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Searching for consistent postemergence weed control in progressively inconsistent weather

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Abstract

Foliar applied postemergence herbicides are a critical component of corn and soybean weed management programs in North America. Rainfall and air temperature around the time of application may affect the efficacy of herbicides applied postemergence in corn or soybean production fields. However, previous research utilized a limited number of site-years and may not capture the range of rainfall and air temperatures that these herbicides are exposed to throughout North America. The objective of this research was to model the probability of achieving successful weed control (≥85%) with commonly applied postemergence herbicides across a broad range of environments. A large database of over 10,000 individual herbicide evaluation field trials conducted throughout North America was used in this study. The database was filtered to include only trials with a single postemergence application of fomesafen, glyphosate, mesotrione, or fomesafen + glyphosate. Waterhemp (*Amaranthus tuburculatus (Moq.) J. D. Sauer*), morningglory species (*Ipomoea spp*.), and giant foxtail (*Setaria faberi Herrm.*) were the weeds of focus. Separate random forest models were created for each weed species by herbicide combination. The probability of successful weed control deteriorated when the average air temperature within the first ten d after application was <19 or >25 C for most of the herbicide by weed species models. Additionally, dryer conditions prior to postemergence herbicide application reduced the probability of successful control for several of the herbicide by weed species models. As air temperatures increase and rainfall becomes more variable, weed control with many of the commonly used postemergence herbicides is likely to become less reliable.

Keywords: climate change, foliar applied, herbicide efficacy, postemergence, weather variability

Introduction

Weeds are the most damaging pests in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production fields in North America, causing greater yield losses than all other pest complexes combined (Oerke 2006). Based on a meta-analysis of research compiled across North America, weed interference can reduce corn and soybean yields by an average of 50 and 52%, respectively (Soltani et al. 2016, 2017). Herbicides remain the primary method for controlling weeds and protecting crop yield from weed interference, with 289,000 and 72,000 t of active ingredients applied in the US and Canada, respectively (FAOUN, 2024). Foliar applied postemergence herbicides constitute a major portion of the total herbicides applied in corn and soybean. Six of the most commonly used herbicides in corn and seven of the most commonly used herbicides in soybean are primarily applied postemergence for control of emerged weeds (USDA-NASS, 2024). Efficacy of POST herbicides is dependent on many factors including weed population density and size (Blackshaw et al,2006), herbicide rate (Johnson et al. 2002), herbicide antagonism (Starke and Oliver, 1998), time of d (Martinson et al. 2005), and adjuvant selection (Young and Hart, 1998). Additionally, herbicide efficacy is also affected by prevailing environmental conditions (Johnson and Young, 2002).

Extreme temperature events, specifically heatwaves, have become more common and severe throughout much of North America since the 1980’s and these trends are expected to continue in the future (Marvel et al. 2023). Prolonged higher air temperatures can increase weed seedling growth rate and reduce the length of time when a foliar-applied postemergence herbicide is most effective (Guo and Al-Khatib 2003). Warmer air temperatures caused by heatwaves can also increase herbicide metabolism within the weed thus reducing herbicide efficacy (Matzrafi et al. 2016; Shyam et al. 2019). Godar et al. (2015) reported a 3.1 to 3.5-fold increase in the amount of 4-hydroxyphenylpyruvate dioxygenase (HPPD) enzymes at high daily air temperatures compared to low or optimum temperatures, leading to faster metabolism of HPPD-inhibiting herbicides, and ultimately reduced herbicide efficacy.

Much of the major corn and soybean growing regions in North America are expected to experience increased yearly precipitation, and much of the increase is expected to occur from extreme precipitation events (Marvel et al. 2023; Romero-Lankao et al. 2014). The seasonal distribution of precipitation is expected to shift toward increased winter and spring precipitation and reduced summer precipitation. Greater spring precipitation reduces the number of field working d which can delay planting and herbicide application (Tomasek et al. 2017). Less summer precipitation can compromise the efficacy of soil-residual herbicides applied d after planting or crop emergence. Landau et al. (2021) discovered an approximate ~10 cm precipitation threshold for several soil-applied residual herbicides, below which the risk of unacceptable weed control escalated. Weeds that survive soil-applied residual herbicides often are targeted with postemergence herbicides. Low precipitation prior to postemergence herbicide application increases the thickness, morphology, and chemical composition of cuticular wax and decreases herbicide uptake (Trezzi et al. 2020). That postemergence herbicides may be affected by precipitation and air temperature is generally recognized; however, a quantitative understanding of postemergence herbicide efficacy across a range of weather conditions is limited.

Individual studies on postemergence herbicide efficacy often are based on ten or fewer environments or site years. Additionally, few studies have investigated the effect of weather before and after postemergence application on herbicide efficacy across a broad range of environments. Individual studies of postemergence herbicide efficacy capture limited snapshots of the range of weather conditions in which crops are grown and weeds are treated. The present study aims to provide new insights from compiling and analyzing data from herbicide efficacy trials conducted across North America over the last 30 yr in an attempt to establish a broader understanding of postemergence herbicide performance. The objective of the study was to quantify the effects of precipitation and air temperature prior to and after postemergence herbicide application on the probability of successful weed control.

Materials and Methods

Data Collection

Many North American land-grant universities have herbicide evaluation programs (HEP) that report the efficacy of herbicides, adjuvants, and non-chemical control tactics on agronomically important weed species. Most HEPs have been active for decades and conduct 50 or more small-plot trials each year. Data were collected from 20 HEPs and standardized into one common relational database (hereafter referred to as the HEP database). Field trials included on average 15 herbicide treatments and were organized as randomized complete block designs with 3 or 4 replications. Trials typically included data on visual assessments of weed control where 0% was no effect and 100% was weed mortality. The HEP database is further described by Landau et al. (2023).

Database Management

At the time of publication, the HEP database has >10 million observations from >10,000 field herbicide efficacy trials; however, not all treatments were postemergence herbicides, and not all treatments and weed species were represented equally. As such, only the most common weed species and herbicides were selected for analysis. The most common postemergence herbicides were fomesafen, glyphosate, mesotrione, and fomesafen + glyphosate. Selected weed species were waterhemp [*Amaranthus tuberculatus* (Moq.) *J.D. Sauer*] and giant foxtail [*Setaria faberi* Herm]. More than 90% of the time morningglory species were rated as a collective group by the individual HEPs, rather than as individual species; therefore, *Ipomoea spp.* was included. This Ipomoea spp. group often consisted of multiple species including tall morningglory [*Ipomoea purpurea* (L.) Roth] and ivyleaf morningglory (*Ipomoea hederacea* Jacq.), which may not respond identically to certain postemergence herbicides including mesotrione and fomesafen (Higgins et al. 1988; Ribeiro et al. 2018).

The HEP database was filtered to include only treatments consisting of one application of the aforementioned postemergence herbicides. Additionally, treatments were only included if they contained the recommended spray adjuvant. Treatments including any soil-applied residual herbicide were excluded. Treatments with sequential postemergence herbicide applications were included only if there was a weed control rating prior to the second postemergence herbicide application. Only treatments with a herbicide use rate of ±10% of the current maximum rate described in the herbicide label were included.

The database was further filtered to include only weed control ratings recorded 14 to 28 d after treatment. Mean weed control for each treatment within a trial was calculated from the 3 or 4 replicates. Most trials (≥95%) contained weed height information at the time of application and ratings on weeds taller than the thresholds set by the herbicide labels were removed. The individual HEPs follow best management practices when applying the individual treatments unless a request is made by the funding source of the trial. In those cases where weed heights outside of the labeled range are requested, notes are made within the trial program. Trials with heights greater than the labeled size range make up <1% of all trials within the database. As such, if no height was listed or no notes were written in the trial data, it was assumed that the weeds were within the height range set by the label. Additionally, several HEPs have field sites where known herbicide-resistant weed populations are located. Data from these locations were removed prior to analysis to prevent confirmed resistance cases from confounding the results. After filtering, data from sixteen institutions representing fourteen US states and one Canadian province were used for analysis (Figure 1). To further standardize rating procedures across multiple programs, weed control was converted to a binary variable using a scale modified from the Canadian Weed Science Society, where weed control of ≥85% was considered acceptable (hereafter called ‘successful’ weed control) and weed control <85% was considered unacceptable (hereafter called ‘unsuccessful’ weed control) (CWSS, 2018). The threshold value was set to 85% after numerous conversations between several of the authors and growers who stated 85% was the lowest level of control they would consider successful weed control in their fields (personal communication). Total precipitation and average air temperature for the 5, 10, and 20 d before and after postemergence herbicide application were added using the daymet database (Thornton et al. 2022) with the *daymetr* package in R (Hufkens et al. 2018).

Statistical analysis

Preliminary analysis indicated that weather variables over the 10 d before and 10 d after postemergence herbicide application provide more accurate predictions compared to models using either 5 or 20-d intervals. As such, only the 10-d intervals were used for analysis. Random forest analysis was used to model the effects of total precipitation and average air temperature, 10 d before and 10 d after postemergence application, as well as trial location (state or province) on the probability of successful weed control. Separate models were constructed for each combination of herbicide and weed species. The random forest analysis was conducted using the *randomForest* package in R (Liaw and Wiener 2002). Random forest was chosen because no assumptions are made about the distribution of the data, unbalanced designs can be used, and the analysis can handle quantitative data, qualitative data, and missing data. The random forest algorithm creates numerous regression tree models using random subsets of the independent variables and observations for each tree. The individual trees are then aggregated into one final model. The number of trees created by random forest was set to 500 for this analysis. The mean squared error (MSE) of each tree was initially calculated and then recalculated after permutating each individual variable in the model. Importance of each independent variable was calculated as the difference between the two MSEs averaged across trees divided by the standard error (Breiman 2001).

To visualize the final random forest models, partial dependency plots were created to show the partial effects of precipitation and air temperature, either before or herbicide after application, while keeping other variables static using the *pdp* package in R (Greenwell 2017).

Results and Discussion

The analyses modeled the effects of a larger range of weather conditions than has previously been attempted on the efficacy of some of the most commonly used postemergence corn and soybean herbicides (USDA-NASS, 2024). The weed species included in this study are among the most common and/or troublesome weeds in corn and soybean (Van Wychen 2020, 2022). All random forest models had high accuracies for predicting the probability of successful control of the weed species with the four postemergence herbicides. All models had an area under the curve of the receiver operating characteristic (AUC ROC) of 0.83–0.96 (Table 1), which is considered excellent to outstanding (Mandrekar 2010). The experimental approach provides a quantitative understanding of the influence of weather on the probability of successful weed control with postemergence herbicides.

Location

Location had little effect on the probability of successful weed control except for *S. faberi* treated with mesotrione (Table 1). Mesotrione is known to provide low levels of control of *Setaria spp*. (Anonymous 2021) and was observed in the present study as a higher proportion of unsuccessful control compared to successful control (Table 1). In the present study, *S. faberi* was rarely successfully controlled with mesotrione at most locations, although a single location had a frequent number of successful control cases. Moreover, this weed-herbicide combination was tested across the second-fewest environments (n=184), and while lower than other weed-herbicide combinations in this study, the data are still an order of magnitude greater than previous research on weather and herbicide efficacy. Conceivably, the number of observations *S. faberi* treated with mesotrione may be pushing the lower limits of sample size or event frequency with our analytical approach, since political boundary (i.e., city or state) was expected to have limited effect on herbicide efficacy.

Weather before POSTEMERGENCE **herbicide application**

Few important trends were observed between weather 10 d prior to postemergence application and weed control. One example was *A. tuberculatus* control with fomesafen, where a critical precipitation threshold of ~30 mm or more greatly improved weed control (Figure 2). Unacceptable control at low rainfall amounts is supported by the herbicide label for fomesafen which states that weeds exposed to drought stress will have reduced control (Anonymous 2019). Previous research found that drought conditions prior to postemergence application increased cuticular wax thickness and can alter the chemical composition and morphology which can reduce absorption of glyphosate (Trezzi et al. 2020). Skelton et al. (2016) observed that *A. tuberculatus* experienced reduced herbicide translocation under drought conditions. Additionally, drought stress can reduce the photosynthetic capacity of a plant, which contributes to reduced weed growth rate and lower translocation (de Ruiter and Meinen, 1998).

Colder average air temperatures 10 d prior to postemergence herbicide application reduced the probability of successful weed control for some combinations of herbicides and weed species. Glyphosate and fomesafen + glyphosate had lower probabilities of successful control of *S. faberi* at air temperatures ≤15 C (Figure 2). Zhou et al. (2007) reported similar reductions of glyphosate phototoxicity when applied to cold-stressed velvetleaf (*Abutilon theophrasti* Medik.). The low probability of successful weed control at low air temperatures observed for some of the herbicides in the present study might be due to reduced weed growth and translocation of the herbicides as well as reduced permeability of the cuticular wax for foliar absorption (Gauvrit and Gaillardon 1991; Grafstrom and Nalewaja 1988; Trezzi et al. 2020). Additionally, the herbicide label for a premix of fomesafen + glyphosate states that temperature stress prior to application may reduce efficacy (Anonymous 2020). While warmer air temperatures may increase the probability of successful weed control with some of the herbicides investigated in this study, greater variation predicted in future precipitation is likely to increase the risk of unsuccessful weed control in the future.

Weather after postemergence **herbicide application**

Weather 10 d after postemergence application tended to be more important than weather 10 d before application, with average air temperature after postemergence application often being the most, or second most, important predictor in a majority of models (Table 1). Two air temperature thresholds were observed where the probability of successful weed control deteriorated, depending on the weed species and herbicide. Average air temperatures ≥25C greatly reduced the probability of successful weed control while a few herbicide by weed species combinations showed reduced probability of successful weed control at <19C for most of the weed species and herbicide combinations (Figure 3). The decreased probability of successful weed control at higher air temperatures might be caused by a combination of several factors, including faster plant growth rate (Guo and Al-Khatib 2003), greater herbicide metabolism (Johnson and Young 2002; Kells et al. 1984), rapid drying of the herbicide solution on the leaf surface (Devine et al. 1993), or increases in the quantity of herbicide binding sites (Godar et al. 2015).

Lower air temperatures after postemergence application have been associated with decreased herbicide uptake and translocation (Sharma and Singh 2001) and in the present study could be the cause of the reduced probability of successful weed control observed for glyphosate and mesotrione when average air temperatures were <19C. While the predicted future warming across much of North America may improve the efficacy of certain postemergencE herbicides on specific weeds, results from the present study suggest a higher risk of weed control failure and weed escapes could become the norm rather than the exception.

While not as influential, excess precipitation following postemergence application was often an important predictor of the probability of successful weed control. There appeared to be a precipitation threshold of ~75mm, above which weed control deteriorated for *Ipomoea spp*. treated with glyphosate or mesotrione and *A. tuberculatus* treated with fomesafen (Figure 3). Herbicide labels often state that heavy rainfall following application may reduce efficacy, although labels typically refer to the first 24 hours after application (Anonymous 2019; Anonymous 2020). Excessive precipitation resulting in soil flooding can reduce plant growth and herbicide translocation resulting in sublethal herbicide doses within the plant though the severity of the reduction in translocation will vary by herbicide mode of action (Gealy 1998; Raju 2007; Stewart et al. 2012). The literature is replete with observations on the effect of precipitation during the first four hours after postemergence application (i.e., rainfast periods); however, results from the current study indicate that precipitation up to ten days after application relates to a POSTEMERGENCE herbicide’s ability to completely control common weed species.

A common theme observed in the present study was that herbicide performance deteriorated in certain types of weather conditions, but not necessarily in the same way. Likewise, weed species varied in their response to the full scale of precipitation and air temperature conditions (Figures 2 and 3). Previous research reported that *I. hederacea* control with glyphosate was 73% in low precipitation environments compared to 90% in wetter environments, while *S. faberi* experienced ≥94% control across precipitation environments (Wiesbrook et al. 2001). Differences in the probability of successful weed control among the species and herbicides in the present study are likely due to differential species sensitivity as well as previously mentioned differences in plant growth and herbicide uptake, metabolism, and translocation (Guo and Al-Khatib 2003; Johnson and Young 2002). As weather becomes more extreme in the future, the risk of unsuccessful control of individual species from a postemergence herbicide is likely to increase.

Rising temperatures across much of North America over the past 50 years have allowed growers to plant corn and soybean earlier within the year (USDA-NASS 2024). Planting earlier has the potential for reducing the chance that a postemergence herbicide would be exposed to daily average temperatures in excess of 25C after application even under predicted future temperature increases. However, earlier planting will also expose the weeds and herbicides to more extreme rainfall events which reduces the probability of successful control of several of the tested postemergence herbicides (Marvel et al. 2023; Romero-Lankao et al. 2014). Such weed control factors, along with other agronomic, ecological, and economic factors, will need to be considered by growers as climate change progresses. The dataset analyzed in the present study contains millions of observations which may be useful in testing future hypotheses, including changes in production timing.

Herbicide combination vs individual products

Successful outcomes from the combination of fomesafen + glyphosate were more robust across weather variability than the herbicides applied alone. The combination had smaller regions of unsuccessful weed control due to weather before, and after, postemergence application

(Figures 2 and 3). There are reports of synergistic and antagonistic effects of fomesafen + glyphosate. Shaw and Arnold (2002) reported 90% control of pitted morningglory (*Ipomoea lacunosa* L.) with fomesafen + glyphosate, while individually, fomesafen and glyphosate provided 63 and 67% control, respectively. Conversely, Starke and Oliver (1998) reported antagonism between fomesafen and glyphosate on *A. palmeri* S. Wats. and several *Ipomea spp*. Perhaps these conflicting results from previous studies were the result of differences in weather conditions that were not included in their respective analyses. Results from the current study suggest that herbicide combinations may be useful in reducing the risk of unacceptable weed control caused by variable weather; however, postemergence combinations alone will not eliminate the risk. As such, additional tactics such as effective soil-applied residual herbicides and non-chemical tactics should be used in conjunction with postemergence herbicide combinations to provide consistent weed control (Birthisel et al. 2021).

Major North American corn and soybean growing regions will continue to experience a shifting climate coupled with a greater frequency of extreme weather events over the next century (Marvel et al. 2023). Some of the trends that were observed in this study have been shown in previous research using 2–3 years of data. However, the present study utilizes data from 16 research programs over a broad temporal range and can more accurately model the effects of rainfall and temperatures on postemergence herbicide efficacy than has previously been done. Results from the present study, comparing data across 129 to 3,271 environments per treatment, showed average air temperature 10 d after postemergence application was the most important predictor of weed control success, with weed control deteriorating rapidly below 19 or above 25C. Additionally, precipitation 10 d before and after postemergence application were important predictors in some cases, although the direction (positive or negative effect) varied by weed species and herbicide. As air temperatures increase and precipitation becomes more variable for most of North America, the risk of at least one weed species escaping control with these commonly applied postemergence herbicides will likely increase. While the use of postemergence herbicide combinations may mitigate some of the risk of weeds escaping control, additional cultural, mechanical, biological, and chemical weed management tactics should be adopted to provide more consistent weed control in more inconsistent weather.

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Table 1. Random forest model variable importance and performance. Higher variable importance values indicate a variable is more influential for predicting the probability of successful weed control (≥85% weed control).

	Number of environments by control level		Variable importance (mean decrease in accuracy)					
	Unsuccessful control[1]	Successful control[2]	Precipitation 10 d before application	Precipitation 10 d after application	Temperature 10 d before application	Temperature 10 d after application	Location	Model AUC[3]
Amaranthus tuberculatus								
fomesafen	192	479	69.2	54.5	34.5	54.8	21.6	0.96
glyphosate	950	1,808	85.1	81.0	77.6	92.6	57.7	0.91
mesotrione	68	159	16.1	18.3	14.7	20.5	9.1	0.95
fomesafen +glyphosate	153	1,301	35.1	39.6	32.7	46.6	23.5	0.90
Ipomoea spp.								
fomesafen	178	349	39.1	35.4	34.1	49.6	17.1	0.89
glyphosate	1,162	1,065	106.8	92.2	110.5	128.5	37.7	0.91
mesotrione	51	110	11.1	23.1	10.4	12.3	2.2	0.83
fomesafen +glyphosate	307	849	65.9	45.4	64.4	73.7	28.4	0.95
Setaria faberi								
fomesafen	53	76	18.5	26.3	26.6	19.7	6.6	0.90
glyphosate	667	2,604	47.3	45.6	56.0	51.0	30.8	0.90
mesotrione	105	79	23.1	26.3	24.3	32.7	39.6	0.91
fomesafen +glyphosate	356	892	27.8	33.2	34.9	40.0	24.0	0.83

[1] Visual assessments of injury <85%

[2] Visual assessments of injury ≥85%

[3] Area Under the Curve of the receiver operator curve

Figure 1. Postemergence herbicide data was compiled from 14 US states and 1 Canadian province (1992-2021). Data from two universities (University of Illinois and Southern Illinois University) were collected for Illinois.

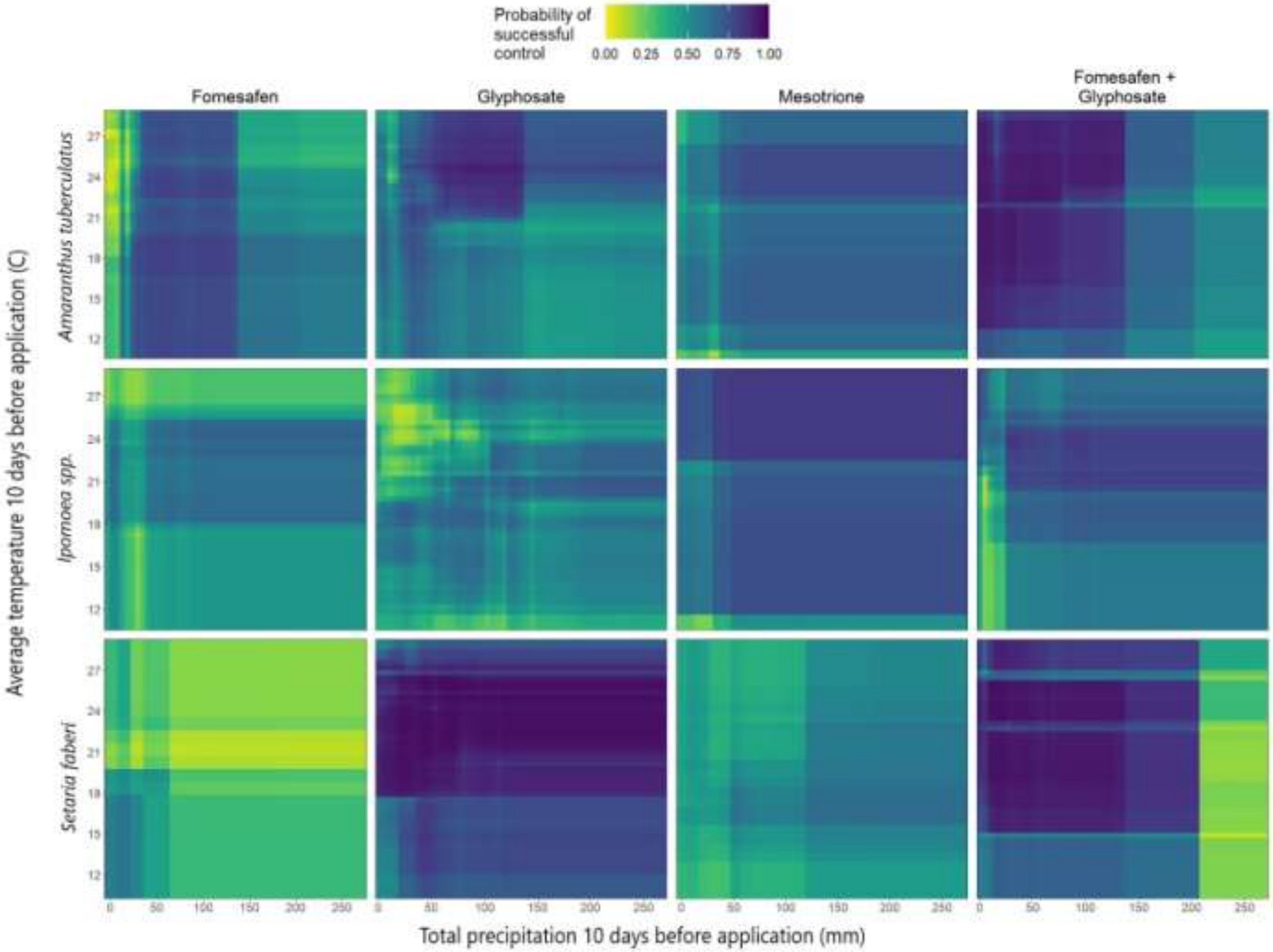

Figure 2. Partial dependency plots of the effects of total precipitation and average air temperature 10 d before postemergence herbicide application on the probability of successful control (≥85% weed control).

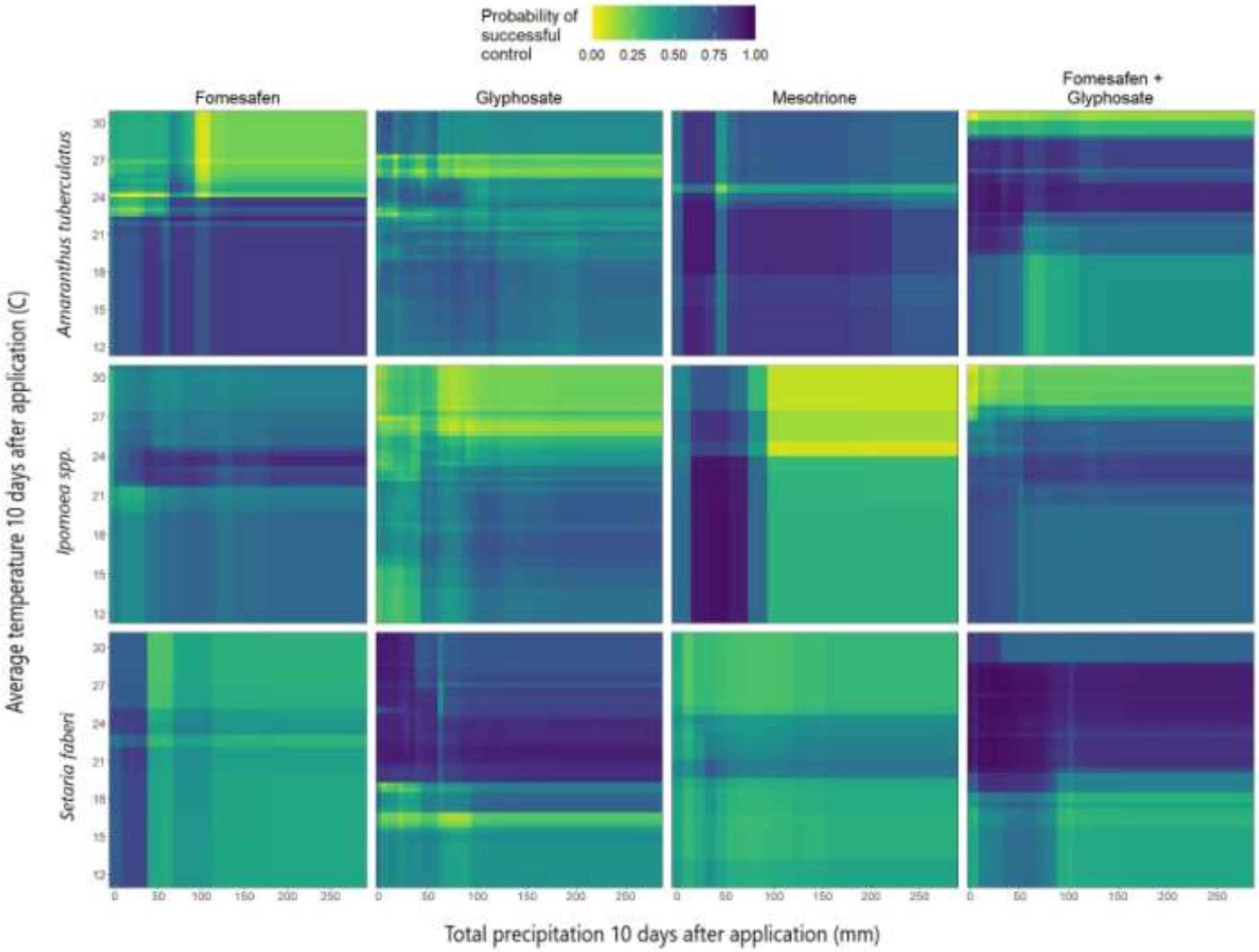

Figure 3. Partial dependency plots of the effects of total precipitation and average air temperature 10 d after postemergence herbicide application on the probability of successful control (≥85% weed control).