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 to prior to or following application. Additionally, climate models suggest more extreme weather will become the norm, further expanding this weather range glufosinate can be exposed to. 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 POST application of glufosinate applied to waterhemp (*Amaranthus tuburculatus (*Moq.*)* J. D. Sauer), morningglory species (*Ipomoea spp*.), and/or giant foxtail (*Setaria faberi Herm.*) <15cm 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 five days prior to glufosinate application was detrimental to the probability of successful control of *A. tuburculatus* and *S. faberi*. Lower relative humidity (≤70%) and solar radiation (≤23 MJ m^{-1} day^{-1}) 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 five days after application was ≤25C. As climate continues to change and become more variable, the risk of unacceptable control of several common species with glufosinate is likely to increase.

Keywords: Climate change; glufosinate; herbicide efficacy; solar radiation; weather variability

Introduction

Glufosinate was first commercialized in the United States (US) and Canada in 1993 as a non-selective 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 US, 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 2–5 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 15/10C to 22/17C. 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 1C 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 30–50% decrease in control of three *Amaranthus* species as relative humidity decreased from 90% to 35% at the time of glufosinate application. Accompanying the changes in temperature and humidity, 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 (Marvel et al. 2023). Extreme rainfall 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 four hours 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 ten 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 years 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 which are 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 US

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 POST application following glufosinate were only included if there was a control rating reported prior to 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 7–21 days 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 hederaceae* Jacq.), although the composition of the group was not always described for each trial) was also included. The species selected are agronomically important weeds as they are ranked in 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 3–4 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 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 filtering the database, data from sixteen institutions representing fourteen US states and one 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 sixteen institutions led to 1,635–2,441 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 five, 10, and 20 days 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 one and five days 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)

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

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, can be used with missing data, and can be used 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 fitted 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 five days before and five days 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 squared error of each tree used in the optimum model was calculated twice, once from the initial tree model, and the second calculated after permutating each independent variable. The difference between the two mean squared errors was averaged across all 500 trees and divided by the standard error in order to calculate the importance of each independent variable (Breiman 2001).

Results and Discussion

The random forest analyses in this study modeled the effects of a larger range of spatial and weather variables than previously have been attempted on glufosinate efficacy. 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 0.90–0.94 (Table 2), which is considered excellent to outstanding (Mandrekar 2010).

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 five days 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 ≥24C (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 21/16C temperature regime compared to 26/21C or 31/26C regimes.

Control probability of *Ipomoea spp.* decreased as temperatures increased above 27C (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 which may have differential responses to temperature (Higgins et al. 1988; Ribeiro et al. 2018).

While not as influential, low total rainfall five days prior to 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 five days prior to application (Figure 2). Steckel et al. (1997a) reported decreased control in years that had ≤4 mm of rainfall prior to glufosinate application compared to 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} day^{-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} day^{-1} (Figure 2). Sellers et al. (2003) showed a significant decrease in velvetleaf (*Abutilon theophrasti* Medik.) dry biomass in plants that received at least four hours of sunlight following glufosinate application compared to 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 to 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 to 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 five days following glufosinate application reduced the probability of successful control of all species though the severity varied by species. Air temperatures ≤25C caused >50% reductions in the probability of successful control of *A.*

tuberculatus and *S. faberi* compared to warmer temperatures while and of 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 rahanistrum* L.) as temperatures decreased from a day/night cycle of 20/25C to 5/10C.

Higher rainfall five days following glufosinate application had varying effects depending on the species/group. Rainfall ≥100 mm five days after application decreased *S. faberi* probability of successful control; however, rainfall above this threshold increased *A. tuberculatus* probability of control, especially when air temperatures were <24C (Figure 2). Furthermore, rainfall had little effect on *Ipomoea spp*. Previous studies typically report rainfall up to 8 hours after application and rarely go beyond 1–2 days 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 five days 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, though the effect of each weather conditions was not consistent across weed species. This difference in species response is likely due to differences in plant structure, biochemistry, and growth rate that requires 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 changing climate coupled with a greater frequency of extreme weather events (Marvel et al. 2023). Results from this study, utilizing glufosinate efficacy data across 1,635–2,441 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 five days before and five days 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. In order to mitigate some of this risk, growers should utilize an integrated weed management strategy that incorporates additional cultural (e.g., increased planting density and decreasing row spacing), mechanical (e.g., interrow cultivation), biological, and chemical (e.g., herbicide mixes and rotating herbicides) weed control tactics.

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

State/province	Years	*Amaranthus tuberculatus* (Moq.) J. D. Sauer	*Ipomoea spp.*	*Setaria faberi* Herm.
		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

Table 2. Random forest model fits for models using varying weather timepoint variables to predict the probability of control of key weed species with glufosinate. The optimum model providing the highest fit for each species/group is boldface.

Species	Number of environments	Total rainfall	Average air temperature	Total solar radiation	Average relative humidity	Model AUC[a]
			Time range (days before and after glufosinate application)			
Amaranthus tuberculatus	2,231					
		5	**5**	**0[b]**	**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	2,441	**5**	**5**	**0**	**0**	**0.91**

faberi

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]Area under the curve of the receiver operator curve
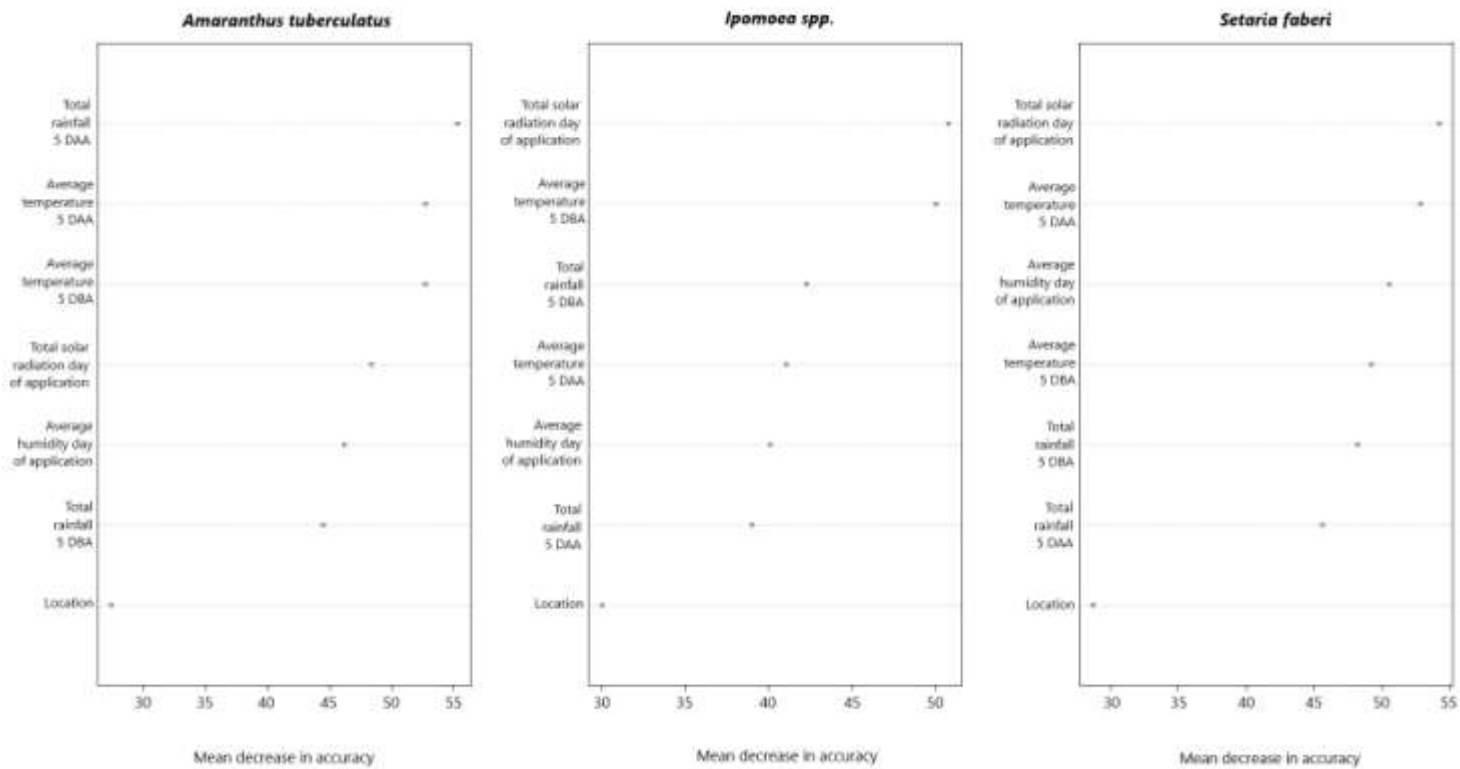
[b]0 days signifies values on the day of application

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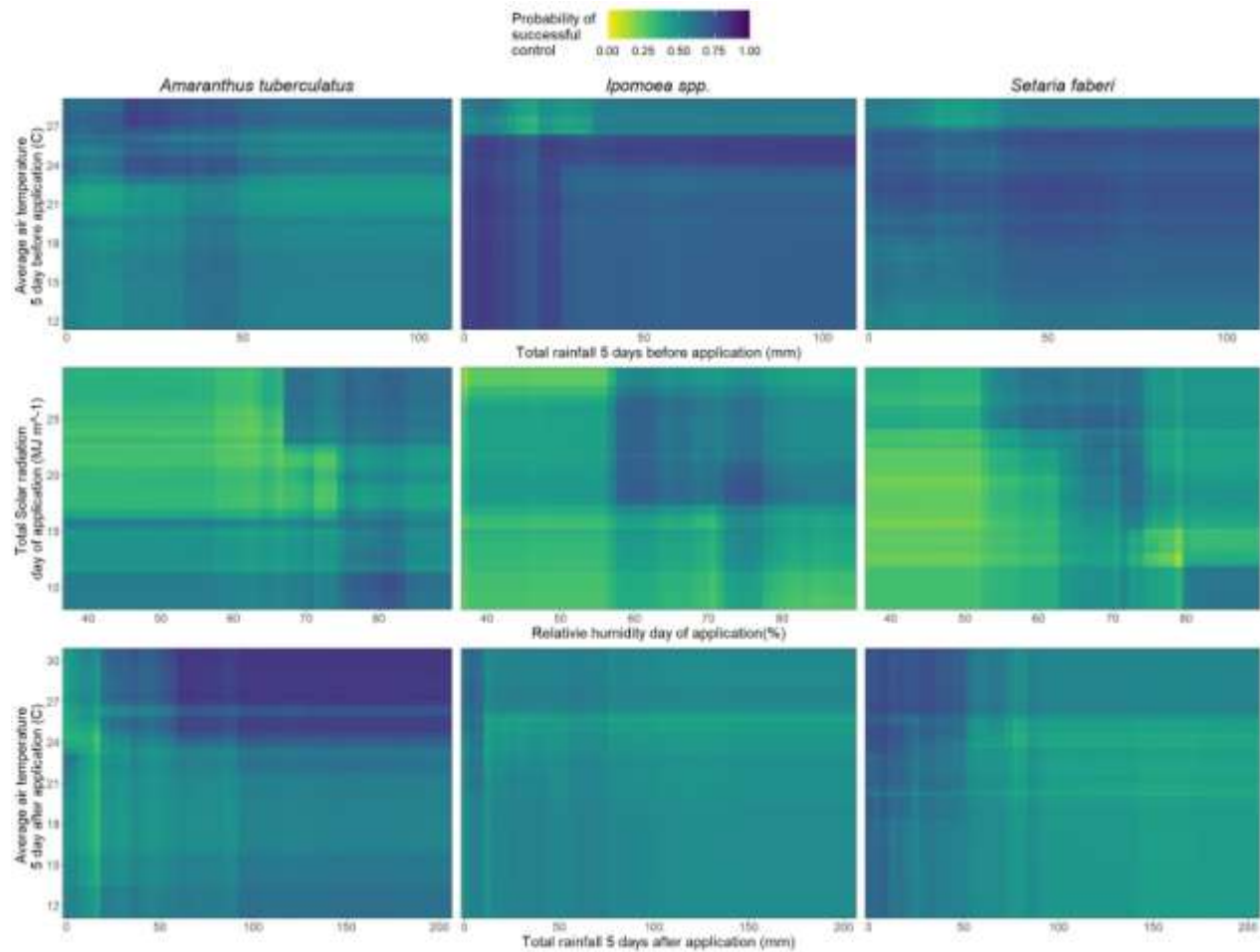
Figure 2. Partial dependency plots of the effects of total precipitation and average air temperature over the first 5 days before and 5 days after glufosinate application as well as solar radiation and relative humidity 1 day after application on the probability of successful control (≥85% weed control)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