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WEED SCIENCE

Emergence Date Influences Growth and Fecundity of Palmer Amaranth in Cotton

Jason K. Norsworthy, Brandon W. Schrage, Tom L. Barber, and Lauren M. Schwartz*

ABSTRACT

Research was conducted in 2012 and 2013 in Fayetteville, AR to evaluate the impact of Palmer amaranth (*Amaranthus palmeri* (S.) Wats.) emergence date on plant biomass, height, and seed production as well as the corresponding influence on cotton (*Gossypium hirsutum* L.) biomass and yield. Palmer amaranth was evaluated in the presence and absence of cotton and when emergence was delayed in cotton (0, 2, 4, 6, 8, and 10 wk). Seed production per plant was reduced by a greater extent in the presence of cotton, compared to the absence of cotton. Palmer amaranth plants emerging 10 wk after cotton were able to produce on average 880 seed per plant, which is a sufficient amount to replenish a soil seedbank. The late-emerging plants competing with cotton were smaller in size than earlier emerging plants. Seed production in the presence of cotton was correlated with Palmer amaranth biomass production (r^2 = 0.63). Furthermore, the later-emerging cohorts responded to the presence of cotton by producing less biomass more so than a reduction in plant height with delayed emergence. This research shows that Palmer amaranth cohorts emerging as late as 10 wk after cotton emergence must be removed to prevent weed seed production.

Weed control has always been a crucial step in successful cotton (*Gossypium hirsutum* L.) production as problematic weed species, if not controlled, can effectively out-compete cotton for light, nutrients, space, and water. Cotton can require up to 8 wk of weed-free maintenance after planting to maximize yields; whereas corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] require 2 to 4 wk (Buchanan and Burns, 1970). The release of glyphosate-resistant (GR) cotton in 1997 enabled growers to make multiple POST glyphosate applications, controlling a broad spectrum of weeds without disrupting the growth of the crop (Funke et al., 2006). Ultimately, the availability of GR cotton prompted growers to widely adopt the technology because of cost savings, improved weed management, and simplicity of the system (Duke and Powles, 2009; Norsworthy et al., 2016). In 2000, after the loss of patent rights to glyphosate, the price of glyphosate decreased by 40% in the United States (U.S.) (Duke and Powles, 2009; USDA-NASS, 2006). The low price of glyphosate and its ability to control a broad spectrum of weed species with POST applications resulted in extensive use of the herbicide. Annual weeds having high rates of reproduction were a target for control, and sole use of the herbicide, especially early in the cropping season, resulted in immense selection for herbicide resistance (Nichols et al., 2009; Neve et al., 2011). Today, there are 32 GR weed biotypes worldwide and seven of these occur in Arkansas, of which Palmer amaranth is the most problematic in cotton (Heap, 2015; Riar et al., 2013).

Palmer amaranth is a dioecious, summer annual capable of producing over 600,000 seed per female plant in the absence of competition (Keeley et al., 1987). It is highly competitive with crops, having been found to reduce soybean yield 68% at densities of 10 plants m^{-2} (Klingaman and Oliver, 1994). In cotton, for every one Palmer amaranth per 10 m of row, yield was reduced 5.9 to 11.5% at two sites in Oklahoma (Rowland et al., 1999). Additionally, its rapid erect growth and allelopathic potential directly hinder the yield potential of cotton (Menges, 1987; 1988). Palmer amaranth densities of 1 to 10 plants per 9.1 m^{-1} of row in cotton decreased crop canopy volume 35 and 45% by 6 and 10 wk after cotton emergence (WAE), respectively (Morgan et al., 2001). Furthermore, light interception is considered to have the greatest impact on cotton canopy volume, biomass, and yield when soil moisture and nutrients are not limiting (Donald, 1958; Morgan et al., 2001). The rapid, erect growth of Palmer amaranth can result in individuals reaching over 2 m in height, leav-

J.K. Norsworthy, B.W. Schrage, and L.M Schwartz*, Crop, Soil, and Environmental Sciences, University of Arkansas, 1366 West Altheimer Drive, Fayetteville, AR 72704; and T.L. Barber, Crop, Soil, and Environmental Sciences, University of Arkansas, 102 NE Front St. Suite 2, Lonoke, AR 72086
*Corresponding author: lmschwar@uark.edu

ing little doubt that cotton in close proximity could experience decreased lint yield via shading (Keeley et al., 1987; Rowland et al., 1999). The high level of Palmer amaranth interference with cotton results in the need for effective control, even to the point of complete elimination of escaped plants in cotton (Norsworthy et al., 2014).

New herbicide chemistry is limited as industry research and development efforts slowed following the release of GR crops (Norsworthy et al., 2012). While great attention has been focused on redeveloping existing technologies, the use of integrated weed management (IWM) strategies has gained renewed attention. In 2012, best management practices (BMPs) were put forth to address the ever-increasing occurrence of herbicide-resistant weeds (Norsworthy et al., 2012). Understanding the biology of the targeted weed was noted as a critical component in designing resistance management strategies and is essential for modeling the evolution of herbicide resistance. The BMPs to mitigate herbicide resistance encourage attention to weed biology and ecology; namely, weed growth, fecundity, and overall competitiveness in a given crop (Bagavathiannan et al., 2012). Weed fecundity and biomass are highly dependent upon time of emergence relative to the crop, weed and crop density, and proximity of the weed to the crop (partially impacted by seeding rate and row spacing) (Clay et al., 2005; Knezevic and Horak, 1998; Murphy et al., 1996). Previous research shows that as emergence date becomes later in the growing season, weed fecundity decreases (Clay et al., 2005; Knezevic and Horak, 1998). Continued exploration of weed biology and ecology benefits cotton producers striving to quantify the competitive interactions between cotton and Palmer amaranth within varying environments and agronomic scenarios (Clay et al., 2005; Gressel, 2011; Uscanga-Mortera et al., 2007; Van Acker, 2009). Hence, the objective of this research was to determine to what extent biomass production, mature height, and fecundity of Palmer amaranth in cotton are affected by emergence date relative to the crop and the resulting effect on cotton biomass and seed cotton yield.

MATERIALS AND METHODS

In 2012 and 2013, a field experiment was conducted at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR, as a randomized complete block with a 2 x 6 factorial treatment structure with two levels of cotton (presence or absence) and six Palmer amaranth emergence dates. There were four replications. Cotton cultivar ‘PHY 375 WRF’ (Dow AgroSciences, Indianapolis, IN) was planted at a 2-cm depth into a Leaf silt loam soil (Fine, mixed, active, thermic Typic Albaquults) (USDA-NRCS, 2015) with 34% sand, 53% silt, 13% clay, 1.5% organic matter, and a pH of 6.9 at 125,000 seed ha^{-1} and supplemented with over-head sprinkler irrigation to maintain optimal growing conditions. Planting occurred on 1 June 2012 and 15 May 2013, using a four-row planter. The twelve treatments were grown in four-row plots on a 92-cm row spacing and 9.1 m plot length. Approximately 20 Palmer amaranth seeds were hand-planted in close proximity to the inner two rows (< 13 cm from row center) of each four-row plots approximately 4 d after seeding cotton in order for Palmer amaranth emergence to coincide with cotton emergence. Cotton emerged on 5 June 2012 and 23 May 2013 and was shortly thereafter removed in one treatment of each of the six Palmer amaranth emergence dates (0, 2, 4, 6, 8, and 10 wk after cotton emergence). Removal of cotton in one-half of the plots allowed for the effect of cotton on Palmer amaranth to be assessed, accounting for the delayed emergence of cohorts after typical planting of cotton. Palmer amaranth seedlings were manually thinned to one plant per m^{-1} of row within 2 wk after emergence, resulting in a final density of 1.1 plants m^{-2} competing with the two innermost rows of cotton in each four-row plot.

A known glyphosate- and trifloxysulfuron-resistant Palmer amaranth biotype was used, which allowed for use of glyphosate and trifloxysulfuron for control of unwanted weeds. Additionally, clethodim was used later in the growing season to remove grasses and some unwanted Palmer amaranth plants were hand-removed throughout the season to promote as close of a weed-free environment as possible. Only slight injury to Palmer amaranth was observed following any of the herbicide applications, and the plants had often fully recovered by 2 to 3 wks after treatment. All applications were made using a CO_2-pressurized backpack sprayer equipped with four TTI 110015 nozzles (TeeJet Technologies, Glendale Heights, IL) calibrated to deliver 187 L ha^{-1} at a pressure of 276 kPa and a walking speed of 4.8 kph.

Prior to cotton defoliation each fall, the height of three Palmer amaranth and three cotton plants in each plot was measured and aboveground biomass of all existing female Palmer amaranth plants were harvested for biomass determination. Palmer amaranth biomass was placed in individual bags and oven dried at 66ºC and then weighed. All inflorescences of the female plants were then removed and threshed to determine seed production per plant. Seed shattered prior to collection were not accounted for, only the number of seeds on the plant at the time of collection were utilized. Seed production was determined by counting the number of seed in four 100-g samples of threshed seed heads and then extrapolating for the mass of the entire sample. Following cotton defoliation, seed cotton was harvested from 4 m row^{-1} of the two center rows of each treatment and weighed.

All data were subjected to ANOVA using JMP PRO 11 (JMP Statistical Discovery, Cary, NC) (Table 1). Data were square-root transformed to meet normality assumptions for Palmer amaranth height, biomass, and seed production, and in all cases, replications were nested within years and considered a random effect. Nonlinear models were established based on the best pseudo-r^2 value (Pseudo-r^2 = 1-SS(Residual)/SS(Total$_{\text{Corrected}}$) (Chism et al. 1992). Based on this process, a two-parameter exponential decay model was utilized (Y = a*exp(-b*x)) to describe end-of-season Palmer amaranth biomass over the evaluated cohorts. The interacting effect of cotton competition and year proved to significantly impact Palmer amaranth height and a mixed model with an effect leverage personality under a residual maximum likelihood (REML) was utilized. This analysis is comparable to ProcMixed GLM in SAS (Statistician, Dr. Weisz, NC State University, personal communication). Means were separated using Tukey's HSD at the alpha level of 0.05. Transformation of data achieved homoscedasticity for linear regression methods and fitted equations with associated pseudo-r^2 values were presented. Years were not pooled in regards to the interaction of Palmer amaranth biomass and seed production. For Palmer amaranth biomass and seed production, a bivariate fit was constructed blocking for replication and applying year as a by-variable for the associated linear equation, $Y = ax + b$, and pseudo-r^2 values.

RESULTS AND DISCUSSION

The establishment of successful IWM requires an understanding of the biology of major weed species. In current midsouthern U.S. cotton production, this directly relates to Palmer amaranth as a major competitor for light, space, water, and nutrients. Averaged over 2012 and 2013, Palmer amaranth end-of-season height and biomass production were significantly impacted by the interaction of Palmer amaranth emergence date in the presence and absence of cotton (Table 1). Of the three Palmer amaranth parameters measured, only end-of-season height was influenced by the effect of year.

Table 1. Effects tests for the impact of year, Palmer amaranth emergence date relative to cotton (WAE), and presence and absence of cotton (Cotton) on Palmer amaranth end-of-season height, aboveground biomass, seed production per female plant, and cotton end-of-season height and seedcotton yield

Source	Palmer amaranth			Cotton	
	Height[z]	Biomass[y]	Seed production[x]	Height[w]	Seedcotton yield
	Prob > F[u]				
Year	0.0351	0.2092	0.5872	0.0007	0.0022
WAE[v]	<.0001	<.0001	<.0001	0.1936	<.0001
Year*WAE	0.7906	0.4794	0.8649	0.0702	0.0022
Cotton	<.0001	0.9560	0.0022	-	-
Year*Cotton	0.0203	0.3444	0.4356	-	-
WAE*Cotton	<.0001	0.0038	0.3839	-	-
Year*WAE*Cotton	0.2634	0.6119	0.5678	-	-

[z] Palmer amaranth height was measured at 17 wk after cotton emergence.

[y] Aboveground Palmer amaranth biomass collected 17 wk after cotton emergence, oven-dried, and weighed.

[x] Seed production per female Palmer amaranth plant collected immediately prior to defoliating cotton.

[w] Height of cotton at 17 wk after emergence.

[v] Weeks after emergence (WAE).

[u] Source values less than 0.05 are statistically significant.

Cotton Height and Seed Cotton Yield. Cotton height was greater in 2013 than in 2012 (Table 1). In 2012, there was a 4 to 5 wk period when the overhead irrigation system was not functioning (Figure 1), which most likely contributed to reducing cotton heights in addition to the interference imposed by Palmer amaranth. The greater rate of seed cotton yield loss as a function of Palmer amaranth emergence date in 2012 than in 2013 may partially be a result of the drier conditions in 2012 (Figure 1). However, Palmer amaranth emergence date did not interact with year nor did the main effect of Palmer emergence date relative to cotton impact cotton height. Conversely, the interaction of Palmer amaranth emergence date and year did interact in regards to seed cotton yield.

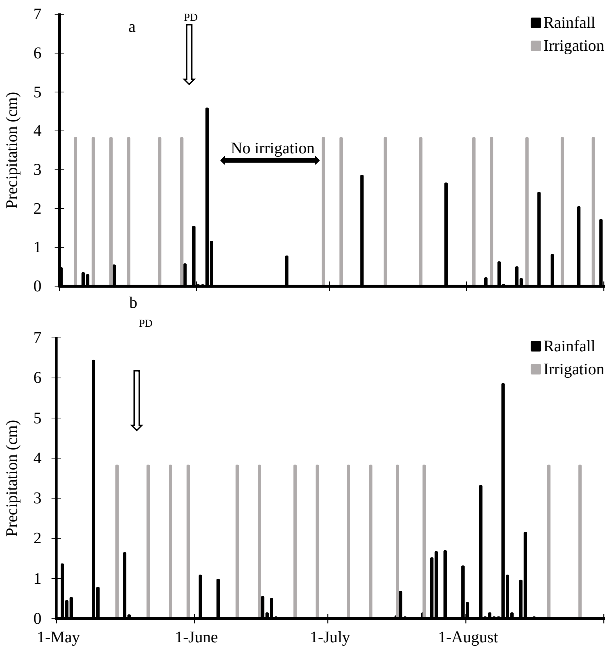

Figure 1. Rainfall and irrigation distribution at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR in 2012 (a) and 2013 (b) with respective planting dates (PD).

For both years, seed cotton yield declined as Palmer amaranth emergence date occurred earlier in the year relative to that of cotton (Figure 2), illustrating the impact of early season emergence on Palmer amaranth competitiveness with cotton and in turn reduction in seed cotton yield. This relationship of competition is well documented (Ehleringer, 1983; Jha et al., 2008; Menges, 1987, 1988; Morgan et al., 2001; Rowland et al., 1999). At a density of 1.1 Palmer amaranth plants m^{-2}, seed cotton yields increased by 487 kg ha^{-1} for every week delay in Palmer amaranth emergence through 10 wk after cotton emergence in 2012. At the same density in 2013, seed cotton yields were less impacted by Palmer amaranth emerging in cotton; hence, seed cotton yields were improved only 278 kg ha^{-1} for each week delay in weed emergence relative to the crop. Webster and Grey (2015) conducted a closely related experiment in Georgia on Coastal Plain soils in 2011 and 2012. They concluded that there was a log-logistic relationship between seed cotton yield loss and relative timing of Palmer amaranth establishment, beginning with a 67% seed cotton reduction when Palmer amaranth was established at cotton planting at a density of 0.42 plants m^{-2}. It was evident in both studies that delayed weed emergence resulted in higher seed cotton yields.

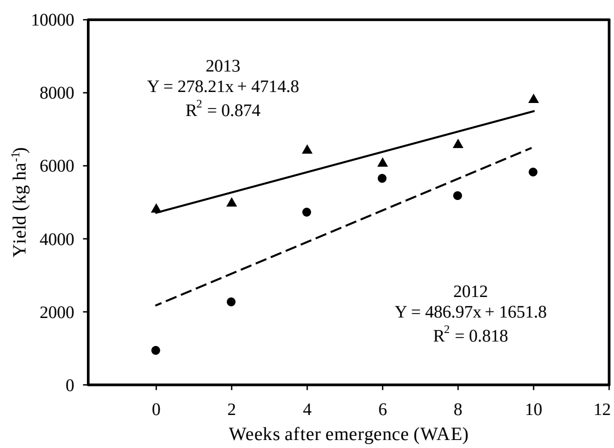

Figure 2. Seedcotton yield in 2012 and 2013 at the Arkansas Agricultural Research and Extension Center. Significance interaction of WAE and year was achieved using a mixed model in JMP Pro 11. Under a standard least squares personality, the REML method conceived linear regression emphasizing effect leverage.

Palmer Amaranth Height and Biomass. The presence of cotton had a greater impact on Palmer amaranth end-of-season height averaged over emergence dates in 2012 than in 2013 (Figure 3). Palmer amaranth heights averaged over emergence dates were similar in 2012 and 2013 in the absence of cotton, ranging from 119 to 123 cm. The lack of irrigation for a short period in 2012 may have enhanced the level of interference between cotton and Palmer amaranth, but in the absence of cotton, the drier conditions did not influence Palmer amaranth height. Furthermore, the spring of 2012 was uncharacteristically warm, which may have aided early-season growth of cotton, resulting in greater suppression of Palmer amaranth. The fact that these plots were oversprayed with glyphosate and trifloxysulfron during the growing season and transient injury was sometimes observed may have contributed to the heights being lower than that reported in other research. In Kansas, for instance, Palmer amaranth heights ranged from 174 to 231 cm when grown without crop competition at a density of one plant per 0.76 m^{-1} of row (Horak and Loughlin, 2000). Furthermore, the cool growing conditions at Fayetteville, AR are likely to have a greater impact on growth of Palmer amaranth, a C_4 plant that normally thrives under hot, dry conditions. Trends for Palmer amaranth height in Fayetteville experiments complimented those conducted by others. Hartzler et al. (2004) determined that a linear decline in plant height existed as common waterhemp (*Amaranthus rudis* Sauer) emergence date became later in soybean.

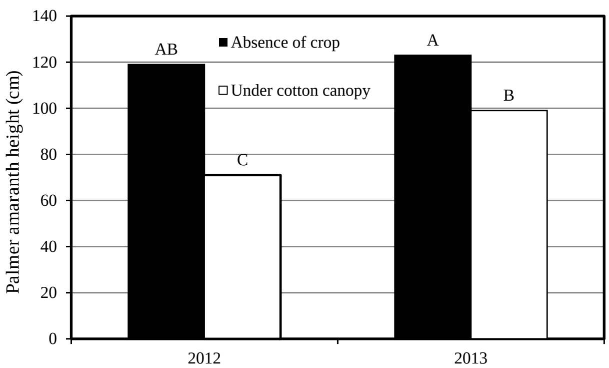

Figure 3. Palmer amaranth heights at 17 wk after cotton emergence at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR in 2012 and 2013 in the presence and absence of cotton, averaged over emergence cohorts (wk after cotton emergence). A mixed model emphasizing effect leverage, REML method, and standard least squares personality presented significance with means separated by Tukey's HSD at the alpha level of 0.05.

Biomass of Palmer amaranth was reduced when grown in the presence of competition with cotton (Table 1). Just as competition for light could have been the deciding factor in regards to significant differences in Palmer amaranth height so too was the case of biomass. Year did not significantly impact Palmer amaranth biomass, and competition became more intense as emergence date of Palmer amaranth became later in the year (Figure 4). Similar to the findings of Uscanga-Mortera et al. (2007), there was a significant exponential decay associated with weed biomass as emergence date became later in the year (Figure 5). In Georgia, it was found that early emerging Palmer amaranth (comparable to 2 to 4 WAE) growing in competition with cotton produced 29 and 40% less biomass compared to the absence of cotton (Webster and Grey, 2015). Palmer amaranth plants did not display appreciable phototropism as heights decreased linearly as weed emergence was delayed relative to the crop, and biomass per plant was likewise reduced with delayed emergence, even in the absence of cotton competition.

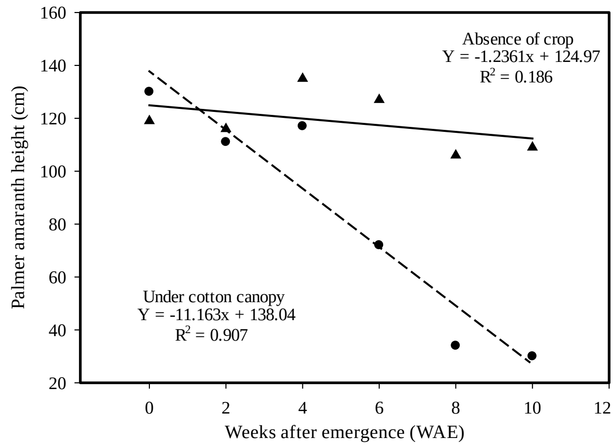

Figure 4. Palmer amaranth heights at 17 wk after cotton emergence at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR in the presence and absence of cotton competition as a function of Palmer amaranth emergence date relative to cotton (x-axis; WAE). Data were pooled over years and analysis conducted as a mixed model in JMP Pro 11. Effect leverage emphasis under the REML method provided linear regression.

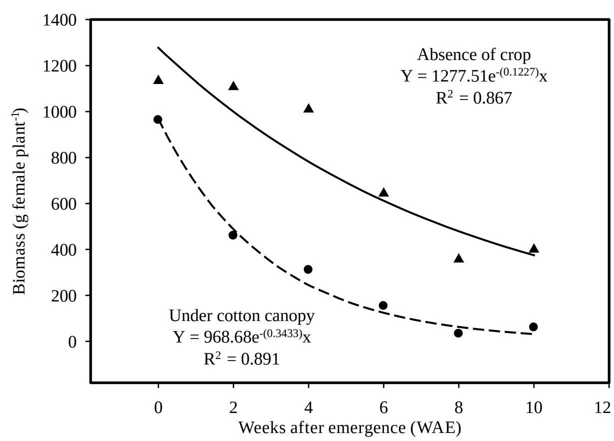

Figure 5. Amount of biomass collected from female Palmer amaranth plants within cotton and noncrop plots that were planted at different timings following the emergence date of cotton at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR. Mixed model analysis in JMP Pro 11 fitted for an exponential decay function; data were pooled over 2012 and 2013.

Palmer Amaranth Fecundity. Palmer amaranth emerging as late as 10 WAE was still able to produce 880 seed female per plant (Figure 6). This displays the weed species' ability to reach reproductive maturity and disperse viable seed rather quickly even under the reduced light quantity imposed by the existing cotton crop. The decreasing day lengths to which later-emerging weeds are exposed could result in the hastening of flowering similar to the findings of Bagavathiannan et al. (2015) and Keeley et al. (1987). Palmer amaranth fecundity was highly correlated with plant biomass (Figure 7). Biomass and associated fecundity were significantly reduced when in competition with cotton in 2012 and 2013, complimenting existing research (Keeley et al., 1987; Webster and Grey, 2015). The correlation between biomass and fecundity, irrespective of cotton presence, allows late-emerging Palmer amaranth to produce viable seed. This is similar to the findings of Uscanga-Mortera et al. (2007) regarding common waterhemp fecundity in corn. Fecundity per Palmer amaranth female averaged considerably less in all treatments compared to Keeley et al. (1997), Webster and Grey (2015), and MacRae et al. (2013). This is most likely attributed to the cooler, finer-textured soils in Northwest Arkansas compared to other more southern cotton-producing regions of the United States. Additionally, the glyphosate and trifloxysulfuron applications and the transient injury following these applications may have contributed to the lower seed production in this research. The similarities in response to delayed Palmer amaranth emergence found between this research and those of Webster and Grey (2015) suggest that herbicide-resistance in Palmer amaranth has initiated a need for IWM tactics (Norsworthy et al., 2012).

Palmer amaranth fecundity decreased as emergence occurred later in comparison to cotton emergence. Although late-emerging Palmer amaranth produces less biomass and can be less prolific, it can still produce viable offspring that can result in failure to maintain a static seedbank. A 50% annual recruitment (Keeley et al., 1987) supplemented by an estimated 33 to 55% of female plants (Smith and Norsworthy, unpublished observation; Keeley et al., 1987), suggests that even minimal escapes can become detrimental to fields where cotton is grown. The delayed emergence of Palmer amaranth can also simulate the premature loss of herbicide efficacy, as concluded by Culpepper et al. (2013), even in the absence of significant seed cotton yield reduction. Thus, it is the recommendation of current BMPs and findings from this research that cotton producers make every effort to control or remove Palmer amaranth throughout the season; hence, the goal of a 'Zero Tolerance' threshold (Norsworthy et al., 2014; Barber et al., 2015).

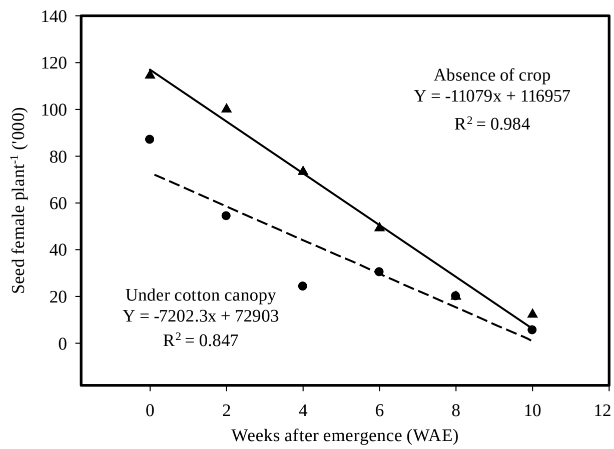

Figure 6. Number of Palmer amaranth seeds produced per female plant as a function of Palmer amaranth emergence dates at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR in 2012 and 2013. A mixed model was utilized in JMP Pro 11. Under a standard least square personality the REML method conceived linear regression emphasizing effect leverage.

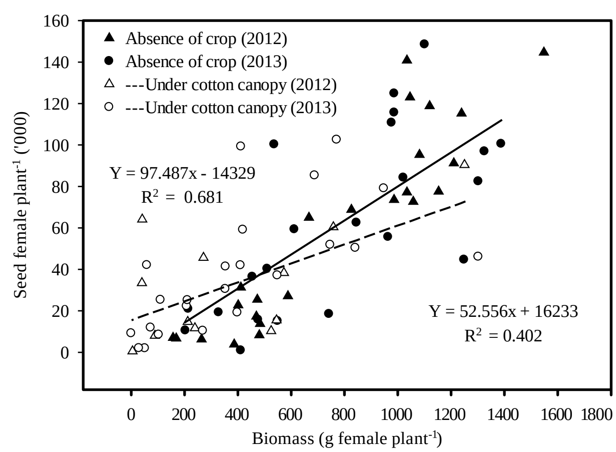

Figure 7. Relationship between Palmer amaranth biomass and seed production at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR in 2012 and 2013. Analysis achieved with a bivariate fit conceived in JMP Pro 11; blocking for replication and utilizing a by-variable (year). The solid line is in the absence of cotton and the dashed line is in the presence of cotton.

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