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Weather and glufosinate efficacy: a retrospective analysis looking forward to the changing climate

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Abstract

Foliar-applied postemergence applications of glufosinate are often applied to glufosinate-resistant crops to provide nonselective weed control without significant crop injury. Rainfall, air temperature, solar radiation, and relative humidity near the time of application have been reported to affect glufosinate efficacy. However, previous research may have not captured the full range of weather variability to which glufosinate may be exposed before or following application. Additionally, climate models suggest more extreme weather will become the norm, further expanding the weather range to which glufosinate can be exposed. The objective of this research was to quantify the probability of successful weed control (efficacy ≥85%) with glufosinate applied to some key weed species across a broad range of weather conditions. A database of >10,000 North American herbicide evaluation trials was used in this study. The database was filtered to include treatments with a single postemergence application of glufosinate applied to waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer], morningglory species (*Ipomoea* spp.), and/or giant foxtail (*Setaria faberi* Herrm.) <15 cm in height. These species were chosen because they are well represented in the database and listed as common and troublesome weed species in both corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] (Van Wychen 2020, 2022). Individual random forest models were created. Low rainfall (≤20 mm) over the 5 d before glufosinate application was detrimental to the probability of successful control of *A. tuberculatus* and *S. faberi*. Lower relative humidity (≤70%) and solar radiation (≤23 MJ m^{-1} d^{-1}) on the day of application reduced the probability of successful weed control in most cases. Additionally, the probability of successful control decreased for all species when average air temperature over the first 5 d after application was ≤25 C. As climate continues to change and become more variable, the risk of unacceptable control of several common species with glufosinate is likely to increase.

Introduction

Glufosinate was first commercialized in the United States and Canada in 1993 as a nonselective herbicide applied postemergence to weeds (Takano and Dayan 2020). Following the commercialization of glufosinate-resistant corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] between 1995 and 2009, growers could apply glufosinate in-crop without significant crop injury. Currently, glufosinate is applied to 2%, 14%, and 23% of corn, cotton, and soybean hectares in the United States, respectively (USDA-NASS 2024).

Glufosinate inhibits glutamine synthetase, resulting in an accumulation of ammonia and reactive oxygen species (ROS) when exposed to light (Takano et al. 2019; Wild et al. 1987). Overabundance of ROS leads to rapid membrane destruction and, ultimately, cell death (Takano et al. 2019). This effect occurs more rapidly as light intensity increases, and injury symptoms can be observed within a few hours after application (Takano and Dayan 2020). However, it takes a few days for complete death of sensitive plant species.

Average yearly air temperatures throughout the major North American corn- and soybean-growing regions are expected to increase by 2 to 5 C over the coming century (Marvel et al. 2023). These warmer temperatures could prove beneficial to glufosinate efficacy. Anderson et al. (1993a) showed a 20% increase in glufosinate efficacy on green foxtail [*Setaria viridis* (L.) P. Beauv.] as the day/night temperature regime increased from 15/10 C to 22/17 C. A similar trend was observed in several *Amaranthus* species (Coetzer et al. 2001). However, while glufosinate efficacy may increase as temperatures increase, so too will the growth rate of many common weed species (Varanasi et al. 2016). This increased growth rate will likely cause increased weed height by the time a postemergence application can be made and will ultimately reduce glufosinate efficacy (Anonymous 2023; Guo and Al-Khatib 2003; Wall 1993).

Increased air temperatures may also decrease relative humidity. For every 1 C increase in temperature, the water-holding capacity of the air will increase by 7%, meaning more moisture would be required to reach the same humidity level (Zhou et al. 2023). Lower humidity can be detrimental to the effectiveness of glufosinate. Coetzer et al. (2001) reported a 30% to 50% decrease in control of three *Amaranthus* species as relative humidity decreased from 90% to 35% at the time of glufosinate application. Much of North America is expected to experience a slight increase in yearly rainfall from an increase in the number of rainfall events as well an increase in extreme rainfall events alongside these changes in temperature and humidity (Marvel et al. 2023). Extreme rainfall events can reduce the number of field working days within a season, and delay postemergence applications of glufosinate, reducing the efficacy of the herbicide (Tomasek et al. 2017). It has been well documented that rainfall is most detrimental to glufosinate efficacy when it occurs within the first 4 h after application (Anderson et al. 1993b; Everman et al. 2009; Souza et al. 2014); however, little has been reported about how longer periods of rainfall affect efficacy.

Beyond climatic conditions, glufosinate efficacy is impacted by a variety of other factors, including weed species, weed height at application, weed density, time of day, spray equipment, nozzle size, droplet size, adjuvant, and herbicide resistance (Anonymous 2023). Globally, six weed species have been confirmed to have evolved glufosinate resistance (Heap 2024; Takano and Dayan 2020). A better understanding of how glufosinate interacts with weeds and their environment will be essential for providing guidance on the utility and limitations of glufosinate.

Previous research pertaining to changes in glufosinate efficacy due to weather variability have included 10 or fewer environments. Additionally, few studies have investigated the combined effects of rainfall, temperature, solar radiation, and relative humidity near the time of application on glufosinate efficacy. As such, the inference space may not adequately capture the full range of weather conditions in which glufosinate is applied. The objective of this research was to utilize herbicide efficacy and weather data from the past 30 yr to quantify the effects of rainfall, temperature, humidity, and solar radiation near the time of application on the probability of successfully controlling agronomically important weeds.

Materials and Methods

Data Collection

Many North American land-grant universities maintain a herbicide evaluation program (HEP). These HEPs often provide results on the efficacy of commonly used herbicides for control of the most common/troublesome weed species in agronomic cropping systems. Most HEPs conduct more than 50 herbicide trials each year, which include an average of 15 treatments, each replicated 3 to 4 times. Herbicide efficacy is rated as visual assessments of weed control (0% being no control and 100% being total weed death). Data from 20 HEPs from the United States and Canada were combined and standardized into a common queryable database in 2020. For more details on the HEP database, see Landau et al. (2023).

Database Management

The HEP database was filtered to include only treatments that had glufosinate as the only postemergence herbicide treatment. Treatments that included a preemergence herbicide component were excluded to prevent confounding effects. Treatments that contained a second postemergence application following glufosinate were only included if there was a control rating reported before the second postemergence herbicide application. Treatments were only included if they were applied with ammonium sulfate (AMS) in accordance with label guidelines (Anonymous 2023). Additionally, treatments were only included if they were within ±10% of the current label-recommended glufosinate use rate of 595 g ai ha^{-1} (Anonymous 2023). The database was further filtered to include ratings recorded 7 to 21 d after glufosinate application. Following this initial filtering, several weed species had sufficient data for analysis. These species were waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] and giant foxtail (*Setaria faberi* Herrm.). Morningglory (*Ipomoea* spp.) species were often rated as a collective group by the individual HEPs. As such, *Ipomoea* spp. (primarily composed of tall morningglory [*Ipomoea purpurea* (L.) Roth] and entireleaf morningglory [*Ipomoea hederacea* Jacq.], although the composition of the group was not always described for each trial) were also included. The species selected are agronomically important weeds, as they are ranked among the most common and troublesome weed species in both corn and soybean (Van Wychen 2020, 2022).

Mean weed control ratings for each treatment were calculated as the mean for the three to four replicates. More than 95% of the trials contained information on weed heights at the time of glufosinate application. Control ratings for weeds taller (or longer in the case of the vining *Ipomoea* spp.) than the height limit on the

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Table 1. Year range and number of environments for key weed species, *Amaranthus tuberculatus, Ipomoea* spp., *and Setaria faberi*, in each state/province.

State/province	Years	*Amaranthus tuberculatus*	*Ipomoea* spp.	*Setaria faberi*
		Number of environments		
Delaware	2010–2019		70	
Illinois	1992–2021	1,118	748	1,009
Indiana	2007–2019	85	95	150
Iowa	2005–2021	87	53	82
Kansas	2011–2020		148	
Michigan	2008–2021	51		55
Minnesota	1993–2022	51	88	99
Missouri	2010–2022	647	299	456
Nebraska	2012–2021	60	50	
Ohio	1997–2021		51	302
Ontario	1998–2010			128
Pennsylvania	2006–2010			58
South Dakota	2012–2021	72		41
Virginia	2015–2021		33	31
Wisconsin	2018–2022	60		30

glufosinate label of 15 cm at the time of application were removed (Anonymous 2023). Best management practices, including correct application timing and using recommended spray equipment, are followed by the HEPs when applying herbicide treatments. If weed height was not recorded at the time of application or no notes were written in the trial data, weed height was presumed to be below the height threshold. After the database was filtered, data from 16 institutions representing 14 U.S. states and 1 Canadian province remained for analysis. Not all institutions had data for each of the species, and year range varied by location (Table 1). Varying herbicide application dates among individual trials across the 16 institutions led to 1,635 to 2,441 unique weather environments in which the weed species selected in this study were analyzed (Table 1).

Total precipitation and average air temperature were added for time intervals of 5, 10, and 20 d before and after glufosinate application using the Daymet database (Thornton et al. 2022). Total solar radiation was added for the day of application as well as 1 and 5 d after application using the Daymet database. Additionally, relative humidity was calculated at the same time points as solar radiation using the following equation from Alduchov and Eskridge (1996):

$$\mathrm{RH} = 100 * \left[\frac{e^{\frac{17.625*D_p}{243.04+D_p}}}{e^{\frac{17.625*T}{243.04+T}}}\right] \quad [1]$$

where RH is relative humidity, D_p is the dew point extracted from the Daymet database, and T is the average daily temperature from the Daymet database. Weed control was converted to a binary variable using a modified scale developed by the Canadian Weed Science Society, where ≥85% was considered acceptable (hereafter called "successful" control) and control <85% was considered unacceptable to no control (hereafter called "unsuccessful") in order to standardize weed control ratings across the various HEPs (CWSS 2018).

Statistical Analysis

Random forest analysis was used to model the effects of location, total precipitation, average temperature, relative humidity, and total solar radiation around the time of application on the probability of successful weed control with glufosinate. The random forest analysis was conducted using the RANDOMFOREST package in R (Liaw and Wiener 2002). Model parameters and area under the curve of the receiver operator curve (AUC ROC) values are listed in Table 2. Random forest is a machine learning algorithm that makes no assumptions about the distribution of the data and that can be used with missing data and with both quantitative and qualitative variables. Random forest algorithm aggregates numerous tree models built from random subsets of the independent variables and observations into one final model. The number of individual trees in this analysis was set to 500.

Several random forest models were initially fit using the weather data values for the aforementioned time intervals added to the HEP database, and separate models were made for each weed species/group. Model descriptions and AUC ROC values are shown in Table 2. The model that provided the best fit included location, rainfall, and temperature 5 d before and 5 d after application, and relative humidity and solar radiation the day of application. Only this optimum model was used for model visualization and further analysis. To visualize the optimum model, partial dependency plots were created using the PDP package in R (Greenwell 2017) to show the partial effects of two select variables at a time (rainfall and temperature before application, rainfall and temperature after application, or relative humidity and solar radiation the day of application) while keeping the other variables in the model static at their respective means.

The mean-square error of each tree used in the optimum model was calculated twice, once from the initial tree model and then again after permutating each independent variable. The difference between the two mean-square errors was averaged across all 500 trees and divided by the SE to calculate the importance of each independent variable (Breiman 2001).

Results and Discussion

The random forest analyses in this study modeled the effects on glufosinate efficacy of a larger range of spatial and weather variables than previously attempted. The weeds selected in this study are among the most troublesome and/or common weeds in corn and soybean (Van Wychen 2020, 2022). The optimum random forest models had high accuracies for predicting the probability of successful weed control with glufosinate. The optimum model for all species had an AUC ROC of 0.90 to 0.94 (Table 2), which is considered excellent to outstanding (Mandrekar 2010).

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Table 2. Random forest model fits for models using varying weather time point variables to predict the probability of control of key weed species with glufosinate[a].

Species	Number of environments	Total rainfall	Average air temperature	Total solar radiation	Average relative humidity	Model AUC ROC[b]
		Time range (days before and after glufosinate application)[c]				
Amaranthus tuberculatus	2,231	**5**	**5**	**0**	**0**	**0.94**
		5	5	1	1	0.91
		5	5	5	5	0.91
		10	10	0	0	0.89
		10	10	1	1	0.89
		10	10	5	5	0.90
		20	20	0	0	0.90
		20	20	1	1	0.90
		20	20	5	5	0.89
Ipomoea spp.	1,635	**5**	**5**	**0**	**0**	**0.90**
		5	5	1	1	0.87
		5	5	5	5	0.88
		10	10	0	0	0.87
		10	10	1	1	0.84
		10	10	5	5	0.84
		20	20	0	0	0.88
		20	20	1	1	0.88
		20	20	5	5	0.86
Setaria faberi	2,441	**5**	**5**	**0**	**0**	**0.91**
		5	5	1	1	0.88
		5	5	5	5	0.87
		10	10	0	0	0.89
		10	10	1	1	0.88
		10	10	5	5	0.88
		20	20	0	0	0.87
		20	20	1	1	0.87
		20	20	5	5	0.87

[a]The optimum model providing the highest fit for each species/group is boldface.
[b]AUC, area under the curve of the receiver operator curve.
[c]0 d signifies values on the day of application.

The importance of each independent variable within the models varied by species/group; however, trial location was the least important predictor for all three species (Figure 1). This was foreseeable, as political boundaries were expected to have little to no effect on herbicide efficacy.

Temperature and Rainfall before Application

Average air temperature 5 d before glufosinate application was a highly important predictor of the probability of successful control of *A. tuberculatus* and *Ipomoea* spp., appearing in the top three most important predictors, although the effect varied by species (Figure 1). Probability of successful *A. tuberculatus* control increased when average air temperatures were ≥24 C (Figure 2). Lower air temperatures may have resulted in lower *A. tuberculatus* growth rate and therefore smaller size at the time of application, thus increasing the probability of successful control (Anonymous 2023; Guo and Al-Khatib 2003; Wall 1993). Coetzer et al. (2001) reported a minor decrease in *A. tuberculatus* control with glufosinate when the plants were grown at a 21/16 C temperature regime compared with 26/21 C and 31/26 C regimes.

Control probability of *Ipomoea* spp. decreased as temperatures increased above 27 C (Figure 2). This is likely caused by higher growth rate at warmer temperatures increasing the weed's size by the time of application (Guo and Al-Khatib 2003; Wall 1993). Everman et al. (2009) previously showed that air temperatures before application had no effect on the efficacy or the translocation of glufosinate in pitted morningglory (*Ipomoea lacunosa* L.). The differential response between the current study and previous results is likely due to differences in species composition. The *Ipomoea* spp. group analyzed in this study consists of multiple species that may have differential responses to temperature (Higgins et al. 1988; Ribeiro et al. 2018).

While not as influential, low total rainfall 5 d before glufosinate application was an important predictor of the probability of successful control. The *A. tuberculatus* and *S. faberi* control probabilities were slightly reduced when total rainfall was ≤20 mm 5 d before application (Figure 2). Steckel et al. (1997a) reported decreased control in years that had ≤4 mm of rainfall before glufosinate application compared with a year with 46 mm of rainfall. The observed decrease in the probability of successful control at lower rainfall amounts in this study may be due to changes in cuticle thickness and chemistry, which could reduce glufosinate absorption through the cuticle (Steckel et al 1997b; Trezzi et al. 2020). While overall warming temperatures throughout corn and soybean production regions may increase the probability of successful control of some weed species evaluated within the present study, predicted greater rainfall and number of extreme rainfall events are likely to increase the risk of unsuccessful control with glufosinate.

Day of Application

Total solar radiation on the day of glufosinate application was the most important predictor for *Ipomoea* spp. and *S. faberi* control (Figure 1). More specifically, lower solar radiation typically led to lower probabilities of successful control. Solar radiation ≤17 MJ m^{-1} d^{-1} reduced the probability of control of *Ipomoea* spp., while probability of successful *S. faberi* control was reduced when solar radiation was ≤23 MJ m^{-1} d^{-1} (Figure 2). Sellers et al. (2003) showed a significant decrease

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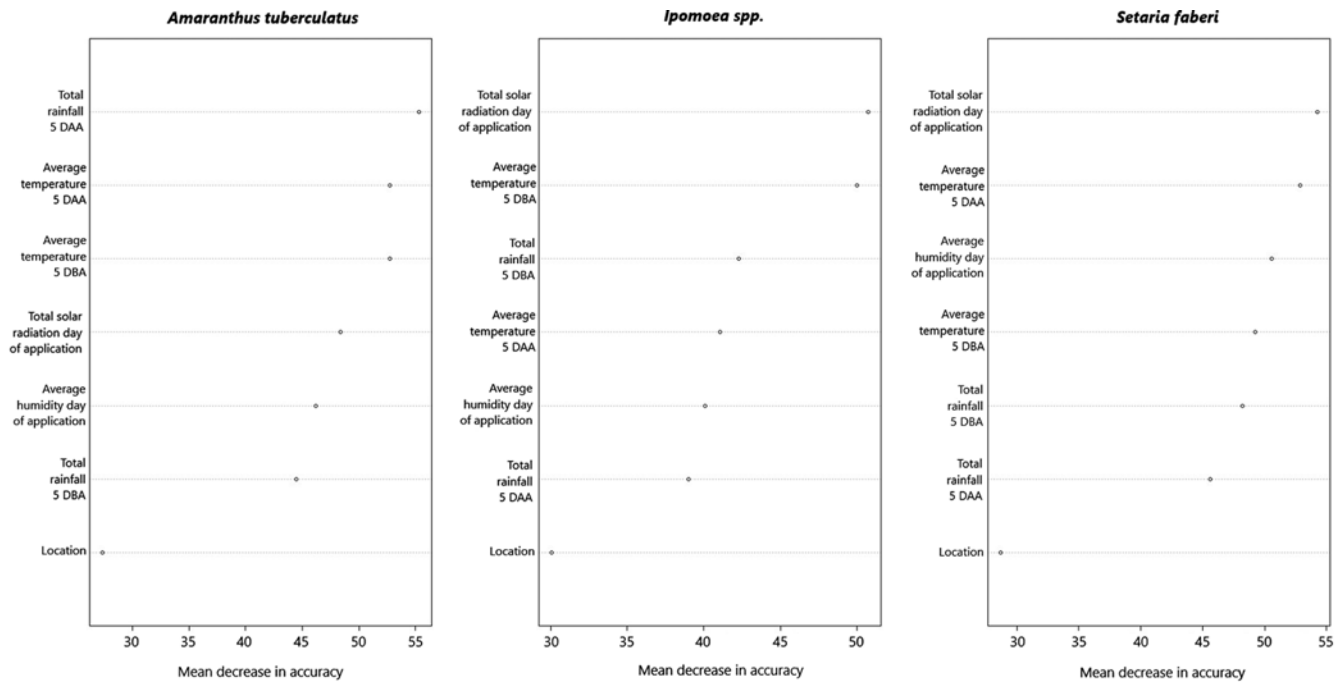

Figure 1. Variable importance plots calculated from the random forest models for predicting the probability of control for *Amaranthus tuberculatus*, *Ipomoea* spp., and *Setaria faberi* with glufosinate. The *x* axis is the mean decrease in accuracy. Higher values suggest a variable is more influential for predicting the probability of successful weed control with glufosinate. DBA, days before application; DAA, days after application.

in velvetleaf (*Abutilon theophrasti* Medik.) dry biomass in plants that received at least 4 h of sunlight following glufosinate application compared with plants that received two or fewer hours. Similar results were shown for common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters (*Chenopodium album* L.), and barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv] (Stewart et al. 2009). Solar radiation is essential for the glufosinate mode of action, as the rapid accumulation of ROS does not occur in the absence of light (Takano et al. 2019; Wild et al. 1987). While other studies have shown that high solar radiation intensity within a few hours is essential for glufosinate efficacy, the results from the current study suggest that total solar radiation on the day of application impacts glufosinate efficacy.

Relative humidity on the day of application was highly important to predicting *S. faberi* probability of successful control but was of lesser importance for predicting *A. tuberculatus* and *Ipomoea* spp. probability of successful control (Figure 1). There appeared to be a threshold of ~70% relative humidity below which the probability of successful control with glufosinate decreased for all species (Figure 2). Coetzer et al. (2001) showed 91% control of three *Amaranthus* species when glufosinate was applied at 90% relative humidity compared with 76% control at 35% relative humidity. Similar results were reported for *S. viridis* and barley (*Hordeum vulgare* L.) (Anderson et al. 1993a). As warmer air temperatures are expected to slightly reduce the relative humidity across most of the globe, the risk of unacceptable weed control with glufosinate is likely to increase (Zhou et al. 2023).

After Application

Cooler average air temperature 5 d following glufosinate application reduced the probability of successful control of all species, although the severity varied by species. Air temperatures ≤25 C caused >50% reductions in the probability of successful control of *A. tuberculatus* and *S. faberi* compared with warmer temperatures, while the probability of control of *Ipomoea* spp. decreased by 10% across the same temperature range (Figure 2). Colder temperatures may reduce the uptake and translocation of glufosinate within the plant. Kumaratilake and Preston (2005) observed decreased glufosinate translocation and injury on wild radish (*Raphanus raphanistrum* L.) as temperatures decreased from a day/night cycle of 20/25 C to 5/10 C.

Higher rainfall 5 d following glufosinate application had varying effects depending on the species/group. Rainfall ≥100 mm 5 d after application decreased probability of *S. faberi* successful control; however, rainfall above this threshold increased probability of *A. tuberculatus* control, especially when air temperatures were <24 C (Figure 2). Furthermore, rainfall had little effect on *Ipomoea* spp. Previous studies typically report rainfall up to 8 h after application and rarely go beyond 1 to 2 d after application (Anderson et al. 1993b; Everman et al. 2009; Souza et al. 2014); however, results from the present study suggest that rainfall within the first 5 d after application is also important for glufosinate efficacy and should be further studied.

The prevailing observation in this study is weed control probability with glufosinate deteriorates to varying degrees under different weather conditions, although the effect of each weather condition was not consistent across weed species. This difference in species' response is likely due to differences in plant structure, biochemistry, and growth rate that require further research (Steckel et al 1997b; Trezzi et al. 2020; Varanasi et al. 2016). Because of these differential responses, the risk of at least one of these weed species escaping control with glufosinate is likely to increase as weather becomes more variable in the future.

Over the next century, major corn- and soybean-growing regions of North America will continue to experience a

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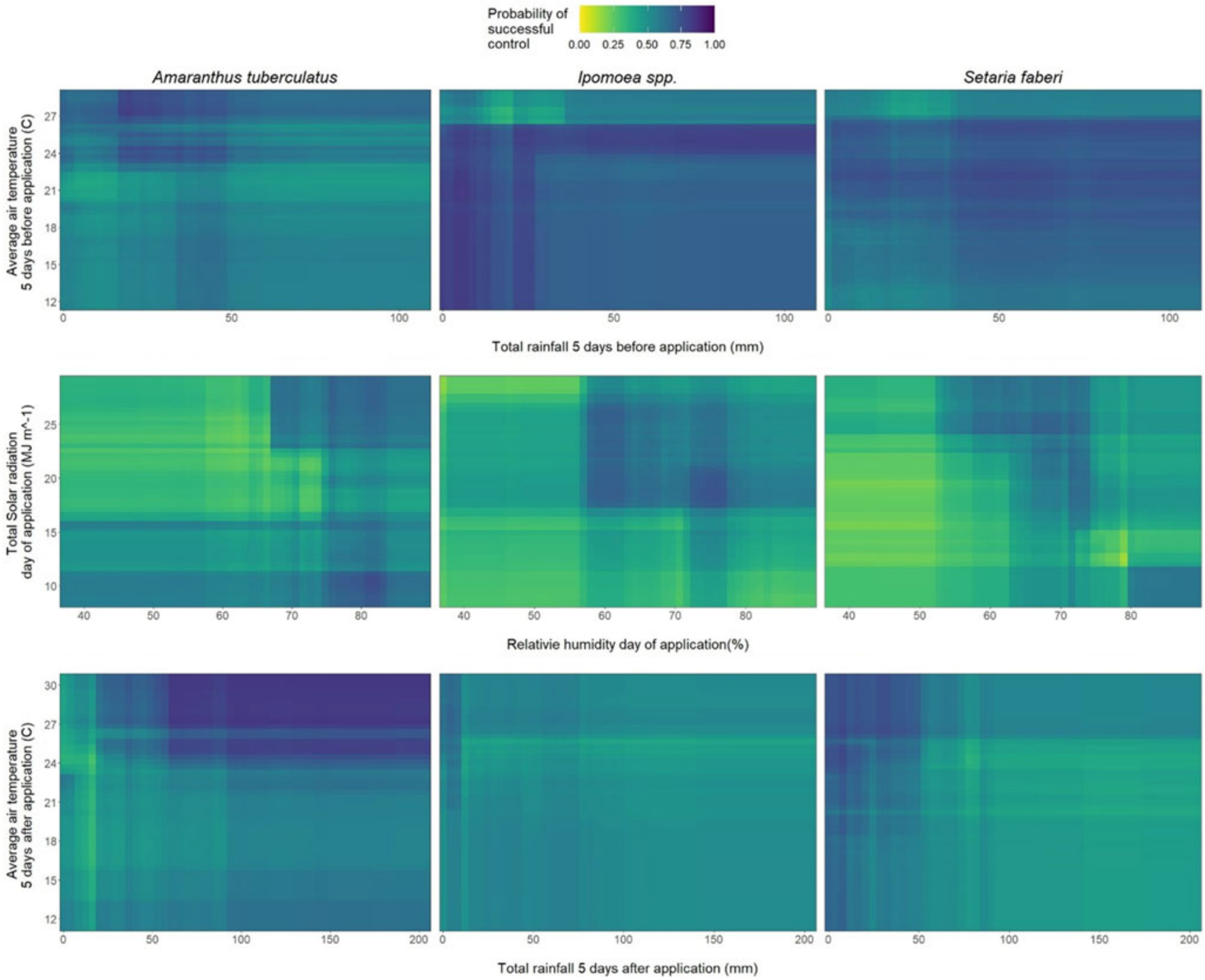

Figure 2. Partial dependency plots of the effects of total precipitation and average air temperature over the first 5 d before and 5 d after glufosinate application, as well as solar radiation and relative humidity 1 d after application on the probability of successful control (≥85% weed control) for *Amaranthus tuberculatus*, *Ipomoea* spp., and *Setaria faberi*.

changing climate coupled with a greater frequency of extreme weather events (Marvel et al. 2023). Results from this study, utilizing glufosinate efficacy data across 1,635 to 2,441 environments, showed low humidity and low solar radiation on the day of glufosinate application were generally detrimental to weed control. Additionally, total rainfall and average air temperatures 5 d before and 5 d after application were important predictors of the probability of successful control, although their impact varied by species. As air temperatures increase and precipitation becomes more variable for most of North America, the risk of unacceptable weed control with glufosinate is likely to increase. To mitigate some of this risk, growers should utilize an integrated weed management strategy that incorporates additional cultural (e.g., increased planting density and decreased row spacing), mechanical (e.g., interrow cultivation), biological, and chemical (e.g., herbicide mixes and rotating herbicides) weed control tactics.

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Competing interests. The authors declare no competing interests.

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