	4,632 a	2,623
	Sulfentrazone/*S*-metolachlor + metribuzin	fb acetochlor + clethodim + lactofen	391.57	2,939 abcd	2,947 d	4,529 ab	3,174 cdef	4,784 a	3,779
	Chlorimuron/flumioxazin/thifensulfuron		315.62	1,674 def	2,744 d	4,475 ab	2,087 ef	4,726 a	2,854
	Flumioxazin/pyroxasulfone + metribuzin		340.98	2,742 bcde	2,897 cd	3,930 b	2,707 def	4,681 a	3,700
	Chlorimuron/flumioxazin/metribuzin		330.8	2,472 cde	2,966 cd	4,431 ab	1,888 fg	4,940 a	3,294
	Imazethapyr/pyroxasulfone/saflufenacil		335.24	1,411 efg	2,987 cd	4092 ab	2,338 ef	4,719 a	2,900
	PRE fb POST *P*-value			**< 0.001**	**0.009**	**< 0.001**	**0.002**	**0.014**	**0.132**

[a] Abbreviations: CON, conventional; DGR, dicamba/glyphosate-resistant; GLU-R, glufosinate-resistant

[b] Yield data for each site year was log(1+x) or square root transformed before analysis; however back transformed values are presented based on interpretations of transformed data.

[c] Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

[d] Weed management program cost was averaged from three independent sources in Nebraska and include custom application cost: PRE (\$17.30 ha^{-1} application^{-1}), non-dicamba containing POST (\$18.94 ha^{-1} application^{-1}), dicamba containing POST (\$31.71 ha^{-1} application^{-1}), and seed costs: DGR (\$132.96 ha^{-1}), GLU-R (\$109.33 ha^{-1}), CON (\$108.58 ha^{-1}).

Table 3-8. Gross profit margin in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.[a,b]

HR-Trait	Herbicide Program		Gross Profit Margin					
			Clay Center 2018	Concord 2018	Lincoln 2018	Scottsbluff 2018	Concord 2019	North Platte 2019
	PRE	POST	$\$ ha^{-1}$					
	Nontreated control	--	59.46	428.54	-126.37	20.70	526.07	617.01
	Weed-free control		974.21	766.96	1,112.68	1,086.53	1,028.32	719.48
	Sulfentrazone/*S*-metolachlor + metribuzin	fb	938.61	807.94	1,099.19	1,169.30	1,055.95	761.51
DGR	Chlorimuron/flumioxazin/thifensulfuron	dicamba +	906.44	850.23	1,138.22	1,109.75	1,136.65	717.66
	Flumioxazin/pyroxasulfone + metribuzin	glyphosate	1,106.40	833.41	1,125.46	1,148.35	1,169.60	857.94
	Chlorimuron/flumioxazin/metribuzin		1,017.84	862.75	1,146.23	822.93	1,091.68	710.96
	Imazethapyr/pyroxasulfone/saflufenacil		956.11	774.07	1,088.55	1,130.41	1,090.58	672.23
	Nontreated control	--	102.72	438.58	-102.01	-2.81	479.21	477.02
	Weed-free control		1,062.80	867.54	1,273.29	1,255.35	1,145.10	572.24
	Sulfentrazone/*S*-metolachlor + metribuzin		888.33	882.64	1,117.27	1,084.54	1,115.23	749.80
DGR	Chlorimuron/flumioxazin/thifensulfuron	fb	1,006.52	906.52	1,154.62	1,297.32	1,149.79	738.34
	Flumioxazin/pyroxasulfone + metribuzin	glyphosate	1,070.96	912.69	1,169.38	1,290.38	1,221.15	740.93
	Chlorimuron/flumioxazin/metribuzin		958.63	921.73	1,188.98	1,209.30	1,204.36	708.79
	Imazethapyr/pyroxasulfone/saflufenacil		942.65	839.39	1,055.16	1,351.35	1,163.36	666.59
	Nontreated control	--	61.02	562.06	91.18	26.60	571.81	527.16
	Weed-free control		1,083.72	875.46	1,235.23	830.95	1,001.50	700.70
	Sulfentrazone/*S*-metolachlor + metribuzin		840.88	813.79	1,181.16	927.25	1,038.09	725.17
GLU-R	Chlorimuron/flumioxazin/thifensulfuron	fb	828.33	820.17	1,053.71	1,069.80	1,118.51	621.54
	Flumioxazin/pyroxasulfone + metribuzin	glufosinate	911.55	844.47	1,131.29	943.52	1,127.95	874.53
	Chlorimuron/flumioxazin/metribuzin		954.97	866.72	1,049.20	861.00	1,078.82	665.26
	Imazethapyr/pyroxasulfone/saflufenacil		886.23	830.00	1,010.47	910.86	1,109.61	752.55
	Nontreated control	--	16.50	505.71	340.02	-25.89	785.62	739.37
	Weed-free control		946.43	682.71	1,302.92	475.96	1,248.26	544.11
	Sulfentrazone/*S*-metolachlor + metribuzin	fb	638.56	641.64	1,195.93	740.37	1,285.35	933.27
CON	Chlorimuron/flumioxazin/thifensulfuron	acetochlor +	271.17	646.14	1,253.13	436.74	1,341.05	684.96
	Flumioxazin/pyroxasulfone + metribuzin	clethodim +	620.20	674.71	686.24	610.01	1,299.75	955.92
	Chlorimuron/flumioxazin/metribuzin	lactofen	535.87	709.09	1,222.29	349.12	1,401.03	823.94
	Imazethapyr/pyroxasulfone/saflufenacil		159.49	712.00	1,099.18	496.03	1,319.11	681.17

[a] Abbreviations: CON, conventional; DGR, dicamba/glyphosate-resistant; GLU-R, glufosinate-resistant

[b] Gross profit margins were calculated as gross revenue from soybean yield based on the average price received in Nebraska from September to December in 2018 and 2019 for GM-soybean and non-GM soybean minus weed management program cost (Table 7). Conventional cultivars include gross profit margins with price premiums equivalent of $\$0.05\ kg^{-1}$.

Table 3-9. Benefit-cost ratio in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019.[a,b]

HR-Trait	Herbicide Program		Benefit/Cost Ratio					
			Clay Center 2018	Concord 2018	Lincoln 2018	Scottsbluff 2018	Concord 2019	North Platte 2019
	PRE	POST	$\$ ha^{-1}$					
DGR	Nontreated control	--						
	Weed-free control		3.28	1.60	4.23	3.73	2.08	0.91
	Sulfentrazone/*S*-metolachlor + metribuzin	fb dicamba + glyphosate	3.08	1.69	4.05	3.83	2.11	1.03
	Chlorimuron/flumioxazin/thifensulfuron		3.53	2.02	5.00	4.38	2.69	0.89
	Flumioxazin/pyroxasulfone + metribuzin		3.97	1.88	4.63	4.23	2.66	1.35
	Chlorimuron/flumioxazin/metribuzin		3.77	2.01	4.83	3.25	2.45	0.87
	Imazethapyr/pyroxasulfone/saflufenacil		3.53	1.70	4.58	4.23	2.43	0.74
DGR	Nontreated control	--						
	Weed-free control		3.91	2.04	5.37	4.96	2.87	0.87
	Sulfentrazone/*S*-metolachlor + metribuzin	fb glyphosate	3.17	2.03	4.61	4.17	2.67	1.47
	Chlorimuron/flumioxazin/thifensulfuron		4.43	2.49	6.00	6.19	3.39	1.57
	Flumioxazin/pyroxasulfone + metribuzin		4.34	2.36	5.55	5.64	3.44	1.52
	Chlorimuron/flumioxazin/metribuzin		4.01	2.46	5.83	5.50	3.47	1.41
	Imazethapyr/pyroxasulfone/saflufenacil		3.89	2.10	5.19	6.00	3.26	1.23
GLU-R	Nontreated control	--						
	Weed-free control		4.29	1.73	4.73	3.50	2.15	1.23
	Sulfentrazone/*S*-metolachlor + metribuzin	fb glufosinate	3.28	1.48	4.34	3.69	2.21	1.30
	Chlorimuron/flumioxazin/thifensulfuron		4.02	1.68	4.91	5.28	3.01	0.93
	Flumioxazin/pyroxasulfone + metribuzin		4.05	1.71	4.83	4.32	2.84	1.98
	Chlorimuron/flumioxazin/metribuzin		4.37	1.84	4.64	4.11	2.71	1.12
	Imazethapyr/pyroxasulfone/saflufenacil		4.01	1.67	4.41	4.26	2.80	1.49
CON	Nontreated control	--						
	Weed-free control		3.19	1.18	3.28	2.05	1.94	0.19
	Sulfentrazone/*S*-metolachlor + metribuzin	fb acetochlor + clethodim + lactofen	2.31	1.07	2.91	2.68	2.00	1.22
	Chlorimuron/flumioxazin/thifensulfuron		1.46	1.10	3.55	2.12	2.42	0.48
	Flumioxazin/pyroxasulfone + metribuzin		2.45	1.18	1.70	2.55	2.19	1.32
	Chlorimuron/flumioxazin/metribuzin		2.24	1.29	3.34	1.81	2.53	0.93
	Imazethapyr/pyroxasulfone/saflufenacil		1.10	1.29	2.94	2.23	2.27	0.50

[a] Abbreviations: CON, conventional; DGR, dicamba/glyphosate-resistant; GLU-R, glufosinate-resistant

[b] Benefit/Cost Ratio were calculated as gross revenue from soybean yield based on the average price received in Nebraska from September to December in 2018 and 2019 for GM-soybean and non-GM soybean minus gross revenue in the nontreated control, divided by weed management program cost. Conventional cultivars include gross profit margins with price premiums equivalent of $\$0.05\ kg^{-1}$.

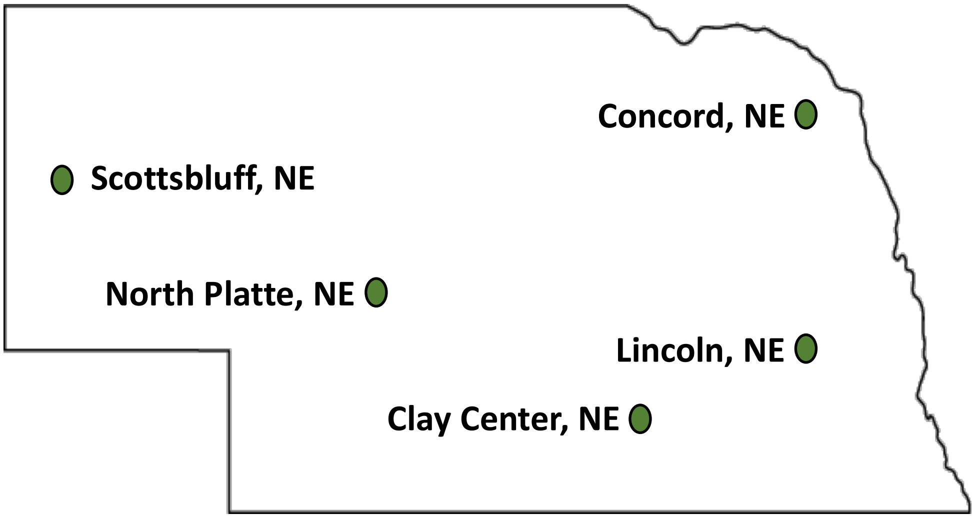

Figure 3-1. State map of Nebraska indicating study locations for field experiments conducted across irrigated (Clay Center, North Platte, and Scottsbluff) and rain-fed (Concord and Lincoln) conditions to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean.

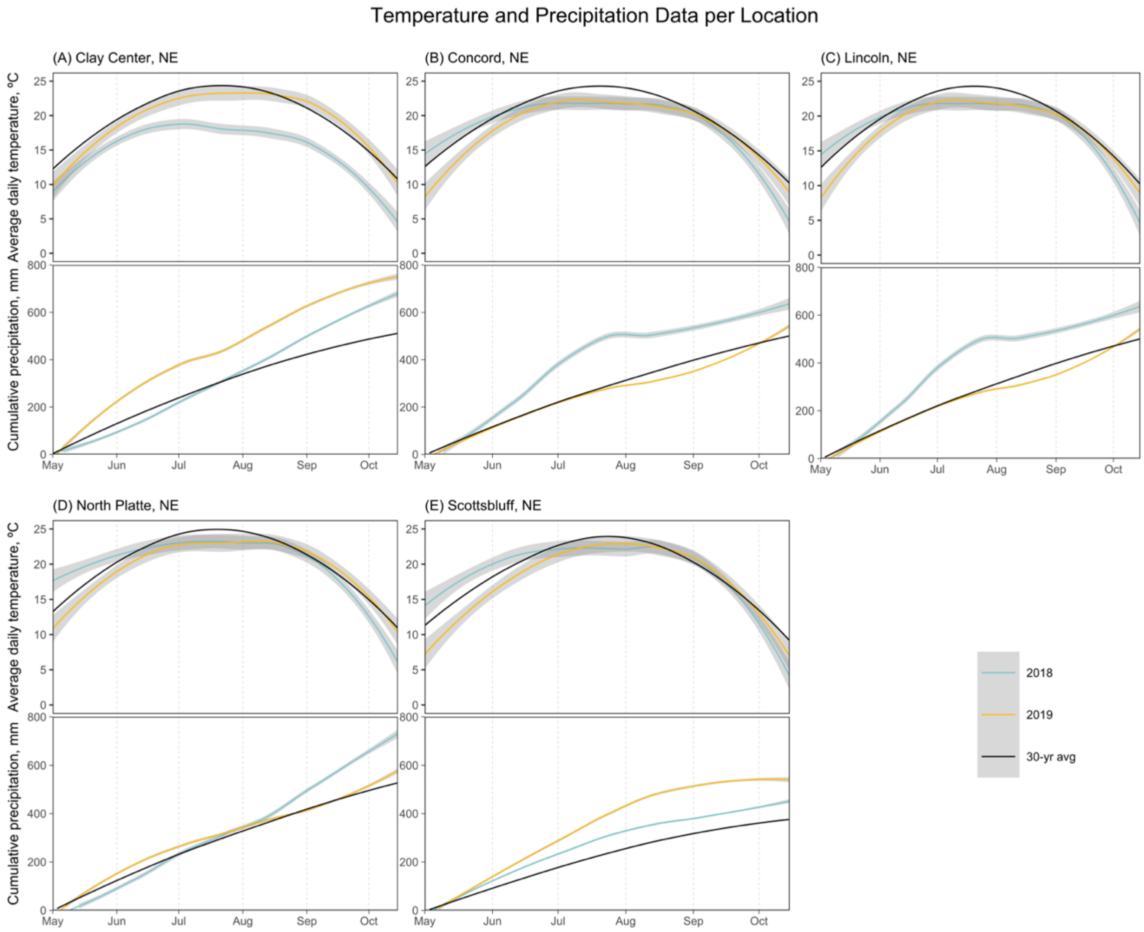

Figure 3-2. Average daily air temperature (ºC) and total cumulative precipitation (mm) received during the 2018 and 2019 growing seasons compared to the 30-year average for field experiments conducted across irrigated and rainfed conditions in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean.

APPENDIX B: SOYBEAN CROP INJURY

Table B-1. PRE visual injury ratings at 14 & 28 DAPRE in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019 [a,b,c,d]

Herbicide Program	14 DAPRE	28 DAPRE
PRE	——%	——
Nontreated control	0.0	0.0
Weed-free control	1.4	4.0
Sulfentrazone/*S*-metolachlor + metribuzin	2.4	2.7
Chlorimuron/flumioxazin/ thifensulfuron	1.2	3.1
Flumioxazin/pyroxasulfone + metribuzin	1.0	3.1
Chlorimuron/flumioxazin/ metribuzin	1.0	3.2
Imazethapyr/pyroxasulfone/ saflufenacil	1.7	3.8
***P*-value**	**0.915**	**0.711**
Site Years (n)	6 (672)	6 (672)

[a] Abbreviations: DAPRE, day after PRE herbicide application.

[b] Crop injury data at 14 and 28 DAPRE were combined for all study locations in 2018 and 2019. Data were logit transformed before analysis; however back transformed values are presented based on interpretations of transformed data.

[c] Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

[d] Mean separation for crop injury at 14 and 28 DAPRE included comparisons to the weed-free control.

Table B-2. POST visual injury ratings at 14 & 28 DAPOST in field experiments conducted across five locations in Nebraska to determine economics of herbicide programs in conventional, glufosinate, and dicamba/glyphosate-resistant soybean in 2018 and 2019 [a,b,c,d]

Herbicide Program	Cultivar HR-Traits	14 DAPOST		28 DAPOST	
		PHYDEF	PHYNEC	PHYDEF	PHYNEC
POST		——————%——————			
Dicamba + glyphosate	DR	0.0 a	0.0 a	0.0 a	0.0 a
Glyphosate	DR	0.0 a	0.0 a	0.0 a	0.0 a
Glufosinate	GLU-R	13.2 b	0.0 a	11.5 b	0.0 a
Acetochlor + clethodim + lactofen	CON	12.7 b	11.7 b	11.9 b	8.5 b
	***P*-value**	**<0.001**	**<0.001**	**<0.001**	**0.031**
	Site Years (n)	6 (672)	6 (672)	6 (672)	6 (672)

[a] Abbreviations: DAPOST, day after POST herbicide application; CON, conventional; GLU-R, glufosinate-resistant; DGR, dicamba/glyphosate-resistant; HR, Herbicide-resistant; PHYDEF, phytotoxic deformities; PHYNEC, phytotoxic necrosis.

[b] Crop injury data at 14 and 28 DAPOST were combined for all study locations in 2018 and 2019. Data were logit transformed before analysis; however back transformed values are presented based on interpretations of transformed data.

[c] Means presented within the same column with no common letters are significantly different according to estimated marginal means with Sidak confidence-level adjustments and Tukey *P*-value adjustments.

[d] Mean separation for crop injury at 14 and 28 DAPOST excluded comparisons to the nontreated control and weed-free control.