Research Article

Received: 1 October 2020 Revised: 11 January 2021 Accepted article published: 29 January 2021 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/ps.6309

Future efficacy of pre-emergence herbicides in corn (*Zea mays*) is threatened by more variable weather

Christopher A Landau,[a] Aaron G Hager,[a] Patrick J Tranel,[a] Adam S Davis,[a] Nicolas F Martin[a] and Martin M Williams II[b*]

Abstract

BACKGROUND: By 2050, weather is expected to become more variable with a shift towards higher temperatures and more erratic rainfall throughout the U.S. Corn Belt. The effects of this predicted weather change on pre-emergence (PRE) herbicide efficacy have been inadequately explored. Using an extensive database, spanning 252 unique weather environments, the efficacy of atrazine, acetochlor, *S*-metolachlor, and mesotrione, applied PRE alone and in combinations, was modeled on common weed species in corn (*Zea mays* L.).

RESULTS: Adequate rainfall to dissolve the herbicide into soil water solution so that it could be absorbed by developing weed seedlings within the first 15 days after PRE application was essential for effective weed control. Across three annual weed species, the probability of effective control increased as rainfall increased and was maximized when rainfall was 10 cm or more. When rainfall was less than 10 cm, increasing soil temperatures had either a positive or negative effect on the probability of effective control, depending on the herbicide(s) and weed species. Herbicide combinations required less rainfall to maximize the probability of effective control and had higher odds of successfully controlling weeds compared with the herbicides applied individually.

CONCLUSIONS: Results of this study highlight the importance of rainfall following PRE herbicide application. As rainfall becomes more variable in future, the efficacy of common PRE herbicides will likely decline. However, utilizing combinations of PRE herbicides along with additional cultural, mechanical, biological, and chemical weed control methods will create a more sustainable integrated weed management system and help U.S. corn production adapt to more extreme weather.

Keywords: pre-emergence herbicides; weather variability; herbicide efficacy; corn; *Zea mays*; integrated weed management

1 INTRODUCTION

Over the next three decades, the weather is expected to be more variable in the U.S. Corn Belt. Current climate predictions for the region suggest an overall increase in spring rainfall followed by decreased summer rainfall.[1] Much of the extra spring rainfall is expected in an increase in the number of extreme rainfall events accompanied by more short drought periods between rainfall events.[2,3] More frequent spring rainfall events will reduce the number of field working days in April and May.[4] In addition, an increase in the average air temperature of 1.1–2.2°C is predicted for the Corn Belt.[1] It is expected that there will be a concomitant increase in soil temperatures, as there is a linear relationship between air and soil temperatures.[5,6] Future weather changes call into question how the efficacy of many soil-applied herbicide-based weed control programs may be affected.

A central component of many weed management programs in corn is the use of soil-applied pre-emergence (PRE) herbicides. The residual activity of PRE herbicides allows growers to control weed cohorts that emerge with the crop or shortly after crop emergence.[7] PRE herbicides improve the efficacy of other weed control strategies by reducing the number and size of early emerging weeds at the time of implementing additional tactics.[8]

Most PRE herbicides require rainfall or irrigation within the first 2 weeks after application to dissolve the herbicide into soil water solution so that it can be absorbed by emerging weeds.[9] Inadequate incorporation of the herbicide into the soil within this period, in general, reduces herbicide bioavailability and efficacy.[10–13] Research on this issue has been limited by relatively few rainfall scenarios. The impact of a broad range of rainfall scenarios on PRE herbicide efficacy is poorly quantified.

* *Correspondence to: MM Williams II, Global Change and Photosynthesis Research Unit, USDA-ARS, 1102 S. Goodwin Avenue, Urbana, IL 61801, USA. E-mail: martin.williams@usda.gov*

a *Department of Crop Sciences, University of Illinois, Urbana, IL, USA*

b *Global Change and Photosynthesis Research Unit, USDA-ARS, Urbana, IL, USA*

The efficacy of many PRE herbicides also is affected by soil temperature. Generally, as soil temperature increases, the efficacy of PRE herbicides declines due to enhanced volatilization, herbicide metabolism within plants, and/or photochemical and microbial breakdown within the soil.[14–16] Additionally, above-average soil temperature promotes germination and early growth of many weeds, thereby shortening the period when the weed is exposed to PRE herbicides.[17,18] Much of the previous research on soil temperature effects on PRE herbicides focused on crop injury and not weed control. Moreover, the study of soil temperature-mediated effects on PRE herbicide efficacy is often isolated to a low number of controlled-temperature treatments. Knowledge of the effect of a broad range of soil temperatures on PRE herbicide efficacy is limited.

Previous studies quantifying the influence of weather on common PRE herbicide efficacy were often based on ten or fewer environments. As such, the inference space used to understand the effects of rainfall and temperature on PRE herbicide efficacy is quite narrow compared with the actual weather conditions in which the products must perform. This study aims to extract new knowledge from 25 years of herbicide performance and weather data to better capture the range of weather conditions affecting PRE herbicide efficacy. Developing a larger inference space would better characterize PRE efficacy and assist U.S. corn producers to adapt to climate change. The objectives of this study were to: (i) determine the risk of reduced weed control efficacy of common PRE products due to variation in rainfall and soil temperature, and (ii) determine the extent to which PRE herbicide combinations improve the success of weed control in variable weather environments compared with PRE herbicides applied individually. Three hypotheses were tested: (i) the probability of successful weed control increases with rainfall accumulation following application; (ii) increasing soil temperature following PRE application negatively affects weed control; and (iii) in variable weather environments, PRE herbicide combinations increase the odds of successful weed control compared with herbicides applied individually.

2 MATERIALS AND METHODS

2.1 Data collection

Between 1992 and 2016, 2695 individual herbicide evaluation trials were conducted across Illinois by the Herbicide Evaluation Program (HEP) at the University of Illinois. Trials contained numerous different herbicide treatments but often consisted of individual herbicides (hereafter referred to as simply 'herbicides'), combinations of two or more herbicides (hereafter referred to as 'herbicide combinations'), adjuvants, and non-chemical weedy controls. A majority of the trials were conducted at the Crop Science Research and Education Center (CSREC) in Urbana, IL. The primary soil types were Flanagan silt loam (fine, smectitic, mesic Aquic Argiudolls), and Drummer silty clay loam (fine-silty, mixed, mesic, Typic Endoaquolls). Both soil types are in the Mollisols soil order, the most common soil order throughout much of the Corn Belt.[19] Treatments within each trial were arranged in a randomized complete block design with three replicates. Within each trial, percent weed control (0% being no control, 100% being complete control) for individual species was recorded at varying times throughout the growing season. Trial data were entered into FieldPro: Bio Data Management Software (Heartland Technologies, Inc.), which allowed for the collected data from each trial to be archived into a single database containing all trials.

TABLE 1. Treatments and rate range used in the analysis. Rate ranges were constructed from the current maximum labeled rates of products represented in the database

Treatment	Rate (kg ai ha^{-1})
Atrazine	1.79–2.24
Acetochlor	1.68–2.24
S-Metolachlor	1.42–1.78
Atrazine + acetochlor	1.12–1.68 + 1.99–2.18
Atrazine + *S*-metolachlor	1.74–1.83 + 1.35–1.41
Atrazine + *S*-metolachlor + mesotrione	0.84–0.85 + 2.25–2.26 + 0.22–0.23

2.2 Database management

Only trials conducted at the CSREC fields were used for analysis. The HEP database was filtered to contain only treatments with weed control ratings taken 21–35 days after treatment (DAT) on the most represented weeds; common lambsquarters (*Chenopodium album* L.), giant foxtail (*Setaria faberi* Herm.), and/or waterhemp (*Amaranthus tuberculatus* (Moq.) Sauer). Additionally, the database was filtered to only contain treatments with at least one PRE application. In order to prevent a postemergence (POST) treatment from confounding the results, treatments that contained a POST application component following PRE application were only included if the POST treatment was applied after the 21–35 DAT control rating was recorded. Therefore, all data, results, and interpretations are based on a relatively early-season assessment of PRE herbicide performance.

Following the filtering process, six PRE herbicide and herbicide combinations were selected: atrazine, acetochlor, *S*-metolachlor, atrazine + acetochlor, atrazine + *S*-metolachlor, and atrazine + *S*-metolachlor + mesotrione. These six treatments were used in the analyses described below. All treatments were labeled for control of common lambsquarters, giant foxtail, and waterhemp with the exception of *S*-metolachlor on common lambsquarters. However, suppression or control of common lambsquarters with *S*-metolachlor has been previously reported.[20,21] Each of the treatments was applied at several rates and under different trade names since 1992. Rate ranges for each treatment were created as ±5% of the maximum recommended rate from the current (2020) labels for the various trade names represented in the database in order to remove experimental rates and focus solely on agriculturally relevant rates. Treatments with rates that did not fall within this range were excluded from analyses. Rate ranges selected for each treatment are presented in Table 1.

Daily mean soil temperature at 10 cm and daily rainfall were obtained from an Illinois State Water Survey weather station within 1 km of the CSREC (Champaign, IL, www.sws.uiuc.edu/atmos/statecli). Although 10 cm is deeper than the weed emergence zone for the three weed species included in this study, soil temperature at this standard depth helps characterize the variable environments. Total rainfall and average temperatures 0–15 DAT were calculated for each trial.

2.3 Statistical analysis

Prior to analyses, percent weed control ratings for each species were converted to a binary variable using a scale modified from the Canadian Weed Science Society, where ratings of 80% of higher were considered acceptable to excellent control (hereafter referred to as 'successful' weed control; response = 1) and ratings lower than 80% were considered poor control to suppression (hereafter referred to as 'unsuccessful' weed control; response = 0).

To test the effects of rainfall and temperature on the probability of successful weed control, data were subjected to logistic regression. Individual models were built for each treatment by weed species combination using a stepwise logistic regression procedure with the following logistic regression equation as the full model:

$$P = \frac{1}{1 + e^{-(\beta_0 + \beta_1 R + \beta_2 T + \beta_3 R^* T)}} \quad (1)$$

Where P is the probability of successful weed control, R is the total amount of rainfall (cm), T is the average soil temperature (°C) at a depth of 10 cm, and β_0, β_1, β_2, and β_3 are regression coefficients.

For each model, the maximum likelihood regression coefficient estimates were calculated, and Wald's chi-square was used to test the statistical significance of each regression term. Goodness of fit was measured with the Hosmer–Lemeshow lack-of-fit test, which indicated reasonable fits for each model ($P > 0.1$).[22] Parameter estimates for weed control models are presented in Table 2. Contour plots were constructed to visualize individual models.

To compare the effect of individual herbicides to that of herbicide combinations on weed control, odds ratios (ORs) and confidence intervals (CIs) were calculated for each weed species by comparing the combined odds of successful weed control of the individual herbicides (atrazine, acetochlor, and *S*-metolachlor) to the odds of successful weed control of each of the herbicide combinations. Herbicide combinations whose CI contains 1.0 are interpreted as not significantly improving the likelihood of having successful weed control compared with individual herbicides. Herbicide combinations whose CI endpoints are greater than 1.0 are interpreted as improving the likelihood of successful weed control.[23]

All statistical analyses were conducted using R version 3.5.3.[24]

3 RESULTS AND DISCUSSION

3.1 Weeds and weather variability

Observed weed species varied by trial, but only common lambsquarters, giant foxtail, and waterhemp were treated with all six herbicides and herbicide combinations in multiple trials. All three weeds are representative of U.S. corn production and are ranked as the top three most common weeds in U.S. corn production.[25] Both common lambsquarters and waterhemp are ranked in the top five most troublesome weeds.

Weather conditions following treatment application varied greatly among herbicide evaluation trials. Throughout the 25 years of herbicide trials, PRE application dates ranged from Julian dates 104 to 179, or approximately 14 April to 28 June. The data set represents a total of 252 environments. Total rainfall from the treatment application to 15 DAT ranged from 0.1 to 18.6 cm (Figure 1a). The average soil temperature (10 cm depth)

TABLE 2. Parameter estimates for the logistic regression models discriminating control of common lambsquarters (*Chenopodium album*), giant foxtail (*Setaria faberi*), and waterhemp (*Amaranthus tuberculatus*) using atrazine, acetochlor, *S*-metolachlor, atrazine + acetochlor, atrazine + *S*-metolachlor, and atrazine + *S*-metolachlor + mesotrione

Weed Species	Herbicide	Intercept	Rainfall (R)	Temperature (T)	R×T	Hosmer–Lemeshow *P*-value	Observations
Common lambsquarters	Atrazine	5.25	−1.76*[a]	−0.38	0.16**	0.25	107
	Acetochlor	0.55	0.33**	0.05*	—	0.15	108
	S-Metolachlor	−3.15**	0.10**	0.20**	—	0.16	204
	atrazine + acetochlor	6.67	1.91**	−0.43*	—	0.15	142
	Atrazine + *S*-metolachlor	−7.37	0.15*	0.63**	—	0.47	136
	Atrazine + *S*-metolachlor + mesotrione	4.91	−4.25**	−0.32	0.34**	0.11	173
Giant foxtail	Atrazine	−5.02**	0.20**	0.24**	—	0.13	138
	Acetochlor	−5.54	0.39**	0.38**	—	0.78	106
	S-Metolachlor	−0.68	0.67**	−0.07*	—	0.15	255
	atrazine + acetochlor	5.24	1.57**	−0.36**	—	0.67	162
	Atrazine + *S*-metolachlor	−4.76	0.57**	0.25*	—	0.72	165
	Atrazine + *S*-metolachlor + mesotrione	−0.64	1.99**	−0.17*	—	0.25	173
Waterhemp	Atrazine	−2.81	0.46**	0.11*	—	0.16	95
	Acetochlor	−1.50	0.76**	−0.05*	—	0.11	102
	S-Metolachlor	−5.97**	0.17**	0.35**	—	0.13	192
	atrazine + acetochlor	1.89	0.89**	−0.12*	—	0.75	162
	Atrazine + *S*-metolachlor	−4.48	1.28**	0.06*	—	0.22	167
	Atrazine + *S*-metolachlor + mesotrione	19.60**	−5.91*	−1.28**	0.47**	0.19	160

[a] Regression parameters statistically significant at *0.10 and **0.05 α level, respectively.

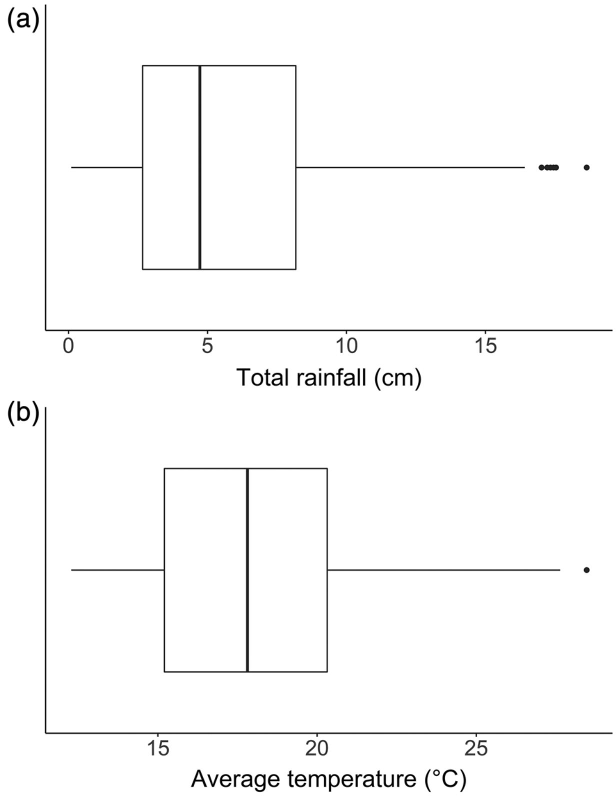

FIGURE 1. Distributions of (a) total rainfall (cm) and (b) average soil temperature at 10 cm (°C) over 15 days after treatment.

over the first 15 DAT ranged from 12.3 to 27.6°C (Figure 1b). The wide range of weather conditions comes closer to representing the diverse weather environments of the Corn Belt than any previous research on PRE herbicide efficacy to date.

3.2 Contour plots

Individual regression models for each treatment by weed species combination are presented (Figure 2). Three of the 18 individual models contained a significant rainfall by temperature interaction term. Total rainfall (cm) within 15 DAT is listed on the *x*-axis and average soil temperature (°C) on the *y*-axis. The probability of successful control is the color gradient with a probability of 0.0 represented as yellow and a probability of 1.0 represented as dark blue.

3.3 Effect of rainfall variation

As hypothesized, the probability of successful control of common lambsquarters, giant foxtail, and waterhemp increased with rainfall following PRE treatment application. Although the total amount of rainfall required to maximize the probability of successful control varied by herbicide treatment and the sensitivity of each species to the treatments, 5–10 cm of rainfall after application maximized the probability of successful weed control for most treatments (Figure 2). By contrast, the absence of rainfall within 15 days proved detrimental for the efficacy of most herbicide treatments. In previous studies comparing efficacy across nine or fewer environments, rainfall within the first 15 DAT was required to prevent loss in efficacy due to poor incorporation of atrazine, acetochlor, *S*-metolachlor, and mesotrione into the soil–water solution, leading to reduced uptake by developing

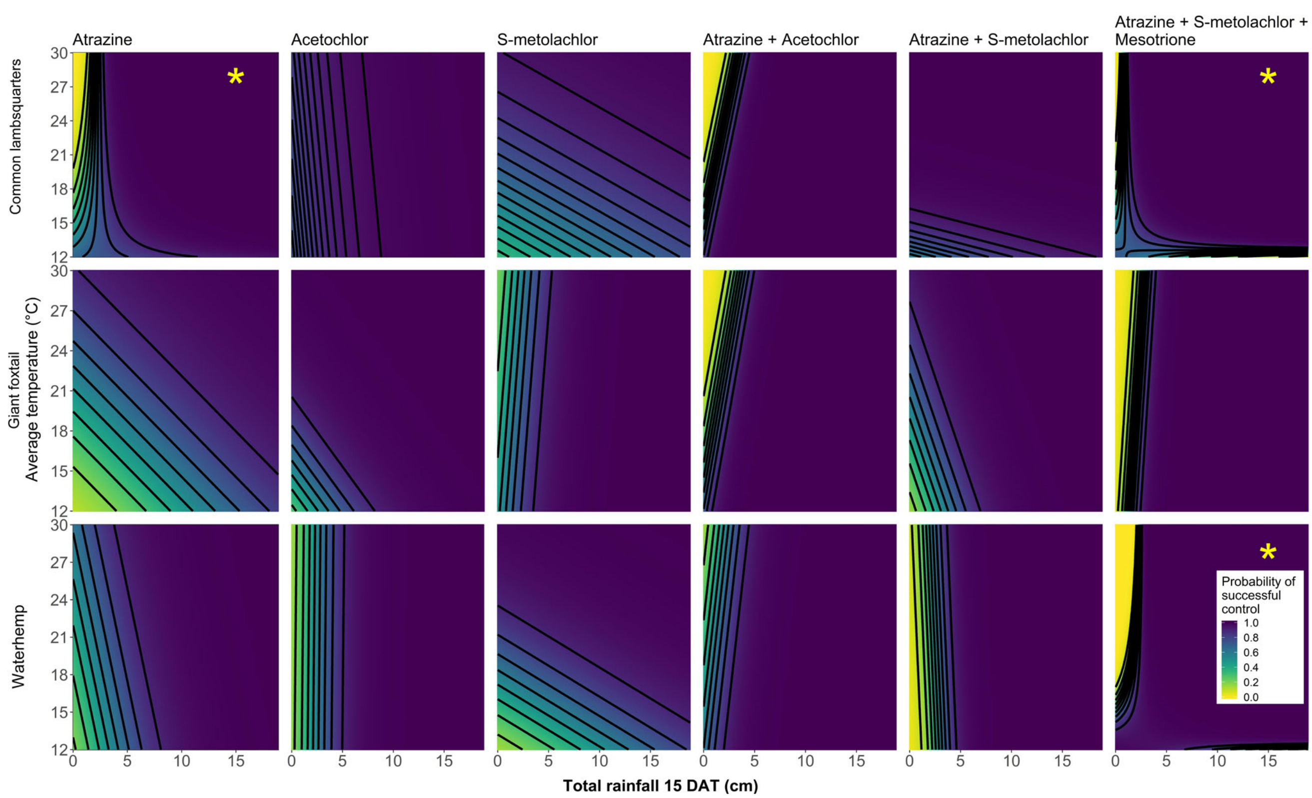

FIGURE 2. Contour plots of probability of successful control of common lambsquarters (*Chenopodium album*), giant foxtail (*Setaria faberi*), and waterhemp (*Amaranthus tuberculatus*) as a function of total rainfall and average soil temperature from application to 15 days after treatment (DAT). *Significant rainfall by temperature interaction at α =0.05.

weed seeds.[11,26,27] Janak and Grichar[28] reported rainfall accumulation less than 5 cm over the first 14 days after planting (DAP) resulted in reduced control of *Panicum fasciculatum* from combinations of atrazine, *S*-metolachlor, and mesotrione. Because rainfall is required to move PRE herbicides into the soil–water solution, poor herbicide efficacy under limited rainfall is likely due to low bioavailability of the PRE herbicides.

The least amount of early-season rainfall required to maximize the probability of successful weed control varied by herbicide treatment and weed species combination; however, the rainfall requirement was lower for most of the herbicide combinations compared with individual herbicides. For example, 10–15 cm of rainfall was required to maximize the probability of successful waterhemp control with *S*-metolachlor, whereas only 5 cm was needed to maximize control with acetochlor (Figure 3). The addition of atrazine to both of these herbicides largely negates the differences in weed control, thereby reducing the amount of rainfall required to maximize control to 5 cm for both combinations. Poor control of giant foxtail with metolachlor and atrazine + metolachlor was previously observed in environments with less than 2 cm of rainfall by 15 DAT compared with environments with 2 cm or more of rainfall, but the efficacy of atrazine + metolachlor was less sensitive to rainfall than the individual herbicides.[29] Results from the current study utilizing 252 environments showed that the herbicide combinations reduce the risk of poor weed control caused by inadequate rainfall. The reduced risk with herbicide combinations in this study is likely caused by numerous factors including selectivity, water solubility, and soil sorption of each component in the herbicide combination.

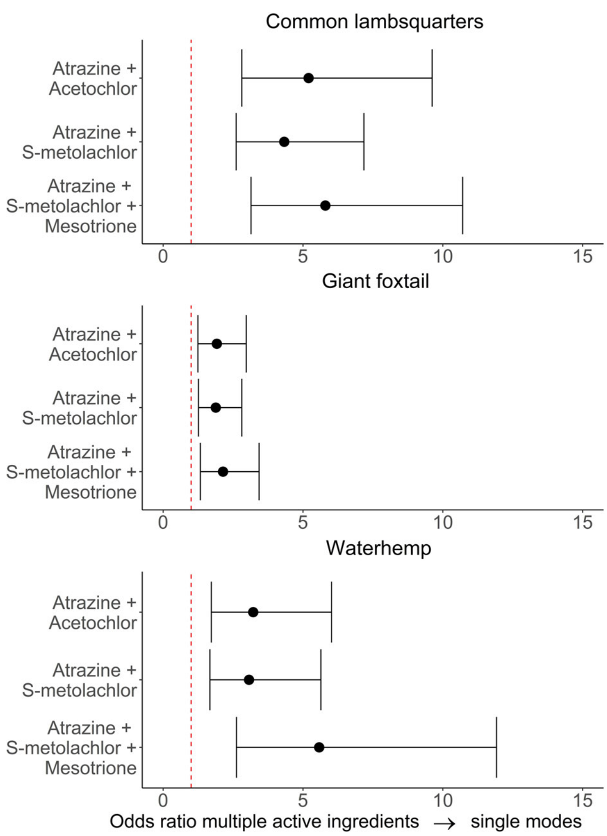

FIGURE 3. Odds ratio (OR) estimates and 95% confidence intervals (CIs) for control of common lambsquarters (*Chenopodium album*), giant foxtail (*Setaria faberi*), and waterhemp (*Amaranthus tuberculatus*) due to differences between individual herbicides and herbicide combinations. The black dot represents the OR and solid black lines represent 95% CIs. The dashed red line represents an OR of 1.0. Herbicide combinations whose confidence intervals are > 1.0 have a significantly higher probability of successful weed control compared with the individual herbicides.

3.4 Effect of soil temperature variation

The hypothesis that increasing soil temperature following PRE application negatively affects weed control was not consistently true across herbicides and herbicide combinations, and in general, soil temperatures only affected early season weed control when rainfall was limiting. When rainfall by 15 DAT was 10 cm or more, the probability of successful weed control with most treatments was maximized under all tested soil temperatures (Figure 2). However, when rainfall was less than 10 cm, increasing soil temperatures either increased or decreased the probability of successful weed control, depending on the herbicide or herbicide combination. The decrease in the probability of successful weed control at warmer soil temperatures observed with some treatments may be due to increased herbicide degradation in both the plant and soil at warmer temperatures.[15,16,30–32] Increased herbicide uptake at warmer temperatures has been reported in velvetleaf (*Abutilon theophrasti* Medik.) and soybean (*Glycine max* L. Merr.) and is a likely cause of the increased probability of successful weed control observed at warmer temperatures in this study.[33,34]

The average air temperature in the Corn Belt is predicted to increase by 1.1–2.2°C over the next three decades, and soil temperature is expected to follow a similar trend.[1,5,6] Results from the current study further demonstrate that future weather is likely to exacerbate variability in herbicide efficacy.

3.5 Overcoming weather variability with herbicide combinations?

The hypothesis that PRE herbicide combinations have increased odds of successful weed control compared with individual PRE herbicides held true for control of common lambsquarters, giant foxtail, and waterhemp. The ORs and CI for each of the herbicide combinations used on the three weed species were greater than 1.0, but the magnitude of this increase varied by weed species and herbicide combination (Figure 3). For example, atrazine + *S*-metolachlor + mesotrione increased the odds of successful waterhemp control by 458% (CI 2.62 to 11.92), whereas the odds of successful giant foxtail control increased by 114% (CI 1.33 to 3.43) compared with the individual herbicides alone. In previous studies comparing efficacy across seven or fewer environments, combinations of atrazine, acetochlor, *S*-metolachlor, and mesotrione often achieved greater control of common lambsquarters, giant foxtail, and waterhemp than that of the herbicides applied alone.[13,35,36]

To prevent corn yield loss from weed interference, weeds must be controlled typically between emergence and the eight-leaf stage in corn.[37,38] To accomplish this, PRE herbicides and herbicide combinations are often used to control early-emerging weeds and increase the efficacy of subsequent chemical or mechanical weed control methods. Results from the current study show future weather can reduce the efficacy of common PRE herbicides; however, combinations of atrazine, acetochlor, *S*-metolachlor, and mesotrione overcome some risk of variable weather on PRE herbicide efficacy. Determining the exact cause of this increased efficacy of PRE herbicide combinations was beyond the scope of this research; however, it does highlight an area of future research. Pre-emergence herbicide combinations are but one component to further integrate with other weed management tactics in a future with changing and more variable weather.

4 CONCLUSION

Over the next three decades, the U.S. Corn Belt is predicted to experience more variable weather. These changes in weather will affect the efficacy of common PRE herbicides. Results from this study, which compared herbicide efficacy across 252 weather environments, show reduced efficacy of atrazine, acetochlor, *S*-metolachlor, and mesotrione under rainfall-limited conditions. Furthermore, future temperatures in rainfall-limited conditions are likely to exacerbate variability in herbicide efficacy. These conclusions are a cautionary note for areas of the Corn Belt where erratic weather, particularly lack of rainfall, is more common than in Illinois. Results also indicate that utilizing herbicide combinations of atrazine + acetochlor, atrazine + *S*-metolachlor, or atrazine + *S*-metolachlor + mesotrione reduces some risks associated with limited rainfall and increases the likelihood of controlling common lambsquarters, giant foxtail, and waterhemp early in the growing season compared with that of the herbicides applied alone. The development and adoption of more integrated weed management strategies that utilize PRE herbicides in combination with additional cultural, mechanical, biological, and POST chemical control options are needed in the quest to adapt U.S. corn production to climate change.

ACKNOWLEDGMENTS

The authors greatly appreciate the work of the many individuals who contributed to the Herbicide Evaluation Program at the University of Illinois Urbana-Champaign. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.

REFERENCES

1 Hayhoe K, Wuebbles DJ, Easterling DR, Fahey DW, Doherty S, Kossin J *et al.*, Our changing climate: in impacts, risks, and adaptation in the United States, in *Fourth National Climate Assessment Volume II*, ed. by Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, KLM L, Maycock TK *et al.* U.S. Global Change Research Program, Washington, DC, pp. 72–144 (2018).

2 IPCC, Managing the risks of extreme events and disasters to advance climate change adaptation, in *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge (2012).

3 Tomasek BJ, Williams MM and Davis AS, Optimization of agricultural field workability predictions for improved risk management. *Agron J* **107**:627–633 (2015).

4 Tomasek BJ, Williams MM and Davis AS, Changes in field workability and drought risk from projected climate change drive spatially variable risks in Illinois cropping systems. *PLoS One* **12**:1–15 (2017).

5 Islam KI, Khan A and Islam T, Correlation between atmospheric temperature and soil temperature: a case study for Dhaka, Bangladesh. *Atmos Clim Sci* **05**:200–208 (2015).

6 Jungqvist G, Oni SK, Teutschbein C and Futter MN, Effect of climate change on soil temperature in Swedish boreal forests. *PLoS One* **9**: 1–12 (2014).

7 Parker RG, York AC and Jordan DL, Weed control in glyphosate-resistant corn as affected by preemergence herbicide and timing of postemergence herbicide application. *Weed Technol* **20**:564–570 (2006).

8 Jha P, *Performance of Preemergence Herbicides on Waterhemp Control in Soybean Integrated Crop Management* (2020). Available: https://crops.extension.iastate.edu/cropnews/2020/04/performance-preemergence-herbicides-waterhemp-control-soybean [20 May 2020].

9 Buhler DD, Early preplant atrazine and metolachlor in conservation tillage corn (*Zea mays*). *Weed Technol* **5**:66–71 (1991).

10 Taylor-Lovell S and Wax LM, Weed control in field corn (*Zea mays*) with RPA 201772 combinations with atrazine and *S*-metolachlor. *Weed Technol* **15**:249–256 (2001).

11 Stewart CL, Soltani N, Nurse RE, Hamill AS and Sikkema PH, Precipitation influences pre- and post-emergence herbicide efficacy in corn. *Am J Plant Sci* **3**:1193–1204 (2012).

12 Stewart CL, Nurse RE, Hamill AS and Sikkema PH, Environment and soil conditions influence pre- and postemergence herbicide efficacy in soybean. *Weed Technol* **24**:234–243 (2010).

13 Armel GR, Wilson HP, Richardson RJ and Hines TE, Mesotrione, acetochlor, and atrazine for weed management in corn (*Zea mays*). *Weed Technol* **17**:284–290 (2006).

14 Prueger JH, Alfieri J, Gish TJ, Kustas WP, Daughtry CST, Hatfield JL *et al.*, Multi-year measurements of field-scale metolachlor volatilization. *Water Air Soil Pollut* **228**:84 (2017).

15 Godar AS, Varanasi VK, Nakka S, Prasad PVV, Thompson CR and Mithila J, Physiological and molecular mechanisms of differential sensitivity of Palmer amaranth (*Amaranthus palmeri*) to mesotrione at varying growth temperatures. *PLoS One* **10**: 1–17 (2015).

16 Zimdahl RL and Clark SK, Degradation of three acetanilide herbicides in soil. *Weed Sci* **30**:545–548 (1982).

17 Hull HM, Morton HL and Wharre JR, Environmental influences on cuticle developement and resultant foliar penetration. *Bot Rev* **41**: 421–452 (1975).

18 Varanasi A, Prasad PVV and Jugulam M, Impact of climate change factors on weeds and herbicide efficacy. *Adv Agron* **135**:107–146 (2016).

19 Soil Survey Staff, *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys; 2nd edn, Agricultural Handbook 436*. Natural Resources Conservatio Service, United States Department of Agriculture, Washington, DC (1999).

20 Clewis SB, Everman WJ, Jordan DL and Wilcut JW, Weed management in North Carolina peanuts (*Arachis hypogaea*) with *S*-metolachlor, diclosulam, flumioxazin, and sulfentrazone systems. *Weed Technol* **21**:629–635 (2007).

21 Chomas AJ and Kells JJ, Triazine-resistant common lambsquarters (*Chenopodium album*) control in corn with preemergence herbicides. *Weed Technol* **18**:551–554 (2004).

22 Hosmer DW and Lemeshow S, Goodness of fit tests for the multiple logistic regression model. *Commun Stat Theory Methods* **9**: 1043–1069 (1980).

23 Villamil MB, Alexander M, Silvis AH and Gray ME, Producer perceptions and information needs regarding their adoption of bioenergy crops. *Renew Sustain Energy Rev* **16**:3604–3612 (2012).

24 R Core Team, *R: A Language and Environment for Statistical Computing*. R Foundation, Vienna (2019).

25 Van Wychen L. 2017 Survey of the most common and troublesome weeds in grass crops, pasture and turf in the United States and Canada. Weed Science Society of America National Weed Survey Dataset. Available: https://wssa.net/wp-content/uploads/2017-Weed-Survey_Grass-crops.xlsx (2017).

26 Geier PW, Stahlman PW, Regehr DL and Olson BL, Preemergence herbicide efficacy and phytotoxicity in grain sorghum. *Weed Technol* **23**:197–201 (2009).

27 Whaley CM, Armel GR, Wilson HP and Hines TE, Comparison of mesotrione combinations with standard weed control programs in corn. *Weed Technol* **20**:605–611 (2006).

28 Janak TW and Grichar WJ, Weed control in corn (*Zea mays* L.) as influenced by preemergence herbicides. *Int J Agron* **2016**:1–9 (2016).

29 Young BG and Hart SE, Giant foxtail (*Setaria faberi*) control in sethoxydim-resistant corn (*Zea mays*). *Weed Sci* **45**:771–776 (1997).

30 Kunkel DL, Bellinder RR and Steffens JC, Safeners reduce corn (*Zea mays*) chloroacetanilide and dicamba injury under different soil temperatures. *Weed Technol* **10**:115–120 (1996).

31 van Rensburg E, van Dyk LP and de Swardt GH, Role of temperature and water potential on the activity of some acetanilide herbicides on three phaseolus taxa. *S Afr J Plant Soil* **7**:113–116 (1990).
32 Viger PR, Eberlein CV, Fuerst EP and Gronwald JW, Effects of CGA-154281 and temperature on metolachlor absorption and metabolism, glutathione content, and glutathione-*S*-transferase activity in corn (*Zea mays*). *Weed Sci* **39**:324–328 (1991).
33 Price TP and Balke NE, Characterization of rapid atrazine absorption by excised velvetleaf *(Abutilon theophrasti*) roots. *Weed Sci* **30**:633–639 (1982).
34 Vostral HJ, Buchholtz KP and Kust CA, Effect of root temperature on absorption and translocation of atrazine in soybeans. *Weed Sci* **18**: 115–117 (1970).
35 Hay MM, Albers JJ, Dille JA and Peterson DE, Control of atrazine-resistant Palmer amaranth (*Amaranthus palmeri*) in double-crop grain sorghum. *Weed Technol* **33**:115–122 (2019).
36 Loux MM, Dobbels AF, Johnson WG and Young BG, Effect of residual herbicide and postemergence application timing on weed control and yield in glyphosate-resistant corn. *Weed Technol* **25**:19–24 (2011).
37 Moriles J, Hansen S, Horvath DP, Reicks G, Clay DE and Clay SA, Microarray and growth analyses identify differences and similarities of early corn response to weed, shade, and nitrogen stress. *Weed Sci* **60**:158–166 (2012).
38 Page ER, Cerrudo D, Westra P, Loux M, Smith K, Foresman C *et al*., Why early season weed control is important in maize. *Weed Sci* **60**: 423–430 (2012).