

# Palmer amaranth (*Amaranthus palmeri*) adaptation to agroecosystems

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## 2 ABSTRACT

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Keywords: Evolution Flowering Management Pigweed Weed

## INTRODUCTION

Palmer amaranth (*Amaranthus palmeri* S. Watson) is currently considered one of the most economically damaged weed species to cropping systems in the United States. Unmanaged Palmer amaranth in competition for water, light and nutrients can drastically impact on crop yields (Berger et al., 2015). For example, Palmer amaranth is documented with potential to reduce 91%, 68%, and 54% of corn (Massinga et al., 2001), soybean (Klingaman and Oliver, 1994), and cotton (Morgan et al., 2001) yields, respectively. Moreover, Palmer amaranth has showed a remarkable capacity to evolve resistance to herbicides. To date, Palmer amaranth has evolved resistance to eight herbicide sites of action (Heap, 2021), increasing the weed management complexity (Lindsay et al., 2017). Thus, Palmer amaranth poses an economical risk to sustainable agriculture.

Palmer amaranth is a fast growing summer annual forb indigenous to Sonoran Desert (Sauer, 1957). The species would eventually emerge as a threat to US agriculture in the 1990s. Palmer amaranth weediness is likely a result of human-assisted selection in combination with species biology. Farm mechanization, conservation agriculture (e.g., no-till), and reliance on herbicides for weed management are the main human-mediated selection of Palmer amaranth into cropping systems (Ward et al., 2013). On the other hand, Palmer amaranth is a prolific seed producer with a C4 photosynthetic apparatus (Wang et al., 1992). With a dioecy nature, Palmer amaranth male and female plants are obligate outcrosser species, increasing the chances of exchanging adaptive traits among plants (Oliveira et al., 2018). Also, Palmer amaranth small seed size (e.g, 1 mm) tend to thrive in no-tillage systems (Price et al., 2011), and spread across locations through farm equipment (Sauer, 1972), manure (Hartzler and Anderson, 2016), animals (Farmer et al.,

26 2017), and plant propagules (Yu et al., 2021). The dispersal capacity of Palmer amaranth make the species  
27 one of the most successful cases of weed adaption to cropping systems.

28 Light and temperature are likely the main environment requirements for Palmer amaranth successful  
29 grow and development. Palmer amaranth is reported with an extended germination period (Jha et al., 2010).  
30 Germination of Palmer amaranth is triggered by 18 C soil temperature (Keeley et al., 1987), and optimal  
31 germination and biomass production occur at 35/30 C day and night temperatures (Guo and Al-Khatib,  
32 2003). Palmer amaranth germination is also human-mediated by tillage timings and preemergence-applied  
33 herbicides (Chahal et al., 2021). Water has not shown to limit Palmer amaranth fitness. Under continuous  
34 water stress, Palmer amaranth survived and produced at least 14000 seeds plant-1 (Chahal et al., 2018).  
35 Seeds from Palmer amaranth growing with limited water conditions were heavier, less dormant, and prompt  
36 for germination (Matzrafi et al., 2021). Growing conditions and management practices also influence  
37 Palmer amaranth sex dimorphism and flowering pattern (Korres et al., 2017; Rumpa et al., 2019). The  
38 continuous global temperature warming can impact agriculture and promote niches for Palmer amaranth  
39 invasion/adaptation into new environments. Currently, it is estimated that the greatest climatic risk of  
40 Palmer amaranth establishment are agronomic crops in Australia and Sub-Saharan Africa (Kistner and  
41 Hatfield, 2018). Temperature is a key factor limiting Palmer amaranth expansion to cooler geographies  
42 (Briscoe Runquist et al., 2019); however, under future climate change Palmer amaranth is likely to expand  
43 northward into Canada and Northern Europe (Kistner and Hatfield, 2018; Briscoe Runquist et al., 2019).

44 Palmer amaranth is already found in agronomic crops of South America (Larran et al., 2017; Küpper  
45 et al., 2017) and Southern Europe (Milani et al., 2021). In the US, Palmer amaranth is well established  
46 at cotton fields (Garetson et al., 2019) and non-crop areas (Bagavathiannan and Norsworthy, 2016) in  
47 the southern United States but its range is expanding northward. For example, herbicide resistant Palmer  
48 amaranth is widespread in Nebraska (Oliveira et al., 2021), Michigan (Kohrt et al., 2017), Connecticut  
49 (Aulakh et al., 2021), and potential damaged to soybean fields in Illinois is reported (Davis et al., 2015). In  
50 Iowa, a study showed that Palmer amaranth is still not well adapted compared to waterhemp (*Amaranthus*  
51 *tuberculatus*) (Baker, 2021). Successful cases of Palmer amaranth invasion and near to eradication is  
52 documented in Minnesota (Yu et al., 2021). No Palmer amaranth actively growing was found in Canada;  
53 however, Palmer amaranth seeds was detected in sweet potato slips (Page et al., 2021). Nonetheless, it  
54 seems fated the need to manage Palmer amaranth in agronomic crops throughout multiple environments  
55 in the near future. Strategies on Palmer amaranth management should encompass the agroecosystem  
56 level but not only attempts to eradicate the weed. Most tactics to manage Palmer amaranth are based on  
57 technology fixes (Scott, 2011), which are short-term (e.g., herbicide and/or tillage) rather than long-term  
58 weed management. Palmer amaranth management should be built on minimizing the species ability to  
59 adapt, grow and develop into agroecossystems.

60 In the southeastern US, early growing Palmer amaranth is well known to have higher impact on cotton  
61 yields than late established plants (MacRae et al., 2013). In the northern states, Palmer amaranth impact  
62 on the agroecosystem is recent. Studies investigating Palmer amaranth in those locations is limited due  
63 to the plant classification as noxious weed species (Yu et al., 2021). Nonetheless, the continuous Palmer  
64 amaranth dispersal and potential establishment across northern United States is concerning and warrant  
65 investigations on species morphology in such environments. Understanding Palmer amaranth biology and  
66 growing strategies under different agroecosystems can enhance our knowledge on species adaptation. It  
67 can also aid on designing proactive and ecological tactics to limit the species range expansion, reduce its  
68 negative impact, and design resilient and sustainable farming systems (MacLaren et al., 2020). Therefore,  
69 the objective of this study was to investigate the flowering pattern, gender, biomass production, and height

70 of Palmer amaranth growing under corn, soybean and bareground at two timings across five locations in  
 71 the United States Midwest.

## MATERIAL AND METHODS

### 72 Plant material and growing conditions

73 The study was performed with a Palmer amaranth accession (Per1) from Perkins County, Nebraska.  
 74 Per1 accession collection is documented with no reported herbicide resistance (Oliveira et al., 2021).  
 75 Three weeks prior to the field experiment, seeds were planted in plastic trays containing potting-mix.  
 76 Emerged seedlings (1 cm) were transplanted into 200 cm<sup>-3</sup> plastic pots (a plant pot-1). Palmer amaranth  
 77 seedlings were supplied with adequate water and kept under greenhouse conditions at Arlington, Clay  
 78 Center, Lincoln, and Macomb; and kept outdoors in Grant. Palmer amaranth seedlings were kept under  
 79 greenhouse/outdoors until the onset of the experiment (2-3 leaf stage/5 to 8 cm height).

### 80 Field study

81 The experiment was conducted in 2018 and 2019 under field conditions at five locations: Arlington, WI  
 82 (43°18'N, 89°29'W), Clay Center, NE ('N, 'W), Grant ('N, 'W), Lincoln ('N, 'W), and Macomb ('N,  
 83 'W).

84 Fields were conventionally tilled and disked prior to planting. Corn hybrid and soybean varieties were  
 85 planted in 76-cm row spacing (Table 1). Monthly mean air temperature and sum precipitation were obtained  
 86 using Daymet weather data from June through September across the five locations in 2018 and 2019  
 87 (Correndo et al., 2021) (Figure 1)

**Table 1.** Field study attributes

Attributes	Arlington, WI	Clay Center, NE	Grant, NE	Lincoln, NE	Macomb, IL
Bareground					
Corn	Weed control	glyphosate	saflufenacil + imazethapyr + pyroxasulfone		
	Hybrid		DKC60-67		
	Seeding rate		86487		
	Weed control	glyphosate / S-metolachlor	S-metolachlor + trazine + mesotrione, + bicyclopyrone		
Soybean	Variety	DSR-1950	AG21X8		
	Seeding rate	296400	321237		
	Weed control	glyphosate / S-metolachlor	saflufenacil + imazethapyr + pyroxasulfone		
Planting day		May 10 to 20	May 10 to 14		
Soil	Type		Crete Silt Loam		
	Ratio (sand-clay-silt)		58-25-6.5		
	pH	6.6	6.5		
	Organic matter (%)		3		

88 The field experimental unit were six adjacent 9.1 m wide (12 rows at 72.2 cm row spacing) by 10.7 m  
 89 long. Each experimental unit was planted with corn or soybean, or under bareground condition. Palmer  
 90 amaranth seedlings (potting mix + two seedlings) were and gently transferring to the ground (6 cm deep  
 91 and 8 cm wide). Twenty-four plants were equidistantly placed (0.76 m apart) between rows within each  
 92 agroecosystems. After a week, one was eliminated and one was kept. There were two transplant timing:  
 93 first (June 1) and second (July 1). There were 24 Palmer amaranth plants in each experimental unit, with a  
 94 total of 144 plants for each location. The study was repeated twice.

95 After transplanting, Palmer amaranth flowering was monitored until the end of the study. When a plant  
 96 started flowering, the day was recorded, plant sex was identified as male or female, and plant height

97 was measured from soil surface to the plant top. Then, aboveground plant biomass was harvested near soil  
98 surface and oven dried at 65 C until reaching constant weight before the weight of biomass (g plant 1) was  
99 recorded.

100 **Statistical analyses**

101 The statistical analyses were performed using R statistical software version 4.0.1. Data across locations  
102 and year were combined.

103 The cumulative Palmer amaranth flowering estimation was determined using an asymmetrical three  
104 parameter log logistic Weibull model of the drc package (Ritz et al., 2015).

105 
$$Y(x) = 0 + (d - 0)\exp(-\exp(b(\log(x) - e)))$$

106 In this model,  $Y$  is the Palmer amaranth cumulative flowering,  $d$  is the upper limit (set to 100), and  $e$  is  
107 the XXX, and  $x$  day of year (doy).

108 The doy for 10, 50, and 90% Palmer amaranth cumulative flowering were determined using the *ED*  
109 function of drc package. Also, the 10, 50, and 90% Palmer amaranth cumulative flowering were compared  
110 among agroecosystems and timings using the *EDcomp* function of drc package. The EDcomp function  
111 compares the ratio of cumulative flowering using t-statistics, where P-value < 0.05 indicates that we fail to  
112 reject the null hypothesis.

113 Palmer amaranth gender was fitted to a binary logistic regression (Bangdiwala, 2018). Binary logistic  
114 regression is used for predicting binary classes, such as the probability of female in dioecious plants. Prior  
115 to the analysis, all missing values were removed from the dataset. Also, data from Grant was not used  
116 in this analysis due to the uniform plant harvesting at that location. The whole dataset was split into  
117 80% train and 20% test data. The 80% train is used for the model training and the rest 20% is used for  
118 checking how the model generalized on unseen dataset. With 80% dataset, a binary response variable,  
119 male (0) and female (1), was fitted to a generalized linear model (*glm* function) including day of year  
120 harvest, height, weight, crop and month as independent variables. The model family was binomial with a  
121 logit function. The model fit was assessed through pseudo R squared values (McFadden, Cox and Snell,  
122 Cragg and Uhler) and likelihood ratio using *nagelkerke* function (“rcompanion” package). The marginal  
123 effects computation was performed with Average Marginal Effects at every observed value of x and average  
124 across the results (AMEs) (Leeper, 2017) using *margins* function from “margins” package. The rest 20%  
125 dataset was predicted using *predict* function with a cutoff estimation for male or female using *performance*  
126 function. The model quality prediction from the classification algorithm was measured with precision  
127 (*precision* function), recall (*recall* function) and F1 score (*f\_meas* function) using “yardstick” package. The  
128 precision determines the accuracy of positive predictions (female plants), recall determines the fraction of  
129 positives that were correctly identified, and F1 score is a weighted harmonic mean of precision and recall  
130 with the best score of 1 and the worst score of 0. F1 score conveys the balance between the precision and  
131 the recall.

132 Palmer amaranth height and biomass were performed with a linear mixed model using *lmer* function  
133 from “lme4” package (Bates et al., 2015). Plant height and biomass were transformed to meet model  
134 assumption of normality. In the model, agroecosystem (crop, soybean, bareground) was the fixed effect  
135 and year nested with location the random effects. Analysis of variance was performed with *anova* function  
136 from “car” package (Fox and Weisberg, 2018). Marginal means and compact letter display were estimated  
137 with *emmeans* and *cld* from packages “emmeans” and “multcomp” (Hothorn et al., 2008).

## RESULTS

### 138 Palmer amaranth height and biomass

139 Palmer amaranth accumulated more biomass when growing in bareground compared to Palmer amaranth  
140 growing in soybean and corn (figure 2A). At first cohort time, Palmer amaranth biomass was 75.5 g plant-1,  
141 28.3 g plant-1 and 16.3 g plant-1 in bareground, soybean and corn, respectively. At second cohort timing,  
142 Palmer amaranth produced 62.6 g plant in bareground, followed by 6.3 g plant in soybean, and 1.4 g plant  
143 in corn.

144 Palmer amaranth height was more uniform across cohort timings, except when growing in corn (figure  
145 2B). Palmer amaranth achieved 69.2 cm tall when growing at first cohort timing in bareground, which  
146 was not different to 70.7 cm tall at second cohort timing ( $P = 0.74$ ). In addition, no difference in Palmer  
147 amaranth height (69.3 cm) was found in soybean at first cohort compared to bareground ( $P > 0.75$ ). At  
148 second cohort in soybean, Palmer amaranth was near to 10 cm lower compared to its first cohort time ( $P =$   
149 0.04). The tallest and smallest Palmer amaranth plants were found in corn. Palmer amaranth reached 85.2  
150 cm tall at first cohort and 38.2 cm at second cohort timings.  
151

### Palmer amaranth cumulative flowering

152 Palmer amaranth growing in corn resulted in a longer flowering pattern compared to bareground and  
153 soybean at first cohort (figure 3A). Nonetheless, the 10% cumulative Palmer amaranth flowering in soybean,  
154 bareground and corn occurred at the end of June. Palmer amaranth reached 10% flowering in soybean at  
155 doy 180, which was slightly different from bareground (doy 180.9;  $P = 0.01$ ) and corn (doy 181.7;  $P =$   
156 0.00). The 50% Palmer amaranth cumulative flowering occurred in July. For example, Palmer amaranth  
157 reached 50% flowering in bareground at doy 193.4, followed by soybean (doy 194.8), corn (doy 206.6).  
158 Similar trend was observed at 90% Palmer amaranth cumulative flowering. Palmer amaranth growing in  
159 corn reached 90% flowering at doy 252.6 (early September), which was 37.8 and 32.2 days after Palmer  
160 amaranth 90% flowering in bareground and soybean, respectively.

161 Palmer amaranth cumulative flowering at second cohort ranged from mid July to mid September  
162 (figure 3B). Palmer amaranth growing in bareground resulted in earlier flowering time compared to soybean  
163 and corn. Palmer amaranth growing in bareground reached 10%, 50%, and 90% flowering time at day  
164 203.8, 214.4, and 232.2, respectively. Palmer amaranth growing in soybean reached 10% flowering at doy  
165 210.9, which was 6 days prior to corn ( $P$ -value = 0.00). Similar trend was observed at 50% flowering,  
166 whereas Palmer amaranth reached 50% flowering in corn (doy 233.0) 4 days after soybeans (doy 228.9;  $P$   
167 = 0.00). The 90% Palmer amaranth cumulative flowering occurred at same day in corn (260.9) and soybean  
168 (260.5;  $P = 0.66$ ).  
169

### Palmer amaranth gender

170 The model fit was 0.23, 0.32, 0.40 with using pseudo R squared test from McFadden, Cox and Snell,  
171 and Cragg and Uhler, respectively. The likelihood ratio test showed a p-value of  $< 0.00$ . The average  
172 marginal effects showed that Palmer amaranth growing in corn resulted in 14.5% less females plants (Table  
173 2). Moreover, increasing a unit doy increases the probability of having a female plant by 0.4% (Table 2 and  
174 Figure 4A). Similar trend is observed to weight as well as height, whereas the probability of being female  
175 increase by 0.2% (Figure 4B) and 0.1% (Figure 4C) when a unit of weight (g) and height (cm) increases,  
176 respectively.

**Table 2.** Average marginal means of gender logistic model. Factor pararemter values (e.g. crop) is shown related to soybean.

Term	AME	SE	Lower	Upper	Z-score	P-value
crop_bareground	-0.048	0.054	-0.154	0.059	-0.876	0.381
crop_corn	-0.148	0.052	-0.250	-0.046	-2.842	0.004
doyh	0.004	0.001	0.003	0.006	4.959	0.000
height	0.002	0.001	0.001	0.003	2.953	0.003
weight	0.001	0.000	0.000	0.001	2.179	0.029

<sup>a</sup> Average Marginal Effects. <sup>b</sup> Standard Error.

177 The model accuracy evaluation accuracy in the unseen 20% dataset was 0.62 with a cutoff value for  
 178 female and male plants of 0.43. The model classification showed a precision of 0.64, recall of 0.66, and a F  
 179 means score of 0.65. In addition, the area under the curve was 0.64.

## DISCUSSION

180 Our study showed that Palmer amaranth biomass, height, flowering pattern and gender varied within  
 181 agroecosystems and cohort timings. In general, Palmer amaranth produced more biomass and taller plants  
 182 when growing at first cohort rather than second cohort. At first cohort, resources (e.g., soil nutrients) and  
 183 conditions (e.g., light) were more timely available for both species, crop and weed. High biomass and  
 184 taller Palmer amaranth plants are likely a weed strategy to compete for light in between crop rows in  
 185 absence of canopy. In such condition, Palmer amaranth showed an extraordinary plasticity to adapt upon  
 186 the agroecosystem. This is evident when comparing Palmer amaranth canopy shape, and its extended  
 187 flowering pattern when growing into corn compared to soybean. The Palmer amaranth competition strategy  
 188 was to mimic the crop grow and development (Figure 4). These results suggests that Palmer amaranth  
 189 can fast evolve life-history traits to adapt into agroecosystems and cultural practices, including nitrogen  
 190 fertilization (Bravo et al., 2018). Our results highlight the Palmer amaranth as a threat to agroecosystems  
 191 as breeding more competitive crop varieties is likely to select more competitive biotypes (Bravo et al.,  
 192 2017).

193 Palmer amaranth grow and development at second cohort was limited due to the crop competitive ability  
 194 at advanced development stages. Palmer amaranth was transplanted when corn canopy was nearly closed,  
 195 which reduced Palmer amaranth competitiveness. As a result, Palmer amaranth height and biomass was  
 196 lower compared to its first cohort. Under crop canopy (e.g., second cohort), Palmer amaranth flowering  
 197 pattern was near to similar in corn and soybean. Palmer amaranth growing without crop competition  
 198 produced highest amounts of biomass and less extended flowering pattern. The Palmer amaranth strategy  
 199 in bareground was to invest biomass in growing plant width and height. Nonetheless, Palmer amaranth  
 200 produced 21% less biomass in second cohort compared to first cohort timing. In a bareground study, early  
 201 emerged Palmer amaranth without competition was 50% taller than late emerged plants (Webster and Grey,  
 202 2015). These results suggests that crop competition is not the only factor limiting late Palmer amaranth  
 203 establishment. The limited growth of Palmer amaranth at second cohort is likely a reduced plant response  
 204 to thermal units (e.g, growing degree days). It is hypothesize that reduced day length contributed to smaller  
 205 plants at second cohort as well as shorter flowering period. A study in North Carolina and Illinois predicted  
 206 that less than 10% Palmer amaranth seedlings emergence occurred after June (Piskackova et al., 2021). In  
 207 addition, Palmer amaranth negative impact on soybean (Korres et al., 2020) and cotton (Webster and Grey,  
 208 2015) yields was higher when plants were established near to crop planting.

209 Seed production was not evaluated due to plant harvest at initiation of flowering. Nonetheless, it is well  
210 documented a strong positive correlation between Palmer amaranth biomass and seed production (Schwartz  
211 et al., 2016; Spaunhorst et al., 2018). In our study, Palmer amaranth growing at first cohort accumulated an  
212 overall 36% more biomass when compared to second cohort. Therefore, Palmer amaranth plants growing  
213 in the second cohort is likely to produce less seeds regardless the agroecosystem. Our observation is  
214 consistent with the findings that first Palmer amaranth cohort produced 50% more seeds per plant than  
215 Palmer amaranth plants established six weeks later in bareground (Webster and Grey, 2015). Still, seed  
216 production at second cohort is likely to replenish the soil seedbank. Seed production and deposition in  
217 the seedbank is also a key factor for species perpetuation (Menges, 1987). Palmer amaranth can produce  
218 hundred thousands seeds per plant (Schwartz et al., 2016; Keeley et al., 1987), and stay viable buried in  
219 the seedbank for at least 36 months (Sosnoskie et al., 2013). Therefore, preventing Palmer amaranth seed  
220 production or/and seed migration to its non-native habitat is an essential strategy to minimize weed impact  
221 into agroecosystem (Davis et al., 2015).

222 An ecological approach to reduce seed production in Palmer amaranth is understanding its flowering  
223 pattern. Our study suggests that Palmer amaranth flowering pattern was slightly influenced by cropping  
224 systems and cohort timings. Palmer amaranth growing in bareground and corn resulted in the overall  
225 shortest and longest flowering pattern, respectively. When growing in soybean, Palmer amaranth flowering  
226 pattern was similar to bareground at first cohort but similar to corn at second cohort timing. Plant flowering  
227 initiation is complex and it depends on biological and ecological factors (Lang, 1965). We hypothesize that  
228 when growing in high competition (e.g., second cohort), Palmer amaranth plants tend to initiate flowering  
229 early, as well as having an extended flowering pattern. Early flower initiation is plant strategy when growing  
230 in stress conditions. For example, when growing under water stress, early flowering in Palmer amaranth  
231 resulted in a mismatch between female and male plants by seven days (Mesgaran et al., 2021). A mismatch  
232 in Palmer amaranth male and female flowering period can minimize plant outcross, and thus reduce plant  
233 seed production. Sex dimorphism manipulation is considered a potential ecological pest control (McFarlane  
234 et al., 2018; Schliekelman et al., 2005).

235 The mechanisms of sex-determination in plant species is intriguing and arouse the curiosity of many  
236 scientists, including Darwin (Darwin, 1888). In our study, the gender model performance was decent  
237 considering the biology of plant flowering. A 1:1 male and female sex ratio is a general evolutionary stable  
238 strategy for plant species perpetuation (Fisher, 1930). However, a slight deviation from 1:1 sex ratio might  
239 occur in some dioecious species. For example, the dioecious *Halophila stipulacea* is a female-biased plant  
240 in its native habitat, but the naturalized *H. stipulacea* have a 1:1 ratio (Nguyen et al., 2018). Naturalized of  
241 *H. stipulacea* reduced female-male ratio to expand into its non-native habitat (Nguyen et al., 2018). Also,  
242 biotic and/or abiotic stress can influence plant sex determination. Palmer amaranth male-to-female ratio was  
243 greater under high plant densities (Korres and Norsworthy, 2017) and after herbicide application (Rumpa  
244 et al., 2019). Our model estimated that late flowering, heavier and taller Palmer amaranth plants deviated  
245 from 1:1 ratio in favor to female plants. It was reported that female Palmer amaranth plants invested more  
246 in height, stem and biomass while male invested more in leaf area and leaf dry weight under nutrient  
247 deficiency (Korres et al., 2017). Our model also estimated more female plants in soybean and bareground  
248 compared to corn, which might linked to plant competition strategy in each agroecosystem. Our results  
249 showed the influence of life-history and ecological traits on sexual dimorphism in Palmer amaranth. Sexual  
250 dimorphism is documented in other dioecious species (Barrett and Hough, 2013). For example, stronger  
251 female plant competition and greater male tolerance to herbivory was reported in *Spinacia oleracea*  
252 (Pérez-Llorca and Sánchez Vilas, 2019). Research on candidate genes for sex determination in *Amaranthus*  
253 species are currently underway but it is far to complete (Montgomery et al., 2021, 2019). Further studies are

254 also needed to understand the ecological basis of Palmer amaranth flowering, including the plant behavior  
255 under climate change.

256 Our study demonstrated the short-term Palmer amaranth plasticity to grow and develop into cropping-  
257 systems. Is likely that Palmer amaranth range will continue to expanding to new geographies. Therefore,  
258 preventive management is a priority to minimizing Palmer amaranth dispersal. Reactive management  
259 should focus on early-season management programs, which would have a large negative effect on Palmer  
260 amaranth growth and development. Tactics that promote early-season crop advantage against Palmer  
261 amaranth, including early crop planting, crop rotation (Oliveira et al., 2021), plant width, preemergence  
262 applied herbicide (Sanctis et al., 2021), and crop residue (e.g. cover crops) would minimize the negative  
263 impact of Palmer amaranth in agroecosystems. The aggressiveness and differential Palmer amaranth  
264 adaptation to agroecosystem is striking and require national efforts to minimize the species impact on  
265 economy and sustainability.

## DISCLOSURE/CONFLICT-OF-INTEREST STATEMENT

266 Flower manipulation is a promising ecological Palmer amaranth but it is not well understood.

267 The authors declare that the research was conducted in the absence of any commercial or financial  
268 relationships that could be construed as a potential conflict of interest.

## AUTHOR CONTRIBUTIONS

269 RW: designed the experiments; AJ, CP, MB, MO, and SS: conducted the experiments; MO: analyzed the  
270 data and wrote the manuscript; AJ, CP, MB, MO, SS, and RW: conceptualized the research. All authors  
271 reviewed the manuscript.

## ACKNOWLEDGMENTS

272 Funding: This work received no specific grant from any funding agency, commercial, or not-for-profit  
273 sectors

## 1 SUPPLEMENTAL DATA

274 Supplementary Material should be uploaded separately on submission, if there are Supplementary Figures,  
275 please include the caption in the same file as the figure. LaTeX Supplementary Material templates can be  
276 found in the Frontiers LaTeX folder

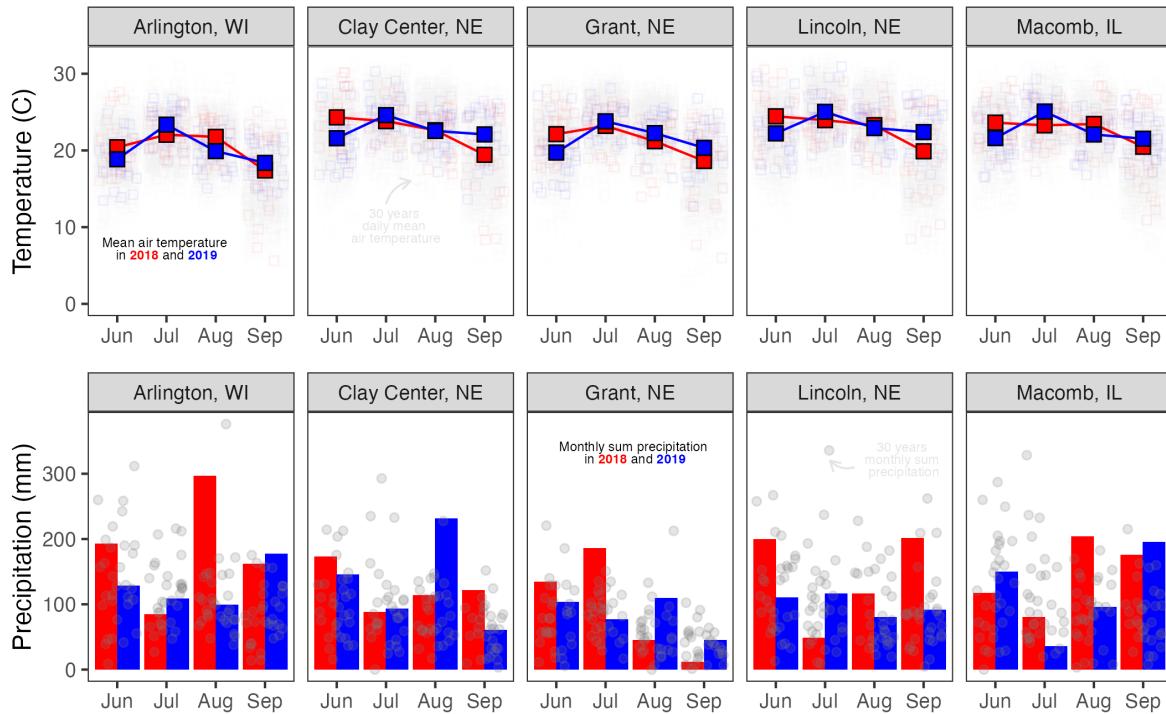
## 2 REFERENCES

277 A reference list should be automatically created here. However it won't. Pandoc will place the list of  
278 references at the end of the document instead. There are no convenient solution for now to force Pandoc to  
279 do otherwise. The easiest way to get around this problem is to edit the LaTeX file created by Pandoc before  
280 compiling it again using the traditional LaTeX commands.

## FIGURES

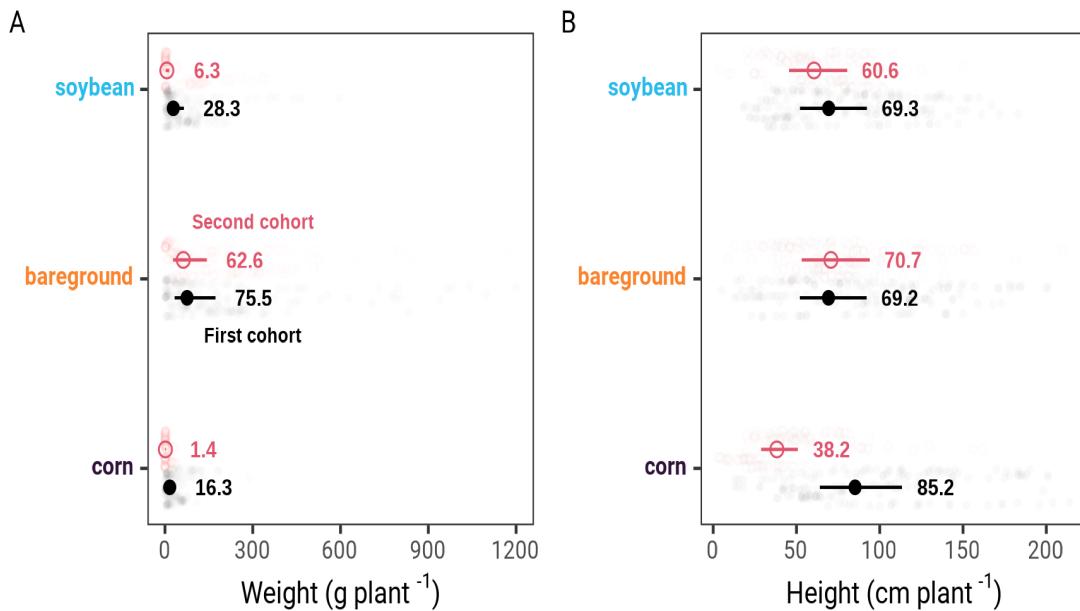
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**Figure 1.** Mean average temperature (C) and monthly sum precipitation (mm) at Arlington, WI, Clay Center, NE, Grant, NE and Macomb, IL

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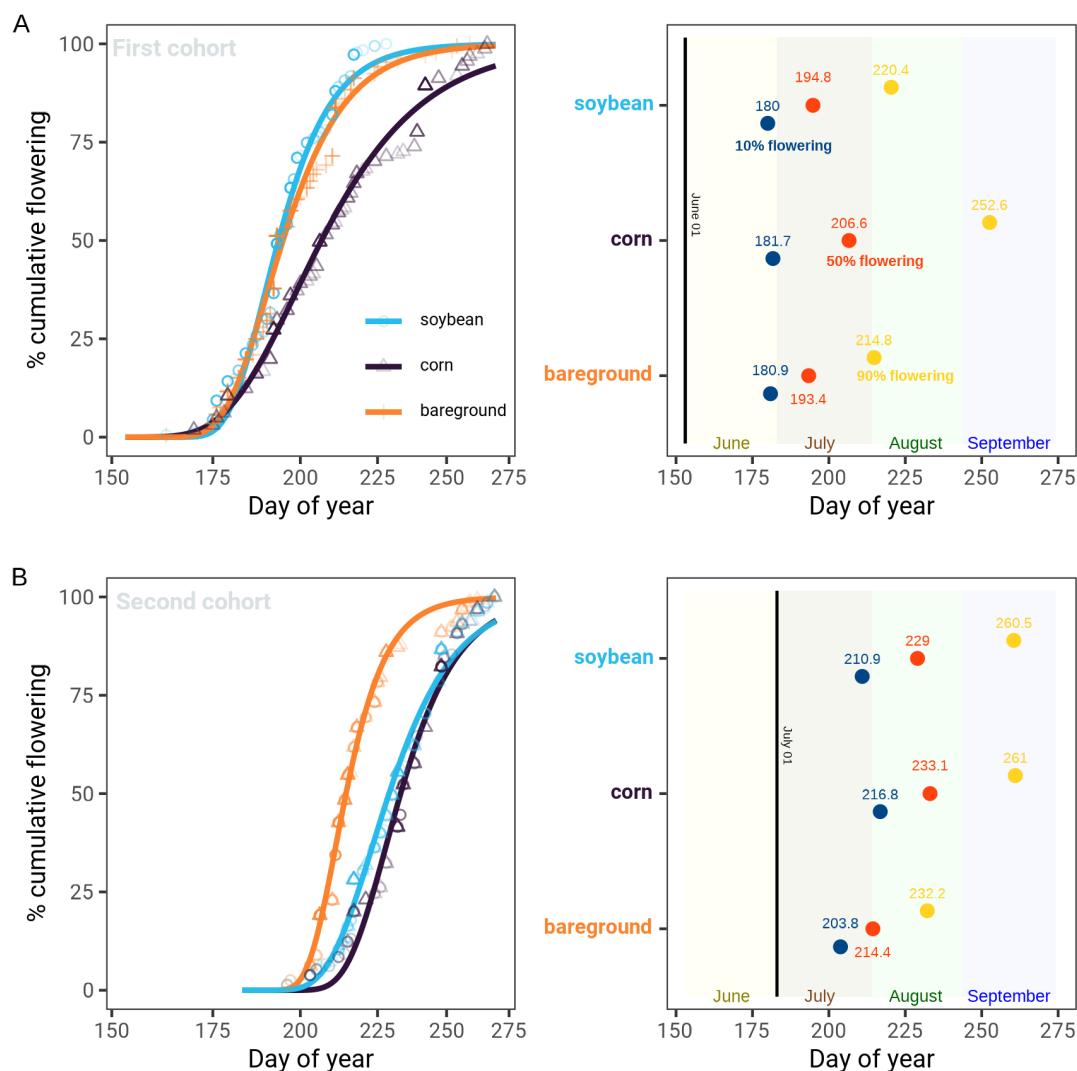


**Figure 2.** Palmer amaranth biomass (A) and height (B) growing in corn, bareground, and soybean across Arlington, WI, Clay Center, NE, Grant, NE, Lincoln, NE and Macomb, IL



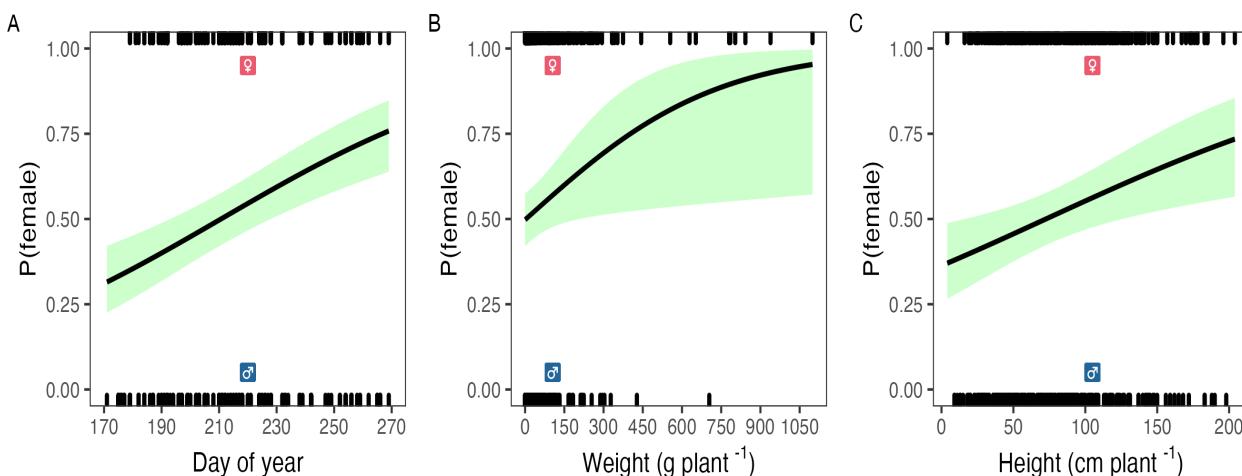
**Figure 3.** Harvest Palmer amaranth plants at 40 days after first transplant timing. From left to right, Palmer amaranth growing in bareground, soybean and corn in Arlington, Wisconsin

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**Figure 4.** Cumulative flowering of Palmer amaranth at first and second transplant timing (A) and day of year of 10, 50, and 90 cumulative flowering at first and second transplant timing (B)

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**Figure 5.** Cumulative flowering of Palmer amaranth at first and second transplant timing (A) and day of year of 10, 50, and 90 cumulative flowering at first and second transplant timing (B)

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