Weed Science 2014 62:237–249

In-Field Movement of Glyphosate-Resistant Palmer Amaranth (*Amaranthus palmeri*) and Its Impact on Cotton Lint Yield: Evidence Supporting a Zero-Threshold Strategy

Jason K. Norsworthy, Griff Griffith, Terry Griffin, Muthukumar Bagavathiannan, and Edward E. Gbur*

This research was aimed at understanding how far and how fast glyphosate-resistant (GR) Palmer amaranth will spread in cotton and the consequences associated with allowing a single plant to escape control. Specifically, research was conducted to determine the collective impact of seed dispersal agents on the in-field expansion of GR Palmer amaranth, and any resulting yield reductions in an enhanced GR cotton system where glyphosate was solely used for weed control. Introduction of 20,000 GR Palmer amaranth seed into a 1-m^2 circle in February 2008 was used to represent survival through maturity of a single GR female Palmer amaranth escape from the 2007 growing season. The experiment was conducted in four different cotton fields (0.53 to 0.77 ha in size) with no history of Palmer amaranth infestation. In the subsequent year, Palmer amaranth was located as far as 114 m downslope, creating a separate patch. It is believed that rainwater dispersed the seeds from the original area of introduction. In less than 2 yr after introduction, GR Palmer amaranth expanded to the boundaries of all fields, infesting over 20% of the total field area. Spatial regression estimates indicated that no yield penalty was associated with Palmer amaranth density the first year after introduction, which is not surprising since only 0.56% of the field area was infested with GR Palmer amaranth in 2008. Lint yield reductions as high as 17 kg ha^{-1} were observed 2 yr after the introduction (in 2009). Three years after the introduction (2010), Palmer amaranth infested 95 to 100% of the area in all fields, resulting in complete crop loss since it was impossible to harvest the crop. These results indicate that resistance management options such as a "zero-tolerance threshold" should be used in managing or mitigating the spread of GR Palmer amaranth. This research demonstrates the need for proactive resistance management.

Nomenclature: Glyphosate; Palmer amaranth, *Amaranthus palmeri* S. Wats.; cotton, *Gossypium hirsutum* L. 'Stoneville 4554 B2/RRF'.

Key words: Crop yield loss, seed dispersal, spatial movement of weeds, spatial statistics, zero threshold.

In 2012, the United States ranked first globally for commercial production of genetically modified crops, with eight crops planted across 69.5 million ha during that year (James 2012). In 2010, a total of 93, 78, and 70% of the U.S. soybean [*Glycine max* (L.) Merr], cotton, and corn (*Zea mays* L.) hectares, respectively, were planted to genetically modified crops (USDA 2011). The majority of these hectares were planted with GR varieties, which were introduced in the mid-1990s. As a result, the use of glyphosate for in-season weed control increased dramatically and has been associated with the selection for several GR weed species. By 2013, a total of 14 GR weed species have been confirmed in the United States, comprising about half of the total GR weed species ever confirmed in the world (Heap 2013).

Weed control based on the economic threshold approach is no longer sufficient for sustaining GR cropping systems (Bagavathiannan and Norsworthy 2012; Norsworthy et al. 2012). The economic threshold was first developed as a decision-making tool in entomology and was based on the biological life cycle of arthropods (Stern et al. 1959). Several differences in the population ecology of weeds and arthropods exist, indicating that economic thresholds can lead to different outcomes in weed management strategies (Jones and Medd 2000; Norris 1999; Swanton et al. 1999; Swanton and Booth 2004). There are various types of thresholds,

---

DOI: 10.1614/WS-D-13-00145.1

* First, second, and fourth authors: Professor, Former Graduate Research Assistant, and Postdoctoral Associate, University of Arkansas, Department of Crop, Soil, and Environmental Sciences, 1366 West Altheimer Drive, Fayetteville, AR 72704; third author: Vice President of Applied Economics, Cresco Ag, Little Rock, AR 72223; fifth author: Professor of Statistics and Laboratory Director, Agricultural Statistics Laboratory, University of Arkansas, 101 Agricultural Annex Building, Fayetteville, AR 72701. Corresponding author's E-mail: jnorswor@uark.edu

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press

and threshold levels differ depending on a weed's fecundity, competitiveness, population growth rate (lambda), seedbank life, and tendency to evolve resistance, among others (see Bagavathiannan and Norsworthy 2012 for a detailed discussion on thresholds). For a weed species that exhibits prolific seed production, high competitiveness with the crop, and rapid dispersal, all seed production must be prevented, especially in a situation where resistance has evolved. Thus a zero-tolerance threshold should serve as a threshold appropriate for such weed species.

Rejmánek and Pitcairn (2002) reported that success rate of eradicating problematic weeds was greatest with early detection, prior to infestations greater than 1 ha in size, because propagule dispersal can thwart management measures. The effects of resistant weeds could be minimized if further spread from the original resistant patch could be prevented. Herbicide resistance can typically spread within and among production fields through the movement of seed, pollen, and regenerative propagules (Bagavathiannan et al. 2013a). Seed movement is particularly important for long-distance dispersal for most weeds and there are several seed dispersal mechanisms involved in the spread of weed species. Wind and water are common abiotic seed dispersal mechanisms, but there are several biotic dispersal mechanisms, such as movement via animals by adhesion (epizoochory) or ingestion (endozoochory), and even movement resulting from human activities (anthropochory) (Van der Pijl 1972).

In the context of within-field dispersal, the contribution of rain and irrigation water to seed movement is noteworthy. Li and Qiang (2009) reported that over 74 weed species belonging to 20 different families were found to float and travel via water, suggesting that dispersal and species composition can be influenced by irrigation pattern and frequency in a given field. Weeds that have the ability to produce numerous small seeds that are capable of floating in water can rapidly spread across a production field. Palmer amaranth is one such weed. It can produce as high as 1,800,000 seed plant^{-1} (Bryson and DeFelice 2009; Smith et al. 2012), with seeds measuring only 1 to 1.3 mm in diameter. In early research conducted by Kelley and Bruns (1975), redroot pigweed (*Amaranthus retroflexus* L.), a closely related *Amaranthus* species, was reported to be one of the most common weed seed found in irrigation canals.

Tillage and harvest equipment are known to disperse weed seed. The combination of cultivation and mechanical harvest prior to weed seed shed resulted in the dispersal of weed seed for distances over 100 m in a corn-based cropping system (Heijting et al. 2008). Other long-distance seed dispersal mechanisms include anthropogenic means such as the movement of animal manure, gin trash, and contaminated crop seed, among others (see Bagavathiannan et al. 2013a for a discussion on dispersal vectors). Norsworthy et al. (2009) reported that Palmer amaranth seed was viable at a depth of 25 cm after 2 yr of gin trash composting. Since gin trash is sometimes used as a cattle feed, and both gin trash and manure are commonly spread over agricultural fields, this could represent short- and long-distance dispersal mechanisms for Palmer amaranth.

Additionally, pollen migration can favor the dispersal of resistance, especially in cross-pollinated weed species (Thill and Mallory-Smith 1997). Because exchange of genetic material must occur for dioecious species such as Palmer amaranth, the likelihood of movement of resistant alleles to susceptible populations is high. Wind-pollinated species have a high rate of gene flow within and between populations (Rognli et al. 2000). In Georgia, pollen-mediated transfer of glyphosate resistance through wind flow occurred for distances up to 300 m in Palmer amaranth (Sosnoskie et al. 2012).

Most weeds exhibit an aggregated or patchy distribution (Wiles et al. 1992), with the patches showing spatial stability over time (Beckie et al. 2005; Marshall and Brain 1999; Rew et al. 1996; Rew and Cussans 1997; Wilson and Brain 1991). An understanding of the patch expansion dynamics is instrumental to the development of appropriate management strategies aimed at containing a weed population. The patchy distribution of weeds is generally most stable for perennial species and for those with high levels of shattering prior to crop harvest (Colbach et al. 2000). Palmer amaranth is a summer annual and only a small proportion of its seeds shatter prior to crop harvest (Bagavathiannan et al. 2013b), suggesting that the field distribution of Palmer amaranth may not be consistent with patchy distribution. Studies also show that large-seeded weeds (e.g., common sunflower [*Helianthus annuus* L.]) and persistent weeds (e.g., velvetleaf [*Abutilon theophrasti* Medik.]), exhibit localized seed dispersal prior to harvest, with patches being somewhat stable over time (Burton et al. 2005; Dieleman and Mortensen 1999). Palmer amaranth is believed to exhibit less of a stable patch

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press

distribution than previously evaluated species because of its unique characteristics such as high seed production and increased likelihood for dispersal via harvest equipment due to the minimal spontaneous seed shattering prior to crop harvest and subsequent seed movement by rain or irrigation water. Thus, an understanding of the distribution of Palmer amaranth through a spatial approach is vital for making informed management decisions.

Monitoring patch expansion and the soil seedbank using site-specific technology such as global positioning systems (GPS) is considered a useful practice for resistance management (Beckie 2006) and has been successfully utilized for monitoring the spread of wild oat (*Avena fatua* L.) (Beckie et al. 2005), purple nutsedge (*Cyperus rotundus* L.), yellow nutsedge (*Cyperus esculentus* L.) (Webster 2005), and hemp dogbane (*Apocynum cannabinum* L.) (Webster et al. 2000), among others. Despite the importance of Palmer amaranth as a troublesome herbicide-resistant weed in various production systems, little research has been carried out to understand the distribution patterns of this species shortly after introduction in a production field and its impact on crop yield.

The objectives of this research were 1) to develop a geo-spatial dataset to characterize the in-field expansion of GR Palmer amaranth through seed production over 3 yr in a GR cotton production system in which glyphosate was the only herbicide used for weed control and 2) to determine the effect of GR Palmer amaranth density on cotton yields.

Materials and Methods

Field studies were conducted from 2007 to 2010 in four fields ranging from 0.53 to 0.77 ha in size at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR. The soil types in these fields included a mix of Captina silt loam (fine-silty, siliceous, active, mesic Typic Fragiudults), a Pickwick silt loam (fine-silty, mixed, semiactive, thermic Typic Paleudults), and a Leaf silt loam (fine, mixed, active, thermic Typic Albaqults) (SSURGO 2012).

These fields—marked as G2, G4, G5, and G6—had no prior history of Palmer amaranth infestation in them. Each year, 'Stoneville 4554 B2/RRF' cotton was planted and managed using standard production practices for midsouthern U.S. furrow-irrigated cotton. Each of these fields had 20,000 GR Palmer amaranth seeds sown into a circular 1-m^2 area on the high end of the field (south) in February 2008, centered approximately 15 m from the field edge. The center and edge of these 1-m^2 patches were georeferenced (± 4 cm) using a Trimble AgGPS 332 Ultimate Choice GPS (Ultimate Choice GPS, Laserplane Arkansas Inc., 882 East Park St, Carlisle, AR 72024) receiver with OmniSTAR HP correction (FURGO; OmniSTAR, Inc., 8200 Westglen, Houston, TX 77063).

Table 1. Amount of precipitation in 2007, 2008, and 2009 at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.[a,b]

Month	2007	2008	2009
		cm	
January	11.7	3.8	1.5
February	6.0	10.5	5.1
March	1.8	25.5	10.2
April	7.7	21.0	9.2
May	11.2	12.0	20.2
June	10.7	8.2	6.4
July	7.9	10.9	11.8
August	6.5	15.0	13.0
September	6.0	23.5	18.4
October	9.1	6.0	26.0
November	0.9	2.2	4.0
December	6.3	6.0	7.3

[a] A single irrigation was applied in June 2007, July 2007 and 2009, and August 2008 and 2009; and two irrigations were applied in July 2008 and August 2007.

[b] A single irrigation accounted for approximately 5.0 cm of rainfall; multiple irrigations were totaled together based on this value.

This initial introduction was intended to represent a conservative estimate of seed production from a single GR plant that survived to maturity in 2007. Since Palmer amaranth seeds are capable of floating in water, rainfall events and irrigation totals in 2008 and 2009 are shown in Table 1.

Each year, glyphosate was applied as needed (four applications) to control all other weed species in the field. In 2008, 2009, and 2010, the final density of Palmer amaranth was determined in a 1.0-m^2 grid, using a Cartesian coordinate system with a continuous scale of 0, 1, 2, 3, 4, 5, and ≥ 6 Palmer amaranth m^{-1} of row. Spatial cotton yield data were collected in 2007, 2008, and 2009 using a cotton yield monitor kit (cotton yield monitor with Insight display, Case-IH 1822 kit; Ag Leader Technology, 2202 S. Riverside Dr., Ames, IA 50010) equipped with Insight display and the GPS unit. It was not possible to harvest the crop in 2010 due to severe infestation of Palmer amaranth in the experimental field and it was considered as a total crop failure. During harvest, yield data were collected every second from the two border rows of

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press

each grid cell, with an approximate harvest speed of 3 km h^{-1}. After harvest, cotton stalks were shredded prior to working and rebedding the ground.

Since yield data were geo-spatially referenced, spatial variability rendered standard ANOVA and least squares regression methods unreliable for statistical analysis. The original yield data were imported into ArcGIS (Esri, Redlands, CA 92373) along with latitude, longitude, elevation, speed, time, and lint mass as the major attributes for each data point. Additional information, such as field name, was added to the attribute table and it was converted to a GIS shapefile (.shp). A soils map was obtained for Fayetteville, AR, through the soil survey geographic database (SSURGO 2012) and imported to ArcGIS. The soils map was added as a separate layer and a polygon was drawn around each soil type, creating a soil polygon for selecting yield data points within each soil type. Soil types were added to the attribute table for use as covariates in the analysis and again saved as a .shp file.

In a separate ArcGIS layer, a 1-m^2 grid was created and aligned for fields G2, G4, G5, and G6, and Palmer amaranth density data were added for each year. The layer containing Palmer amaranth density data was then spatially joined or snapped to the original yield data layer, with each Palmer amaranth 1-m^2 grid taking the average of the respective yield data points to represent cotton lint yield. This dataset was saved as a single .shp file for future analysis. To assess spatial variability, cotton yields and Palmer amaranth density data were subjected to exploratory spatial data analysis (ESDA) using GeoDa 0.9.5-I (Arizona State University; http://geodacenter.asu.edu/). Row-standardized spatial weight matrices were created based on either queen (eight directions) or rook (four directions) contiguity, since the dataset contained aerial units. These spatial weight matrices were used in Moran's *I* (Anselin 1999) test for global spatial autocorrelation, as well as a local indicator of spatial association (LISA) (Anselin 2003) to determine whether significant local clustering occurred. The results from ESDA suggested further statistical analysis using spatial regression to help account for the spatial structure of the dataset.

Moran's *I* test for regression residuals was assumed to be normally distributed under the null hypothesis of no spatial dependence, given by

$$I = \frac{n}{S_o}\frac{\boldsymbol{x}'\mathbf{W}\boldsymbol{x}}{\boldsymbol{x}'\boldsymbol{x}} \qquad [1]$$

where $\boldsymbol{x}$ is an $n \times 1$ vector of observations as deviations from the mean, $\mathbf{W}$ is an $n \times n$ spatial weights matrix, and S_o is the sum of elements of $\mathbf{W}$. This test statistic has previously been interpreted as a correlation coefficient (Anselin 1988), with a large positive Moran's *I* value indicating neighbors having high values, and a negative Moran's *I* indicating that high and low value observations occur as neighbors. Palmer amaranth density and cotton yields were used as the variable of interest in Moran's *I* to determine if spatial autocorrelation existed in each experimental field. Spatially weighted matrices were created using queen contiguity with minimum distances of 1.42 and 3 m to ensure each observation has at least one neighbor.

It was suspected that several field variables were correlated with site-specific cotton yield, including Palmer amaranth density, soil type, and elevation. Since elevation and slope were likely responsible for some Palmer amaranth seed dispersal and yield variability, a relative elevation variable was created for each data point to help account for spatial structure. Topographic modeling techniques have been incorporated into statistical models in the form of digital elevation models and hydrologic models, and have been used to account for the noise component associated with spatial datasets (Griffin et al. 2006).

The fields in this study were furrow-irrigated with slopes at some locations greater than 5%, and seed dispersal was expected to be correlated to elevation and water flow. Although spatial regression techniques have been implemented in other areas of research (Anselin 2001; Goodchild et al. 2000), the application of spatial models in agriculture has been less extensive, with fewer models for addressing large-scale yield monitor datasets (Anselin et al. 2004). Exploratory spatial analysis of these data indicated that spatial structure existed in the dataset, and as a result, spatial regression modeling techniques were investigated. To further validate the use of spatial regression, a spatial specification search was carried out for 2007, 2008, and 2009 lint yields. Standard aspatial model with ordinary least squares (OLS) estimation and spatial autoregressive error (SERROR) model with general moments (GM) estimation were used to carry out aspatial and spatial specification, respectively. The models were estimated in R 2.13.1 (R Foundation for Statistical Computing, Vienna, Austria, www.R-project.org) using the *rgdal* and *spdep* packages. The Akaike information criterion (AIC) was used to determine which statistical model was more appropriate (Anselin 2001).

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press

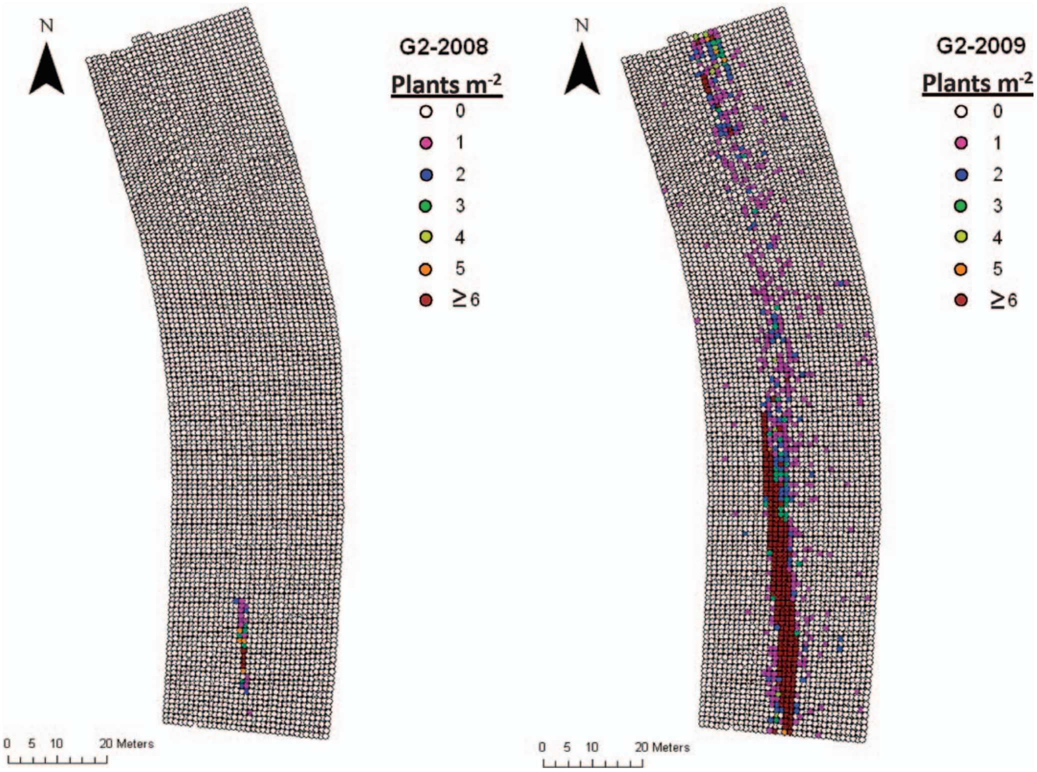

Figure 1. Glyphosate-resistant Palmer amaranth density maps from 2008 (first growing season after introduction) and 2009 (second growing season) for field G2 (0.53 ha) at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.

The following model was used to determine the effects on cotton lint yields:

$$\begin{aligned} Y_i = \text{intercept} &+ PA_{count} + PA^2_{count} \\ &+ W_iPA_{count} + RE + RExPA_{count} \\ &+ LE + CAB + LExPA_{count} \\ &+ CABxPA_{count} + LExW_iPA_{count} \\ &+ CABxW_iPA_{count} \end{aligned} \qquad [2]$$

where Y_i is cotton lint yield in kg ha^{-1} at location i, PA_{count} is the density of Palmer amaranth, W_iPA_{count} is the average density of the ith weighted matrix, RE is the relative elevation, LE is an indicator variable for the presence of a Leaf silt loam soil, CAB is an indicator variable for the presence of a Captina silt loam soil, and the product terms represent the interaction between the indicated factors. This model generated three different equations (one for each soil type). Two soil types were accounted for in the model, whereas the third was represented by the intercept.

Results and Discussion

Palmer Amaranth Density. Palmer amaranth densities for 2008 and 2009 in fields G2, G4, G5, and G6 are presented in Figures 1 to 4. In October 2008, only one growing season after introduction, Palmer amaranth had moved downslope as far as 118 m in field G6 (Figure 4). The few plants that established 118 m downslope quickly led to the formation of a distinct, rapidly enlarging Palmer amaranth patch in 2009 (Figure 4). Tillage and rebedding were not responsible for seed movement because these practices were carried out prior to the introduction of seeds in February 2008. Movement to this distance is likely a result of significant rainfall events in the spring of 2008 (Table 1). Although Palmer amaranth movement in fields G2, G4, and G5 occurred for distances less than 16 m in 2008 (Figures 1 to 3), patch expansion reached the borders of all fields in 2009, infesting 14, 31, 24, and 12% of fields G2, G4, G5, and G6, respectively (Table 2).

These figures indicate that the majority of Palmer amaranth movement occurred along the length of the beds rather than across the beds. Palmer amaranth movement across the beds was up to 6 m from the source of introduction in field G6 (Figure 4). A decrease in lateral seed movement was somewhat expected due to the presence of beds for furrow irrigation and also because the general direction of equipment was in the direction of the

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press

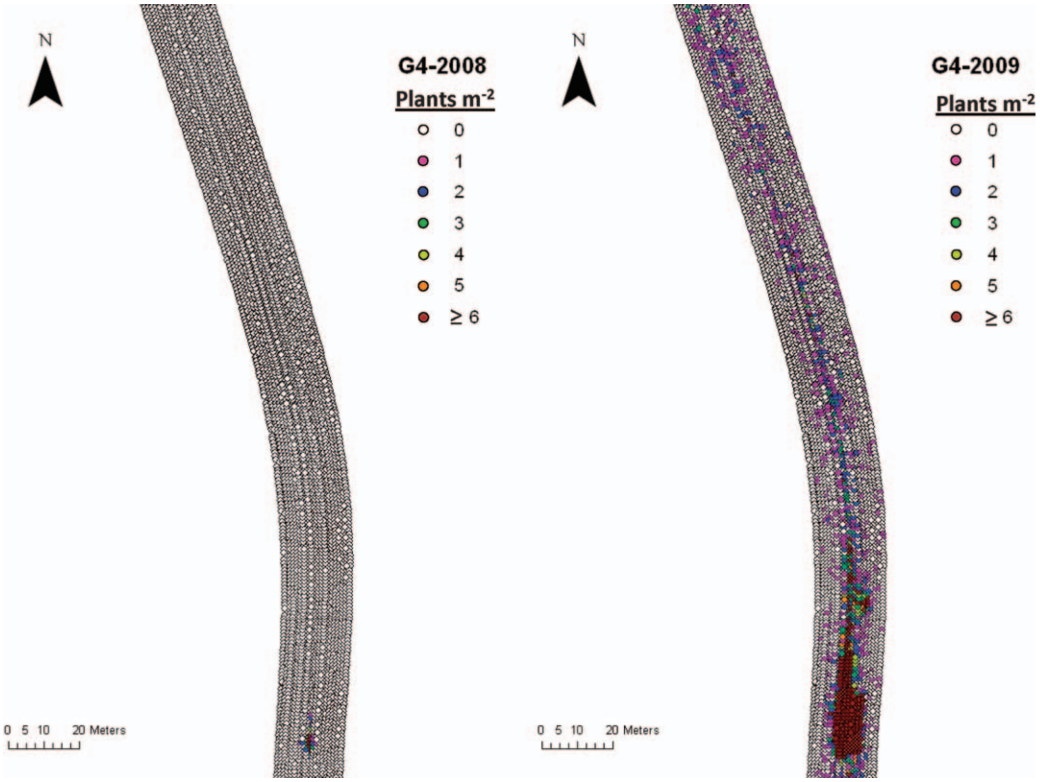

Figure 2. Glyphosate-resistant Palmer amaranth density maps from 2008 (first growing season after introduction) and 2009 (second growing season) for field G4 (0.57 ha) at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.

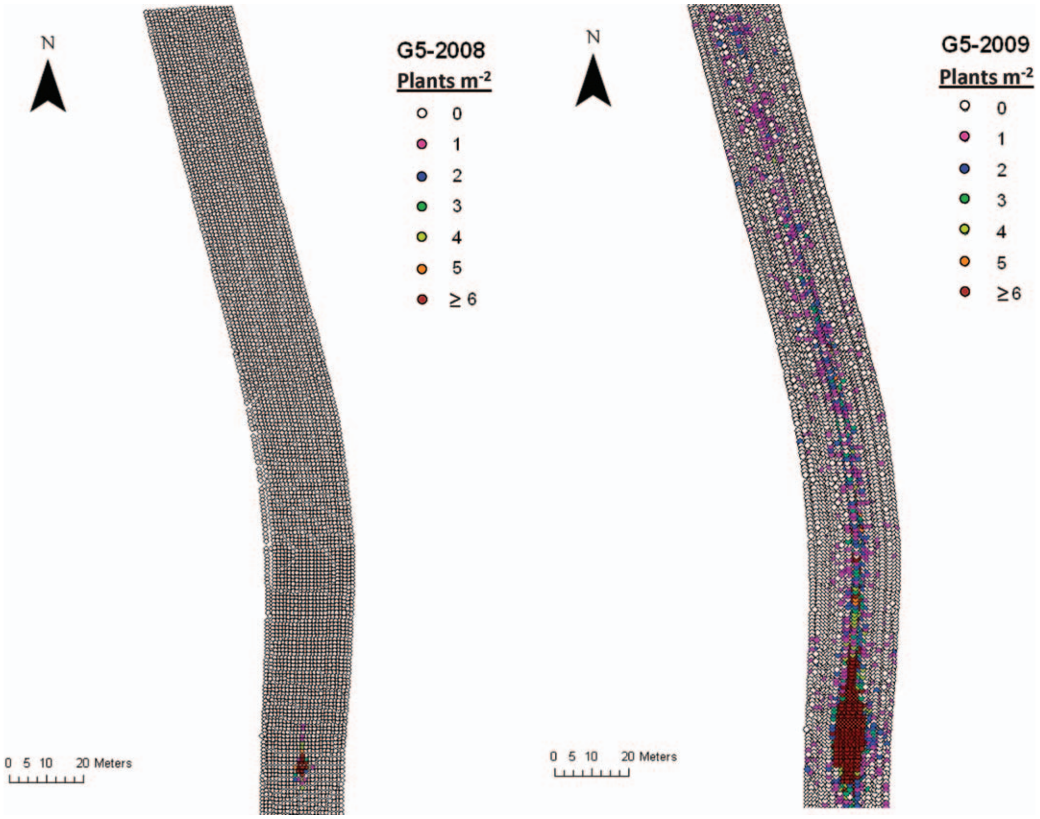

Figure 3. Glyphosate-resistant Palmer amaranth density maps from 2008 (first growing season after introduction) and 2009 (second growing season) for field G5 (0.57 ha) at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press

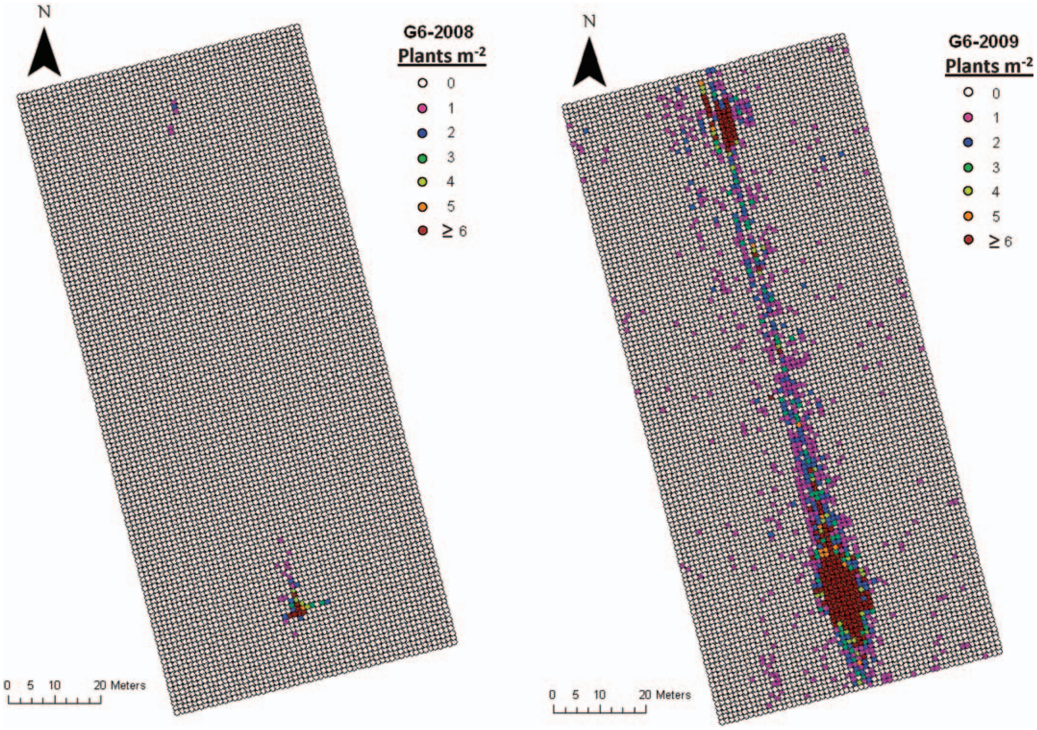

Figure 4. Glyphosate-resistant Palmer amaranth density maps from 2008 (first growing season after introduction) and 2009 (second growing season) for field G6 (0.77 ha) at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.

furrows. Palmer amaranth patch expansion had increased to ≥ 95% of the total area of all fields in 2010, causing total crop failure. The fact that crop failure occurred only 3 yr after the introduction of 20,000 seed in a 1 m^2, simulating a single GR female Palmer amaranth, is a major concern for producers. It is extremely important to monitor fields for suspected GR Palmer amaranth to ensure methods of control can be implemented in a timely fashion, perhaps with the adoption of a zero-tolerance threshold. The critical period for removing plants is relatively short after pollination has occurred, as evident from the studies with closely related species, waterhemp [*Amaranthus tuberculatus* (Moq) Sauer.], where over 75% of seeds germinated only 12 d after pollination (Bell and Tranel 2010).

Table 2. Percentage of total cells (1-m^2) infested by glyphosate-resistant Palmer amaranth in fields G2, G4, G5, and G6 in 2008, 2009, and 2010, at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.[a]

	Infestation		
Field	2008	2009	2010
		%	
G2	0.58	14	> 95
G4	0.56	31	> 95
G5	0.60	24	> 95
G6	0.51	12	> 95

[a] Percentage of infestation calculated by dividing the number of 1-m^2 grid cells containing Palmer amaranth by the total number of cells for that field.

Cotton Lint Yield Maps. Cotton lint yields varied each year as a result of environmental conditions as well as increasing Palmer amaranth densities (Figures 5 to 8). General descriptive statistics for lint yields are given in Table 3. In general, lint yields were the lowest in 2007, likely because of the limited rainfall during the growing season (Table 1). As Palmer amaranth density and interference with cotton increased from 2008 to 2009, so did the variability in cotton lint yield (Tables 2 and 3). Lint yield maps created in ArcGIS helped to visually display the localized effect of increasing Palmer amaranth densities from 2007 to 2009. However, across all fields, crop yields were not useful indicators to assess the long-term effects of early, low-density weed infestations. For instance, the minimum and maximum yields were similar for all years, largely due to the natural effects of environmental variability within these fields (Table 3); albeit, a visual comparison of the 2009 G6 Palmer amaranth density map (Figure 4) and the lint yield map (Figure 8) indicate yield

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press

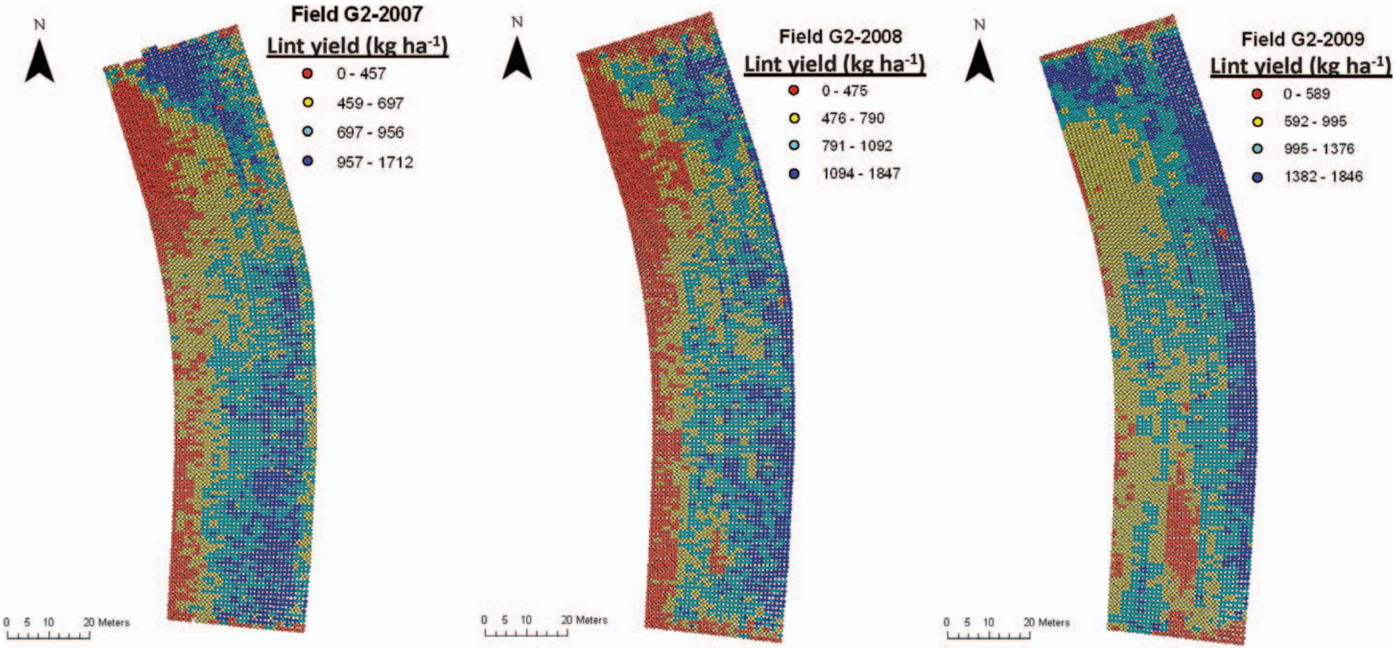

Figure 5. Cotton lint yield maps from 2007 to 2009 for field G2 (0.53 ha) at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.

reduction patterns similar in structure to Palmer amaranth density.

Application of ESDA. Palmer amaranth density and continuous cotton lint yield were used as the variable of interest in Moran's *I* test to characterize the spatial autocorrelation across all fields. Significant values of spatial autocorrelation (Moran's *I* test) rejects the null hypothesis that the processes promoting the observed pattern of values is a random chance. In the present study, significant spatial autocorrelation existed for cotton lint yields in all years and for Palmer amaranth density in 2008 and 2009 (Table 4), indicating that crop yield or Palmer amaranth density observed at a particular site within a field was associated with the

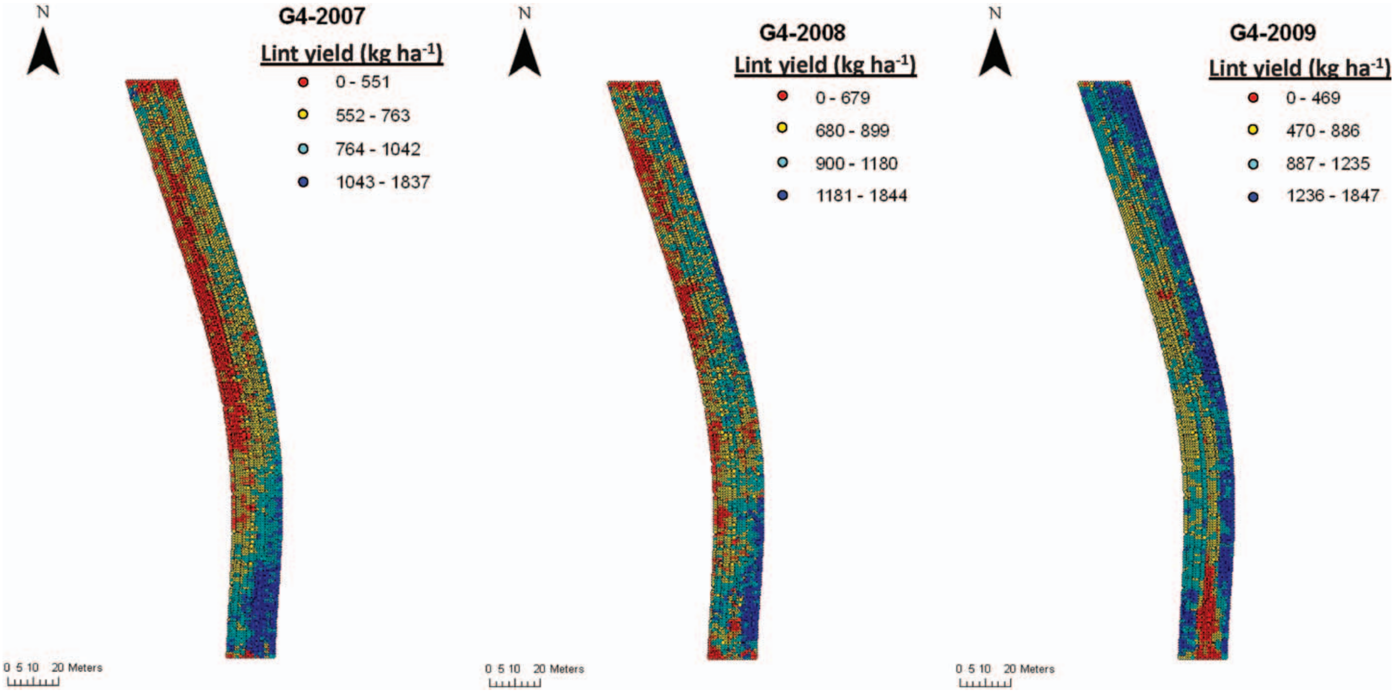

Figure 6. Cotton lint yield maps from 2007 to 2009 for field G4 (0.57 ha) at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press

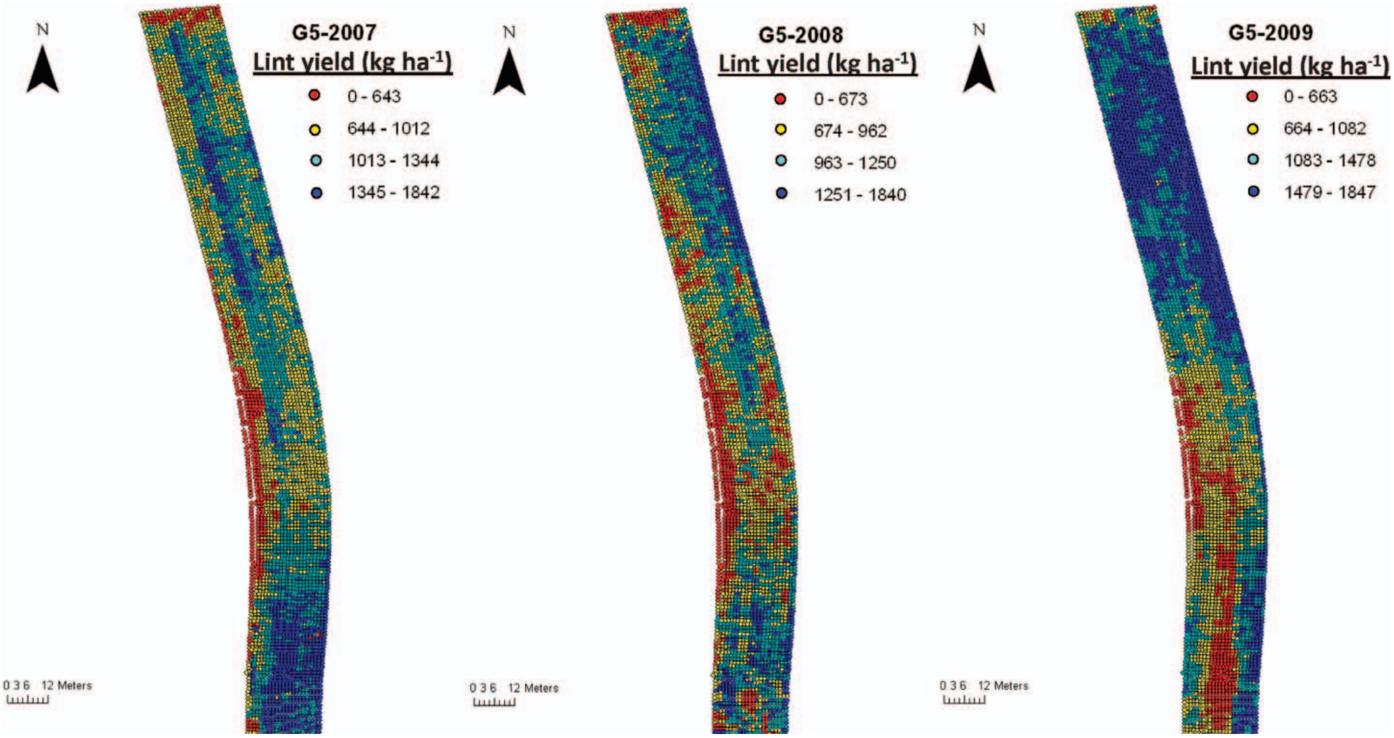

Figure 7. Cotton lint yield maps from 2007 to 2009 for field G5 (0.57 ha) at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.

variables assessed. Results from LISA also indicated significant local clustering (data not shown), suggesting that spatial modeling techniques should be used to account for spatial variability. Welk (2004) reported that distribution patterns of an invasive species at an invasion front are often spatially autocorrelated because of the dispersal characteristics.

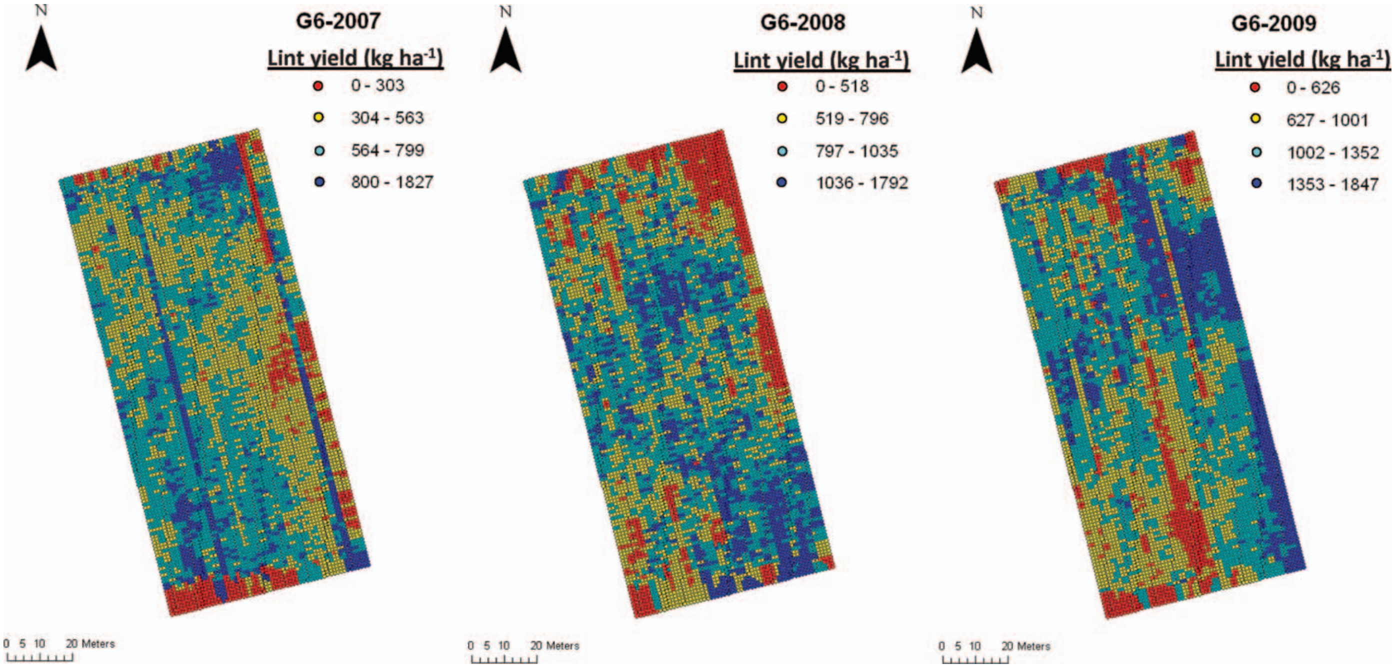

Figure 8. Cotton lint yield maps from 2007 to 2009 for field G6 (0.77 ha) at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press

Table 3. Descriptive statistics for cotton lint yield in fields G2, G4, G5, and G6, in 2007, 2008 (first year after introduction), and 2009 (second year after introduction) at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.[a]

Field	Year	Mean	SE	Min	Max
		kg ha^{-1}			
G2	2007	673	285	6	1,712
	2008	735	346	0	1,848
	2009	1,073	370	0	1,846
G4	2007	706	235	0	1,837
	2008	872	236	0	1,844
	2009	970	349	0	1,847
G5	2007	1,057	325	74	1,841
	2008	972	295	0	1,839
	2009	1,231	437	0	1,847
G6	2007	578	213	0	1,827
	2008	813	254	0	1,792
	2009	1,053	347	0	1,847

[a] Abbreviations: Min, minimum lint yield; Max, maximum lint yield; SE, standard error of mean.

Empirical Analysis. Estimates for cotton lint yields in 2007, 2008, and 2009 were generated from Equation 2 using a cumulative dataset from fields G2, G4, G5, and G6. As Palmer amaranth density increases, cotton yield is expected to decrease nonlinearly; hence, the squared term was included in Equation 2. The gaps between these fields were taken into account when building the cumulative dataset by using XY coordinates. The soil data were expected to account for the field-to-field differences. Our focus was on the model comparison between standard aspatial models estimated by OLS and the SERROR model estimated using GM.

Results from 2007 estimates are shown in Table 5. Since no Palmer amaranth was present in 2007, a reduced version of the model, including relative elevation and soil type, was used to demonstrate the inherent variability in yield associated with those parameters. The spatial autoregressive parameter lambda was 0.93, indicating that spatial dependence inherently exists and that a spatial model is a better alternative than a traditional model. Autoregressive models taking into account spatial autocorrelation were found to be more appropriate than OLS regression models in other ecological studies also (Dormann 2006; Lichstein et al. 2002). Higher elevations yielded more in 2007, likely a result of the direct proximity to the source of furrow irrigation.

Table 4. Characterization of the spatial autocorrelation across all fields in 2008 and 2009 at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR, using Palmer amaranth density and continous cotton lint yield as the variable of interest in Moran's *I* test.[a,b]

	W_1		W_2	
Year	Density	Lint yield	Density	Lint yield
2008	0.48	0.76	0.31	0.66
2009	0.72	0.82	0.62	0.74

[a] W_1 represents the autocorrelation value for a distance of 1.42 m; W_2 represents the autocorrelation at a distance of 3 m.
[b] All values were significant, with $P < 0.0001$.

Table 5. Coefficient estimates and diagnostic statistics for cotton lint yield in 2007 at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.[a]

	OLS		SERROR	
Variables	Estimate	SE	Estimate	SE
	kg ha^{-1}			
(Intercept)	539.1^{b}	4.7	676.3^{b}	11.6
RE	-6.4^{b}	2.1	20.6^{b}	6.8
LE	98.1^{b}	8.0	16.1	21.3
CAB	268.6^{b}	5.4	82.4^{b}	11.1
Lambda			0.93	
AIC	319,889		283,182	

[a] Abbreviations: OLS; aspatial model with ordinary least squares estimation; SERROR, spatial autoregressive error model; SE, the standard error of the estimate; RE, relative elevation; LE, Leaf silt loam soil; CAB, Captina silt loam soil; AIC, Akaike information criterion.
[b] Estimate is greater than two times the SE in magnitude.

Overall, mean cotton lint yields were numerically greater in 2008 than in 2007 (Table 3), regardless of the introduction of GR Palmer amaranth. This is not surprising, since only 0.56% of these fields were infested with Palmer amaranth in 2008 (Table 2). The same scenario often occurs in a producer's field during the early phase of resistance evolution, when small densities of resistant weeds show no yield penalty over large field areas. The coefficients for the model that predicted the 2008 yield estimations are shown in Table 6. The lower AIC value indicates that the spatial model was a better fit for estimation compared to a traditional model. The majority of Palmer amaranth remained in the "high" end of the field in 2008 (Figures 1 to 4), with spatial movement limited to 16 m or less in fields G2, G4, and G5.

After less than 2 yr from introduction, the Palmer amaranth population had expanded to the borders of all fields, infesting over 20% of the total area (Table 2). GR Palmer amaranth was more widespread in 2009, as can be seen from the Palmer amaranth density maps (Figures 1 to 4). Infestation at these levels can be a first indication to producers that they have resistant weeds. The estimates for

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press

Table 6. Coefficient estimates and diagnostic statistics for cotton lint yield in 2008 at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.[a,b]

	OLS		SERROR	
Variables	Estimate	SE	Estimate	SE
	kg ha^{-1}			
(Intercept)	750.8[b]	4.0	791.0[b]	11.2
PA_{count}	−29.9	33.2	32.1	18.5
$PA_{count}{}^2$	2.0	6.0	0.0	3.0
W_1PA_{count}	−80.8[b]	36.5	−42.5	35.7
RE	5.1[b]	2.0	5.2	6.3
RE × PA_{count}	−77.3	88.7	−36.7	47.6
LE	76.5[b]	4.1	71.4[b]	13.1
CAB	106.3[b]	4.6	53.3[b]	10.4
LE × PA_{count}	−49.1	99.6	−38.0	52.8
CAB × PA_{count}	46.1	100.2	−15.3	54.0
LE × W_1PA_{count}	−4.8	39.5	2.7	38.4
CAB × W_1PA_{count}	3.0	7.4	5.7	4.2
Lambda			0.90	
AIC	317,620		287,506	

[a] Abbreviations: OLS; aspatial model with ordinary least squares estimation; SERROR, spatial autoregressive error model; SE, standard error of the estimate; PA_{count}, Palmer amaranth count; $PA_{count}{}^2$, Palmer amaranth count squared; W_1PA_{count}, spatially weighted average of Palmer amaranth counts; RE, relative elevation; LE, Leaf silt loam soil; CAB, Captina silt loam soil; AIC, Akaike information criterion.

[b] Estimate is greater than two times the SE in magnitude.

Table 7. Coefficient estimates and diagnostic statistics for cotton lint yield in 2009 at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.[a]

	OLS		SERROR	
Variables	Estimate	SE	Estimate	SE
	kg ha^{-1}			
(Intercept)	1005.8[b]	4.8	997.6[b]	13.2
PA_{count}	−105.8[b]	8.0	−16.6[b]	5.3
$PA_{count}{}^2$	2.3	1.3	1.8[b]	0.7
W_1PA_{count}	−94.3[b]	7.8	−60.8[b]	7.6
RE	−101.8[b]	2.4	−88.0[b]	7.5
RE × PA_{count}	12.4[b]	5.5	−2.1	3.9
LE	186.7[b]	5.1	160.6[b]	15.8
CAB	116.2[b]	5.6	93.5[b]	12.0
LE × PA_{count}	56.6[b]	7.6	−1.1	4.3
CAB × PA_{count}	5.0	6.2	−2.6	4.8
LE × W_1PA_{count}	−74.8[b]	7.8	−12.3	9.5
CAB × W_1PA_{count}	7.5[b]	1.5	−3.3[b]	1.2
Lambda			0.92	
AIC	323,382		293,141	

[a] Abbreviations: OLS; aspatial model with ordinary least squares estimation; SERROR, spatial autoregressive error model; SE, the standard error of the estimate; PA_{count}, Palmer amaranth count; $PA_{count}{}^2$, Palmer amaranth count squared; W_1PA_{count}, spatially weighted average of Palmer amaranth counts; RE, relative elevation; LE, Leaf silt loam soil; CAB, Captina silt loam soil; AIC, Akaike information criterion.

[b] Estimate is greater than two times the SE in magnitude.

2009 cotton lint yield are shown in Table 7. Yields were significantly impacted by several parameters in 2009, including Palmer amaranth density, weighted density, relative elevation, soil type, and the interaction of weighted Palmer amaranth density and the Captina silt loam soil. The SERROR was a better fit for estimation, as indicated by the lower AIC value (287,506). The positive lambda indicates that inherent spatial variability existed in these data. Relative elevation was significant, with the higher elevations yielding less than lower elevations. This effect is illustrated in Figures 5 to 8, where the lowest-yielding areas of each field are on the higher elevation end (south end) of the field. On average, cotton lint yields were reduced at a level of 17 kg ha^{-1} for each Palmer amaranth. As expected, the weighted average of Palmer amaranth density for a given location was also significant in reducing cotton lint yields. This parameter might be more important in understanding the relationship between Palmer amaranth and yield, because it takes into account the surrounding Palmer amaranth density for a given location in the field. Several factors play a role in determining crop yield loss per Palmer amaranth plant, some of which were not accounted for in the analysis. Examples include the time of Palmer amaranth emergence and duration of weed–crop competition. The intraspecific interference of Palmer amaranth will also have an effect on the ability of Palmer amaranth to reduce crop yields; i.e., a single Palmer amaranth plant in the right environment can be as competitive as or more dominant than a small group of Palmer amaranth plants growing under nonideal conditions in the same given area.

Palmer Amaranth and Yield. A reduced-input model (Equation 2) was created to demonstrate the effect of Palmer amaranth density on cotton lint yields for a given soil type. The SERROR model was chosen based on AIC, and GM estimation was used for determining the yield penalty or gains. The estimates were used to build Figure 9, which represents the relationship among all Palmer amaranth present in a given area of the field, including the spatially weighted average of neighboring Palmer amaranth. This model represents a quadratic relationship for increasing Palmer amaranth densities and decreasing cotton lint yields. Cotton in the Leaf silt loam soil yielded the highest in the absence of any Palmer amaranth, followed by the Captina silt loam soil. Cotton in the Pickwick silt loam soil, which was far less abundant and

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press

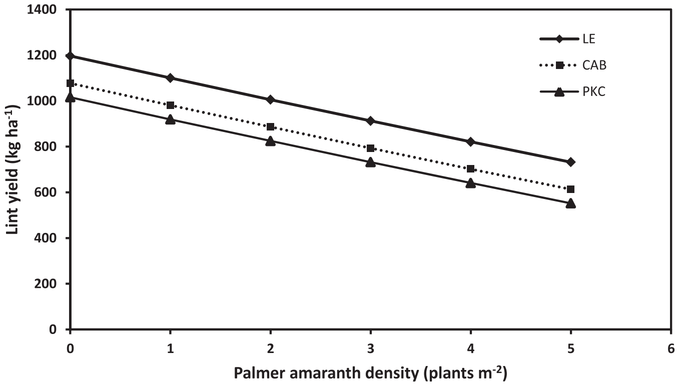

Figure 9. Cotton lint yields for a Leaf silt loam (LE), Captina silt loam (CAB), and a Pickwick silt loam (PKC) soil, as affected by cumulative Palmer amaranth densities across fields G2, G4, G5, and G6 in 2009 at the University of Arkansas–Agriculture Research and Extension Center, Fayetteville, AR.

located in the south end of the fields, yielded the least when no Palmer amaranth was present. Regardless of soil type, increasing Palmer amaranth densities significantly reduced lint yields.

Results from this research highlight the importance of vigilance in managing GR Palmer amaranth. In only 2 yr after introduction, GR Palmer amaranth had colonized each field, spreading from field edge to field edge. Although yields were not affected as a direct result of Palmer amaranth the first year after introduction, the implications of resistance evolution going "unnoticed" in the first year can have a devastating impact in the subsequent years. The amount of seed produced by GR Palmer amaranth allows it to rapidly spread throughout a field or entire farm. By the third cropping season after introduction (Year 2010), complete crop failure had occurred. The competition from high densities of Palmer amaranth resulted in little to no cotton at harvest. Moreover, the high densities in 2010 made harvest impossible due to potential equipment failure.

GR Palmer amaranth possibly spread throughout each field primarily via furrow irrigation, tillage, and harvest equipment, as well as by rainfall after seed maturity. The relatively lower levels of seed movement perpendicular to the bedded rows may have resulted from wind, insects, rodents, or other animals. Seed movement perpendicular to the rows was noted the first year after introduction, prior to the use of tillage or harvest equipment. Seed dispersal was not limited to the confines of field borders in this study, as GR Palmer amaranth were also found outside of each field in 2010. In a production situation, seed dispersal becomes more critical, because there is potential for spreading resistance over thousands of hectares within and across farms (Bagavathiannan et al. 2013a).

The fact that yields were not significantly affected by Palmer amaranth densities in 2008 even though the population quickly expanded and increased the subsequent year leads us to conclude that the economic threshold for Palmer amaranth is in reality a zero-tolerance threshold. Viable seed production and entry into the soil seedbank is critical for rapid buildup of any newly formed resistant population, including herbicide-resistant species other than Palmer amaranth. No Palmer amaranth should be allowed to reach reproductive maturity, meaning that multiple means of control will be needed over an extended growing season due to the season-long emergence of Palmer amaranth (Jha and Norsworthy 2009; Norsworthy et al. 2012). In this research, it took only 20,000 seed initially introduced into 1 m^2 to effectively colonize 0.53- to 0.77-ha fields in less than 2 yr, which is far fewer than the number of seed produced by most Palmer amaranth females. Thus, the spatial approach we implemented in this study was extremely valuable in understanding the pattern of within-field dispersal of Palmer amaranth and demonstrating that a single escape is way too many to allow for this species, justifying the need for a zero-tolerance approach in managing this weed.

Literature Cited

Anselin L (1988) Spatial Econometrics: Methods and Models. Dordrecht, Netherlands: Kluwer Academic. 284 p

Anselin L (1999) Spatial Data Analysis with SpaceStat and ArcView Workbook, 3rd Ed. http://www.terraseer.com/products/spacestat/docs/workbook.pdf. Accessed June 27, 2013

Anselin L (2001) Rao's score test in spatial econometrics. J Stat Plann Inference 97:113–139

Anselin L (2003) GioDa 0.9 User's Guide. Urbana-Champaign, IL: Spatial Analysis Laboratory, University of Illinois. http://www.unc.edu/~emch/gisph/geoda093.pdf. Accessed September 19, 2013

Anselin L, Bondiovanni R, Lowenberg-DeBoer J (2004) A spatial econometric approach to the economics of site-specific nitrogen management in corn production. Am J Agric Econ 86:675–687

Bagavathiannan MV, Norsworthy JK (2012) Late-season seed production in arable weed communities: management implications. Weed Sci 60:325–334

Bagavathiannan MV, Norsworthy JK, Scott RC, Barber TL (2013a) The Spread of Herbicide-Resistant Weeds: What Should Growers Know? University of Arkansas, Agriculture and Natural Resources, FSA 2171-PD-6-13N

Bagavathiannan MV, Walsh MJ, Norsworthy JK, Powles SB (2013b) Palmer amaranth seed collection potential in soybean at harvest. Weed Sci Soc Amer Abst Paper 88. 6 p [Abstract]

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press

Beckie HJ (2006) Herbicide resistant weeds: management tactics and practices. Weed Technol 20:793–814

Beckie HJ, Hall LM, Schuba B (2005) Patch management of herbicide-resistant wild oat (*Avena fatua*). Weed Technol 19:697–705

Bell MS, Tranel PJ (2010) Time requirement from pollination to seed maturity in waterhemp (*Amaranthus tuberculatus*). Weed Sci 58:167–173

Bryson CT, DeFelice MS (2009) Weeds of the South. Athens, GA: University of Georgia Press. 34 p

Burton MG, Mortensen DA, Marx DB (2005) Environmental characteristics affecting *Helianthus annuus* distribution in a maize production system. Agric Biosyst Environ 111:30–40

Colbach N, Forcella F, Johnson GA (2000) Spatial and temporal stability of weed populations over five years. Weed Sci 48:366–377

Dieleman JA, Mortensen DA (1999) Characterizing the spatial pattern of *Abutilon theoprasti* seedling patches. Weed Res 39:455–467

Dormann CF (2007) Effects of incorporating spatial autocorrelation into the analysis of species distribution data. Global Ecol Biogeogr 16:129–138

Goodchild MF, Anselin L, Appelbaum R, Harthorn B (2000) Toward spatially integrated social science. Int Reg Sci Rev 23:139–159

Griffin TW, Florax RJ, Lowenber-DeBoer GM (2006) Field-scale experimental designs and spatial econometric methods for precision farming: Strip-trial designs for rice production decision making *in* Southern Agricultural Economics Association Annual Meeting, Orlando, Florida, February 5–8, 2006. http://ageconsearch.umn.edu/bitstream/35367/1/sp06gr01.pdf. Accessed September 30, 2013

Heap IM (2013) International Survey of Herbicide Resistant Weeds. http://www.weedscience.com. Accessed June 26, 2013

Heijting S, Van der Werf W, Kropff MJ (2008) Seed dispersal by forage harvester and rigid-tine cultivator in maize. Weed Res 49:153–163

James C (2012) Global Status of Commercialized Biotech/GM Crops: 2012. ISAAA Briefs No. 44. http://www.isaaa.org/resources/publications/pocketk/16/. Accessed January 2, 2014

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644–651

Jones RE, Medd RW (2000) Economic thresholds and the case for longer term approaches to population management of weeds. Weed Technol 14:337–350

Kelley AD, Bruns VF (1975) Dissemination of weed seeds by irrigation water. Weed Sci 23:486–493

Lichstein JW, Simons TR, Shriner SA, Franzreb KE (2002) Spatial autocorrelation and autoregressive models in ecology. Ecol Monogr 72:445–463

Li RH, Qiang S (2009) Composition of floating weed species in lowland rice fields in China and the effects of irrigation frequency and previous crops. Weed Res 49:417–427

Marshall EJP, Brain P (1999) The horizontal movement of seeds in arable soil by different soil cultivation methods. J Appl Ecol 36:443–454

Norris RF (1999) Ecological implications of using thresholds for weed management. Pages 31–58 *in* Buhler DD, ed. Expanding the Context of Weed Management. New York: Haworth

Norsworthy JK, Smith KL, Steckel LE, Koger CH (2009) Weed seed contamination of cotton gin trash. Weed Technol 23:574–580

Norsworthy JK, Ward S, Shaw D, Llewellyn R, Nichols R, Webster TM, Bradley K, Frisvold G, Powles S, Burgos N, Witt W, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60:31–62

Rejmánek M, Pitcairn MJ (2002) When is eradication of exotic pest plants a realistic goal? Pages 249–253 *in* Veitch CR, Clout MN, eds. Turning The Tide: The Eradication of Invasive Species. Gland, Switzerland, and Cambridge, UK: IUCN SSC Invasive Species Specialist Group

Rew LJ, Cussans GW (1997) Horizontal movement of seeds following tine and plough cultivation: implications for spatial dynamics of weed infestations. Weed Res 37:247–256

Rew LJ, Froud-Williams RJ, Boatman ND (1996) Dispersal of *Bromus sterilis* and *Anthriscus sylvestris* seed within arable field margins. Agric Ecosyst Environ 59:107–114

Rognli OD, Nilsson NO, Nurminiemi M (2000) Effects of distance and pollen competition on gene flow in the wind-pollinated grass *Festuca pratensis* Huds. Heredity 85:550–560

Smith KL, Doherty RC, Bullington JA, Meier JR, Bagavathiannan MV (2012) Seed production potential of Palmer amaranth in Arkansas. Pages 40–43 *in* Oosterhuis DE, ed. Summaries of Arkansas Cotton Research 2011. Little Rock, AR: University of Arkansas Division of Agriculture AAES Research Series 602

Sosnoskie LM, Webster TM, Kichler JM, MacRae AW, Grey TL, Culpepper AS (2012) Pollen-mediated dispersal of glyphosate-resistance in Palmer amaranth under field conditions. Weed Sci 60:366–373

[SSURGO] Soil Survey Geographic Database (2012) Web Soil Survey. http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm. Accessed September 30, 2013

Stern VM, Smith RF, van den Bosh R, Hagen KS (1959) The integrated control concept. Hilgardia 29:81–99

Swanton CJ, Booth BD (2004) Management of weed seed banks in the context of populations and communities. Weed Technol 18:1496–1502

Swanton CJ, Weaver S, Cowan P, Van Acker R, Deen W, Shreshta A (1999) Weed thresholds: theory and applicability. Pages 9–29 *in* Buhler DD, ed. Expanding the Context of Weed Management. New York: Haworth

Thill DC, Mallory-Smith CA (1997) The nature and consequence of weed spread in cropping systems. Weed Sci 45:337–342

[USDA] U.S. Department of Agriculture (2011) National Agricultural Statistics Service. Agricultural Chemical Use Database. http://usda01.library.cornell.edu/usda/nass/AgriChemUsFC//2010s/2011/AgriChemUsFC-05-25-2011.txt. Accessed September 30, 2013

Van der Pijl L (1972) Principles of Dispersal in Higher Plants. Berlin: Springer. 153 p

Webster TM (2005) Patch expansion of purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*Cyperus esculentus*) with and without polyethylene mulch. Weed Sci. 53:839–845

Webster TM, Cardina J, Woods SJ (2000) Spatial and temporal expansion patterns of *Apocynum cannabinum* patches. Weed Sci 48:728–733

Welk E (2004) Constraints in range predictions of invasive plant species due to non-equilibrium distribution patterns: purple loosestrife (*Lythrum salicaria*) in North America. Ecol Model 179:551–567

Wiles LJ, Olive GW, York AC, Gold HJ, Wilkerson GG (1992) Spatial distribution of broadleaf weeds in North Carolina soybean (*Glycine max*) fields. Weed Sci 40:554–557

Wilson BJ, Brain P (1991) Long-term stability of distribution of *Alopecurus myosuroides* Huds. within cereal fields. Weed Res 31:367–373

Received October 3, 2013, and approved January 8, 2014.

https://doi.org/10.1614/WS-D-13-00145.1 Published online by Cambridge University Press