

## ABSTRACT

STARK, ALLISON M. Selected Aspects of the Ecology of Solanaceous and Amaranthaceous Weed Species. (Under the direction of Dr. David L. Jordan and Dr. Robert J. Richardson.)

Management of Palmer amaranth is difficult due to the spread of glyphosate-resistant germplasm through pollen-mediated gene flow. On four days in 2008 and 15 days in 2009, Palmer amaranth pollen was collected in a compass rose array of traps at heights of 0.75, 1.75, 2.75, and 3.75 m above the ground and distances of 1, 2, 10, 25, and 50 m from a densely planted pollen source containing 37 male Palmer amaranth plants. The BREEZE ISC GIS PRO<sup>®</sup> model did not consistently reflect Palmer amaranth pollen dispersion patterns when compared to pollen collection data for four dates in 2008 and 2009. Empirical data did not consistently correlate with relative humidity, dew point, wind direction, ambient temperature, or wind speed observed in-field or using the North Carolina State Climate Office database. Pollen was found at the extremities of the trap array, suggesting that Palmer amaranth pollen dispersion may extend beyond the area considered in this study. Model parameter calculations revealed that the mean diameter of Palmer amaranth pollen collected from North Carolina is 22.4  $\mu\text{m}$ . Eighty-two percent of pollen captured was within 2 m of the source while 5 to 7% was captured 10 to 50 m from then source. Seventy-five percent of pollen was captured at canopy height (0.75 m) with 10% or less at 1.75, 2.75, or 3.75 m above soil surface. Future research to comprehensively define factors that affect dispersion and viability of Palmer amaranth pollen is recommended.

Solanaceous and Amaranthaceous weed species are a major concern for corn, cotton, and soybean growers in North Carolina. Emergence patterns of apple of Peru, cutleaf groundcherry, eastern blacknightshade, and glyphosate-susceptible and resistant Palmer amaranth biotypes were investigated at two North Carolina locations in corn and cotton (91 cm spacing) and soybean (narrow rows, 35 or 45 cm versus wide rows, 71 or 91 cm spacing). A cropping system by weed species interaction was observed in 2007 and 2008 at both locations for cumulative emergence when compared to both total emergence and total seeds planted. For both these comparisons, the main effect of weeks after planting (WAP) was significant at Kinston in 2008 and maximum emergence was reached at 7 WAP when means were pooled over weed species and cropping system. For cumulative emergence over total seeds planted, a significant weed species by WAP interaction for Kinston in 2007 showed that the emergence of apple of Peru and glyphosate-resistant Palmer amaranth was maximized at 1WAP, while cutleaf groundcherry and eastern blacknightshade was maximized at 4WAP and glyphosate-susceptible Palmer amaranth was maximized at 7WAP. For cumulative over total emergence, a weed species by WAP and cropping system by WAP interactions were found in Goldsboro in 2007, where max emergence of all weed species occurred from 13 to 16 WAP. A significant third order interaction (cropping system\*weed species\* WAP) was observed for cumulative over total emergence in Goldsboro in 2008 and Kinston in 2007. In a second experiment in the greenhouse, ability of these weeds to withstand soybean canopy shading under 25 and 45 cm height was compared. The interaction of weed species by soybean height was significant; weed dry weight was reduced 40 to 81% when planted with the 45 cm tall soybean, whereas dry weight was reduced no more than 14% when planted with 25 cm

tall soybean. Cutleaf groundcherry and eastern blacknightshade biomass were reduced less by soybean than Palmer amaranth biotypes and apple of Peru when grown with 45 cm soybean.

Selected Aspects of the Ecology of Solanaceous  
and Amaranthaceous Weed Species

by  
Allison Marie Stark

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APPROVED BY:

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Jan F. Spears

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Lingjuan Wang

---

David L. Jordan  
Committee Co-Chair

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Robert J. Richardson  
Committee Co-Chair

## BIOGRAPHY

Allison M. Stark grew up in Rocky River, Ohio. She received her undergraduate degree in Biology from The College of Wooster. Her interest in Weed Science was sparked when she read an article about allelopathy in spotted knapweed. Allison pursued this interest by choosing a Weed Science based Independent Study Thesis topic in collaboration with Dr. John Cardina. She went on to work towards a Masters degree in Weed Science under Dr. Michael Burton and subsequently Dr. David Jordan and Dr. Robert Richardson. During her graduate career, Allison has been involved in the Weed Science Society of North Carolina, the Southern Weed Science Society, and the Weed Science Society of America.

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## CHAPTER 1

### Modeling of Palmer amaranth (*Amaranthus palmeri*) Pollen Dispersion

Allison M. Stark, Lingjuan Wang, David L. Jordan, Steve T. Hoyle, Robert J.

Richardson, Janet F. Spears, and Michael G. Burton

#### Abstract

Spread of glyphosate-resistant Palmer amaranth germplasm through pollination makes management challenging. The objective of this study was to determine factors influencing Palmer amaranth pollen dispersal and to ascertain if the BREEZE ISC GIS PRO<sup>®</sup> atmospheric modeling software package accurately predicts Palmer amaranth pollen movement with 50 m of the source. On four days in 2008 and 15 days in 2009, Palmer amaranth pollen was collected in a compass rose array of traps at heights of 0.75, 1.75, 2.75, and 3.75 m above the ground and distances of 1, 2, 10, 25, and 50 m from a densely planted pollen source containing 37 male Palmer amaranth plants. The BREEZE ISC GIS PRO<sup>®</sup> model did not accurately reflect Palmer amaranth pollen dispersion patterns when compared to pollen collection data for four dates in 2008 and 2009. The empirical data also did not consistently correlate with relative humidity, dew point, prevailing wind direction, ambient temperature, or wind speed observed in the field or using the North Carolina State Climate Office database. Pollen was found at the outermost extremities of the trap array (50 m laterally and 4 m above the crop canopy), suggesting that Palmer amaranth pollen dispersion may extend beyond the area considered in this study. Model parameter calculations revealed that Palmer amaranth

pollen collected from North Carolina has a mean diameter of 22.4  $\mu\text{m}$ . Eighty-two percent of pollen captured was within 2 m of the source while 5 to 7% was captured 10 to 50 m from the source. Seventy-five percent of pollen was captured at canopy level (0.75 m above soil surface) with 10% or less at 1.75, 2.75, or 3.75 m above soil surface. Future research focusing on comprehensively defining factors that affect dispersion and viability of Palmer amaranth pollen is recommended.

Nomenclature: Palmer amaranth, *Amaranthus palmeri* (S. Wats); glyphosate

Key Words: Herbicide resistance, pollen dispersal, modeling, weed management

## Introduction

Palmer amaranth is a dioecious, aggressive weed with confirmed glyphosate-resistant biotypes distributed in Alabama (Heap 2010), Arkansas (Norsworthy et al. 2008), Georgia (Culpepper et al. 2006), Mississippi, Missouri, New Mexico (Heap 2010), North Carolina (Culpepper et al. 2008), Tennessee (Steckel et al. 2008). Palmer amaranth biotypes resistant to sulfonylurea, imidazolinone, dinitroaniline, and triazine herbicides have also been recorded (Heap 1997; Gosset et al. 1992; Horak and Peterson 1995). Yield reductions can be caused by as few as two Palmer amaranth plants/m of row in soybean (Klingman and Oliver 1994). Palmer amaranth at a density of 8 plants/m of row can result in 78% and 91% loss in yield for soybean and corn, respectively (Bensch et al. 2003; Massinga et al. 2003). Cotton interference has also been documented and is a major concern among cotton producers (Klingman and Oliver 1994; Massinga et al. 2001). Palmer amaranth is a prolific producer of seeds and grows efficiently at high temperatures (Guo and Al-Khatib, 2003; Hopkins 1999; Horak and Loughlin, 2000; Keeley et al., 1987). Pollen-mediated gene flow (PMGF) in Palmer amaranth has been shown to spread glyphosate-resistance genes as far as 300 m resulting in 20% to 40% resistant offspring (Culpepper et al. 2009; Sosnoskie et al. 2009).

Given the ability of the glyphosate-resistant Palmer amaranth germplasm to spread through pollination (Sosnoskie et al. 2007), there is tremendous concern that resistant germplasm could spread rapidly over large geographical distances. While control methods and phytosanitary measures have been developed to hinder dispersal of resistant Palmer amaranth seeds, investigation of gene flow through long-range pollen dispersal is

a concern that must be addressed in order to adequately control the spread of resistant germplasm through pollen-mediated gene flow (PMGF). In order to make recommendations to hinder PMGF in palmer amaranth, it is important to fully understand the dynamics of pollen dispersal.

Pollen movement can increase the rate of herbicide resistance evolution by spreading resistance alleles within or between populations (Hidayat et al. 2006). Pollen dispersal may transport herbicide resistance genes out of infected areas to susceptible individuals of the same species, or even to hybridize with other species. Species capable of intra-species PMGF in addition to Palmer amaranth include wheat (*Triticum aestivum* L.) (Matus-Cádiz et al. 2004) (300 m), corn (*Zea mays* L.) (<30 m) (Jarosz et al. 2003), kochia (*Kochia scoparia* L.) (29 m) and Italian ryegrass (*Lolium rigidum* Gaudin) (3,000 m) (Stallings et al. 1995; Busi et al. 2008). Inter-species PMGF is also a concern; imidazolinone-resistant domesticated sunflowers (*Helianthus annuus* L.) are able to hybridize with wild sunflower (*Helianthus petiolaris* Nutt.) at a distance of 30 m (Massinga et al. 2003). Pollen-mediated gene flow has also been observed to carry herbicide resistance traits to unintended species in other crop systems, including canola (*Brassica napus* L.) (Brown and Brown 1996; Klein et al. 2006); hare barley (*Hordeum murinum* L. ssp. *leporinum* Arcang.) (Hidayat et al. 2006); and cultivated rice (*Oryza sativa* L.), weedy rice (*Oryza sativa* f. *spontanea* Roshev.), and common wild rice (*Oryza rufipogon* Griff.) (Chen et al. 2004); and wheat (*Triticum* spp. L.) (Gustafson et al. 2005). In addition, PMGF has been documented in turf systems involving creeping bentgrass (*Agrostis stolonifera* L.) at distances up to 21 km from the germplasm source (Watrud et

al. 2004).

Various models have been developed to make species-specific predictions of transgenic pollen movement in wheat (Gustafson et al. 2005; Matus-Cádiz et al. 2004), ryegrass (*Lolium perenne* L.) (Giddings et al. 1997; Giddings 1999), corn (Jarosz et al. 2003; Loos et al. 2003), and meadow fescue (*Festuca pratensis* Huds.) (Nurminiemi et al. 1998). These models are used to predict the range of pollen dispersal for reasons including gene escape associated with transgenic crop cultivars (Loos et al. 2003; Matus-Cádiz et al. 2004). Given that PMGF drives transgenic crop escapes as well as the spread of glyphosate-resistant Palmer amaranth, this study will develop a species-specific modeling approach for Palmer amaranth pollen dispersion.

In a review of pollen modeling methods, Beckie and Hall (2008) state that choosing an appropriate model should be dictated by the ultimate function of the model. Many methods of pollen dispersion modeling are outlined in published literature. Several one-dimensional pollen dispersal models have been based solely on regression methods to describe trends in empirical data (Beckie and Hall 2008; Gustafson et al. 2005; Jarosz et al. 2003). It has been argued that these models are overly simplistic and merely describe a pollen gradient near the source while ignoring environmental conditions that cause large departures from this gradient, causing pollen to be distributed irregularly (Lanner 1965). More complex comprehensive models have been based on particle dispersion equations using situation-specific parameters such as particle emission rate and height, size, and settling velocity; wind direction and speed, turbulence, diffusion, vegetation, and topography (Bateman 1947; Giddings 1999; Nurminiemi et al. 1998; McCartney and

Lacey 1990; Loos et al 2003; Tackenburg 2003). Several software programs have incorporated dispersion equations that let the user tailor the model parameters to suit specific pollen dispersion circumstances. However, these software packages were not used because elements of their design were inappropriate for use with this study. The HUMPOL<sup>1</sup> package is designed to model pollen deposition over long time periods for purposes of paleobotany (Bunting and Middleton 2004). The PAPPUS<sup>2</sup> model calculates the trajectory of single diaspores, such as pollen grains, for pre-determined plant species (Tackenburg 2003). The POLDISP<sup>3</sup> package, a freeware modeling package, is designed to model pollen dispersion based on the genetic makeup and spatial locations of both parental plants (Robledo-Arnuncio et al. 2007). Because Palmer amaranth disperses a very large number of pollen grains over relatively short time periods without a designated second parental plant, development of a more appropriate dispersion model was necessary. Developing an accurate dispersion model tailored to Palmer amaranth will result in a greater understanding of factors influencing pollen movement in this species.

This study will seek to develop a comprehensive (non-regression based), species-specific model of Palmer amaranth pollen dispersal that will incorporate situation-specific parameters to predict pollen distribution. These parameters will be used to mathematically define the model, making it species-specific to Palmer amaranth. Empirical knowledge of factors that influence Palmer amaranth pollen dispersion is limited at this time. Several factors are known about Palmer amaranth pollen dispersal, including that it is an obligate cross-pollinator due to its dioecious nature (Franssen et al. 2001). In order for PMGF to occur, pollen must remain viable in the atmosphere for a

length of time before it reaches a female flower. Like all Amaranthaceous species, Palmer amaranth pollen is tri-nucleate and is difficult to germinate on artificial media, making pollen viability studies problematic (Sosnoskie et al. 2007). It has been shown that Palmer amaranth pollen dehydrogenase activity (which is linked to viability) significantly decreases after 30 min post-dehiscence (Sosnoskie et al. 2007).

The pollen is wind-disseminated, spherical, and polyaperturate (golf-ball like), having an aperture density of 0.042 surface indentations/ $\mu\text{m}^2$  (Franssen et al. 2001). Franssen et al. (2001) measured the mean diameter of Midwestern US Palmer amaranth pollen grains as 19.82  $\mu\text{m}$  using scanning electron microscopy. Palmer amaranth grains collected from Georgia populations have been determined to have a mean diameter of 27  $\mu\text{m}$  and an average terminal settling velocity of 5.0 cm/s, as determined by electronic particle sizer and laboratory settling chamber experiments (Sosnoskie et al. 2009).

Many of the parameters needed to develop a model of Palmer amaranth pollen dispersion were unknown at the outset of this study. In order to accurately construct a model of Palmer amaranth pollen dispersal, several factors must be defined. This study will experimentally determine unknown factors, including daily pollen emission rates, the particle size distribution of the pollen collected in this study, and the total number of pollen grains released/day.

The atmospheric dispersion model used in this study is based on the steady-state Gaussian model of particle dispersion as follows:

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) \left\{ \exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right) \right\} \quad (1)$$

where  $C$  is the particle concentration at a point  $(x, y, z)$  (grains/m<sup>3</sup>),  $Q$  is the particle emission rate (grains/s),  $\sigma_y$  and  $\sigma_z$  are horizontal and vertical particle plume spread parameters (m),  $u$  is the average wind speed at the physical stack height ( $h$ ) (m/s),  $x$  is the distance from the particle source (m),  $y$  is the horizontal distance from the plume centerline (m),  $z$  is the vertical distance from ground level (m), and  $H$  is the effective stack height (m) (Cooper and Alley 1994).  $H$  is defined as

$$H = h + \Delta h \quad (2)$$

where  $h$  is the physical stack height and  $\Delta h$  is the plume rise (Cooper and Alley 1994).

The horizontal and vertical plume spread parameters  $\sigma_y$  and  $\sigma_z$  are defined as

$$\sigma_y = ax^b \quad (3)$$

$$\sigma_z = cx^d + f \quad (4)$$

where  $a$ ,  $b$ ,  $c$ ,  $d$ , and  $f$  represent constants that are dependent on the downwind distance from the particle source ( $x$ ) and the stability class (Cooper and Alley 1994). The stability class assignment is based on surface wind speed, cloud cover, and angle of sunlight (Cooper and Alley 1994). The variable  $y$  is a measure of the crosswind distance from the plume centerline. Using these equations, the theoretical concentration of pollen grains ( $C$ ) at a given point  $(x, y, z)$  can be determined once the values for the parameters  $Q$ ,  $\sigma_y$ ,  $\sigma_z$ ,  $u$ , and  $H$  are known.

BREEZE ISC GIS PRO is an Industrial Source Complex model using the steady-state Gaussian dispersion equation (1) to predict non-reactive particle concentrations under a

variety of circumstances<sup>4</sup>. The software package may be used as either code- or window-driven and enables the user to input information to be incorporated into the model. The user may model an unlimited number of particle sources including point/stack, area, volume, and open pit sources. Emission parameters that may be input into the model include variable emission rates, particle exit velocity, temperature, and multiple particle types. Particle characteristics such as diameter or chemical makeup may be input. The software also allows for an unlimited number of receptors (points where the model will determine the value of C) that may be set in a uniform or non-uniform Cartesian or polar grid or individually placed at user-defined coordinates at any height. The user may also define boundary/fence lines and unlimited buildings or objects affecting particle movement. In addition to source and receptor parameter inputs, BREEZE ISC GIS PRO software package uses a meteorological data file to compute model parameters relating to environmental conditions at the time of particle dispersal. The user may input data from the field including hourly or daily averages for wind direction, speed, variable ambient temperature, date(s) and duration of particle emission, stability class, and rural and urban mixing heights. Once data is input into the meteorological data file, a wind rose showing wind vectors may be viewed.<sup>4</sup>

The BREEZE ISC GIS PRO model is designed to calculate the concentration or particles suspended in the air at a given receptor site as well as user-defined percentile and block average profiles for the period of particle emission. The output consists of several text files, including the code run by the software, a list of model parameters input by the user, the requested particle concentration data, and any warnings generated by

incorrect or missing data. These files are also accompanied by a map of particle concentration data over the area in and around the receptor array.<sup>4</sup>

The objective of this study is to determine unknown model parameters in order to develop a species-specific computer model of Palmer amaranth pollen dispersion using the BREEZE ISC GIS PRO software package. The model will be validated by comparing model predictions of pollen concentrations with empirical values collected from field experiments. Using experimentally measured and previously known parameters to construct the BREEZE ISC GIS PRO model will yield a species-specific model of Palmer amaranth pollen dispersion that may be used to predict pollen movement under various atmospheric conditions. If it is found to be accurate, the model can be used to make predictions about the maximum distance that Palmer amaranth pollen can travel before settling out of the air. Combined with more detailed knowledge of pollen viability, this information will help farmers more effectively prevent PMGF from spreading glyphosate resistance genes into extant Palmer amaranth populations in their fields.

## Materials and Methods

Definition of model parameters. Palmer amaranth pollen emission rate was determined experimentally in several phases. In the first phase of the study, a greenhouse study was conducted in fall of 2007 to determine the timing and rate of Palmer amaranth pollen dehiscence. Previously made observations suggested that pollen emission occurred from early to mid-morning in the field. Sections of male Palmer amaranth inflorescences 2.5 cm in length were selected and cleaned of previously dehisced anthers and pollen the evening before the experiment. Over the course of three days, observations were taken on the timing of anther dehiscence at 15 min intervals for a total of 17 observations. Greenhouse observations taken in the fall of 2007 support field observations on pollen release timing; anthers were presented and dehisced between 8:00 and 10:30 am on all days. The data were pooled to determine the number of flowers dehiscing/cm inflorescence/d (Figure 1). This data was also pooled to calculate the cumulative percentage of flower dehiscence over time (Figure 2). The average total flowers releasing pollen/cm of inflorescence was also determined (Table 1).

In the second phase of the study, male Palmer amaranth flowers presenting unopened anthers (49 total flowers, 5 anthers/flower) were harvested individually from 10 glyphosate-susceptible Palmer amaranth plants into 1.5 ml tubes. Anthers were allowed to open naturally in ambient environmental conditions in the lab. After all anthers had opened, 1 ml distilled water was added to each tube, which was then mixed thoroughly to distribute pollen grains evenly throughout the solution. Five samples of 5  $\mu$ l of the solution were pipetted onto a hemocytometer to be counted. Each of the 1 nl gridded

regions were counted for a total of nine observations per 5  $\mu\text{l}$  sample. Observations were averaged and multiplied by  $10^4$  to determine the number of pollen grains in the original sample (Table 1). The results of both portions of this study were combined to determine the total number of Palmer amaranth pollen grains emitted from a defined length of inflorescence each day (Table 1). Further calculations that led to the pollen emission rates for each date of pollen collection are described later in this section.

Palmer amaranth pollen size distribution was determined using samples collected in North Carolina from a confirmed glyphosate-susceptible biotype (collected near Clayton) (Whitaker 2009) on three dates in June, 2009 and cleaned of visible debris under a dissection scope. Pollen samples were suspended in 10 ml laboratory grade ethanol and subjected to laser diffraction particle size distribution analysis in triplicate using a Beckman Coulter LS 13 320 electronic particle sizer<sup>5</sup> (Cao, 2009). Figure 1 shows the particle size distribution from 20 to 40 microns, encompassing the range of palmer amaranth pollen grain sizes described by Sosnoskie et al. (2009). Data for particle size distribution were subjected to multiple regression in SigmaPlot v9<sup>6</sup> to determine the pollen diameter mode (Figure 1).

Pollen distribution in the field. Palmer amaranth pollen distribution data were collected at the North Carolina State University Cherry Research Farm located near Goldsboro during 2008 and 2009. The experiment was repeated for a total of four replicates in soybean in 2008 and 15 replicates in cotton in 2009. A minimal 800 m diameter area was maintained free of Palmer amaranth individuals in flower with the exception of those in the pollen source area. The pollen source was a 1 m diameter circle of densely planted

male glyphosate-susceptible Palmer amaranth plants. Initially, the 2008 trap arrangement encompassed a 200 m diameter circular trapping area surrounding the central pollen source. This circle size was determined to be too large for pollen trap management with the amount of available labor and all subsequent trap array areas were reduced to a 100 m diameter circle.

A total of 165 pollen traps were arranged in a compass rose array surrounding the point source at distances of 0 (center of pollen source), 1, 2, 10, 25 and 50 m. Spokes of the compass rose trap array included the four cardinal directions (N, W, S, E) as well as four ordinal directions (NW, SW, SE, NE). Pollen traps were placed at heights of 0.75 (crop canopy height), 1.75, 2.75, and 3.75 m above the soil surface. The central pollen sampling location had an additional trap height of 4.75 m to check for upward convective currents that may carry pollen upwards into laminar air currents (Figure 16). Wind speed, direction, and temperature data records were taken every minute during pollen collection events. In addition to the environmental data taken at the site, additional environmental data were obtained from the North Carolina State Climate Office CRONOS Database<sup>7</sup> for the nearest collection point at the Cherry Research Station in Goldsboro, NC (Table 2).

On each sampling day, settling pollen was collected on mineral oil coated microscope slides affixed to clean plastic petri dish bottoms with tape for the duration of pollen dehiscence (8:00 to 10:30 am). These petri dishes were placed in mounting brackets on telescoping lengths of polyvinyl chloride (PVC) pipe that were raised to the correct collection heights for sampling (0.75, 1.75, 2.75, and 3.75 m) immediately prior to pollen

emission on the sampling day. One telescoping PVC pipe was placed at each of the 40 sampling locations in the pollen trap array. In the center of the pollen source, an additional telescoping PVC pole was erected with an added trap height of 4.75 m to determine if updrafts or convection air currents were carrying pollen above the trap array. Once pollen sampling was completed, telescoping PVC poles were collapsed and clean lids were placed each petri dish. Dishes were kept level and stacked for transport to the laboratory for counting. Preliminary studies in 2007 indicate that the Palmer amaranth pollen samples collected in this study may be stored in ambient indoor conditions for up to one year before counting. No deterioration of pollen grains was observed when comparing stored pollen samples to fresh samples. However, all pollen samples presented in this study were counted within three months of collection. Four randomly selected 3.05 mm<sup>2</sup> viewing areas on the sample slide were chosen and Palmer amaranth pollen grains in those areas were counted. These counts were averaged to determine density of Palmer amaranth pollen (grains/viewing area) at each trap.

For each sampling day, the four pollen count observations taken from all traps located in the center of the pollen source were averaged across counting replicate and summed over trap height to determine the total grains that settled at the pollen source. These summed daily pollen source depositions were divided by the total pollen grains released per day (Table 1) to calculate the percentage of the total pollen grains released that will settle out of the air (Table 3).

The BREEZE ISC GIS PRO model was constructed as a point source with 165 flagpole receptors placed individually to ensure identical placement to the traps previously

described in the field study pollen trap arrangement. Customized modeling parameters were calculated for all pollen collection days in 2008 and 2009 subjected to the model. Time-dependent pollen emission factors (not shown) were calculated for 15 min time periods using data determined in the greenhouse pollen dehiscence study (Figures 1 and 2), the total pollen grains emitted/day (Table 1), and the daily deposition rate (Table 3). Meteorological data collected in the field including wind speed, direction, and ambient air temperature were averaged over 5 min time periods to create a meteorological data set of 24 observations spanning the entire 120 minute long pollen collection event. The BREEZE ISC GIS PRO model was set to calculate the accumulation of pollen grains over one day, divided into 24 one hour-long segments. The interval averaged meteorological data set calculated from the field with 24 five-minute long segments was designed to correspond to the 24 one hour-long segments of time required in the BREEZE ISC GIS PRO model input. In order to represent the 5 minute intervals accurately in the meteorological data entered into the model and avoid skewing the final model outputs, the pollen emission rates for each time period were corrected to make the 120 minutes of pollen accumulation in the field equivalent to the accumulation calculated by the model for the entire 24 hour period.

In addition to the meteorological data described above, data that were input into the model include average temperature (calculated as an average of the 120 observations taken at one minute intervals during pollen collection), stack height (1 m for all dates), pollen emission rate (1 grain/s for all dates), stability class (Cooper and Alley 1986), and mixing heights (1000 m for both rural and urban on all dates). The pollen emission rate

in the model input was set at 1 grain/s to accurately calculate the Gaussian model parameter Q (1), which is calculated in the BREEZE ISC GIS PRO model as a product of the pollen emission rate in the model input and the emission factor defined for each of the 24 time intervals.

Given that field observation units are in grains/viewing area, model predictions were converted from volumetric measurements (grains/m<sup>3</sup>) to grains/viewing area using the following equation:

$$\text{model prediction} * V_T * \text{viewing area} * \text{time} = \frac{\text{settled grains}}{\text{viewing area}} \quad (5)$$

where model prediction is the predicted concentration of suspended pollen in grains/m<sup>3</sup>, V<sub>T</sub> is the terminal settling velocity of a Palmer amaranth pollen grain falling by its own weight in m/s, the microscope viewing area is 3.05 mm<sup>2</sup> as previously described, and time is the duration of pollen collection in seconds. V<sub>T</sub> is calculated as follows:

$$V_T = \frac{(\rho_p - \rho_{air})gd_p^2}{18\mu_{air}} \quad (6)$$

where ρ<sub>p</sub> is the particle density for Palmer amaranth pollen (approximately 1218 kg/m<sup>3</sup> as determined by Sosnoskie et al. 2009), ρ<sub>air</sub> is the air density, acceleration due to gravity is g, d<sub>p</sub> represents the particle diameter, and the μ<sub>air</sub> is the viscosity of air (Cooper and Alley 1994). Conversion of model prediction units to grains/viewing area using equations 5 and 6 allowed for comparison of model predictions to field observations (measured in grains/viewing area) by a paired Student's T test in Microsoft Excel 2007<sup>9</sup> (Table 3). Equation 5 assumes that model predictions are equivalent to the number of particles settling out of air onto a pollen trap at a given location.

Daily wind rose charts (Figures 4 through 15) showing wind vectors and intensities were created from the meteorological data by the modeling software package. These charts provide a visual representation of the meteorological data. All twelve runs of the model successfully generated cumulative pollen concentration values for all flagpole pollen receptors for the duration of the 120 minute sampling period (data not shown).

Empirical pollen counts and environmental data collected both on site and by CRONOS were subjected to analysis using the Corr procedure in SAS to determine correlations between environmental factors and pollen deposition. Environmental data used in the analysis are shown in Table 2. The analysis was designed to determine effects of pollen trap height (Table 4), distance from pollen source (Table 5), and overall effects correlated with empirical pollen collection data (Table 6). Missing values represent field data that was not collected due to malfunctioning weather device components.

In order to compare empirical distribution of pollen grains relative to distance from the source, pooled data for percent of total Palmer amaranth pollen grains collected were subjected to analysis of variance for each distance class from the source (1, 2, 10, 25, and 50 m) with sampling dates considered replications (Table 7). A similar analysis was performed to compare percentage of the total pollen captured at four levels in the canopy (0.75, 1.75, 2.75, and 3.75 m above the soil surface) (Table 8). Means were separated using Fisher's Protected LSD test at  $p \leq 0.05$ .

## Results and Discussion

Definition of model parameters. Total Palmer amaranth pollen grains emitted from the 37 plants in the pollen source is approximated to be  $4.1 \times 10^9$  grains/d,  $1.1 \times 10^7$  grains/plant, or  $5.9 \times 10^4$  grains/cm of inflorescence (Table 1). Cubic regression on the particle size distribution data indicates that the most common Palmer amaranth pollen diameter was 22.4  $\mu\text{m}$  (Figure 3). Previous research has reported mean Palmer amaranth pollen diameters of 27  $\mu\text{m}$  for Georgia Palmer amaranth samples measured by laser diffraction analysis in Sosnoskie et al. (2009), and 19.82  $\mu\text{m}$  for Midwestern Palmer amaranth pollen as measured via SEM by Franssen et al (2001).

Given the direct mathematical relationship between settling velocity ( $V_T$ ) and the square of the particle diameter ( $d_p$ ) in equation 6, as the particle diameter decreases, so does its settling velocity (Cooper and Alley 1994). Due to the relationship between these two factors, it can be supposed that pollen grains with smaller diameters have lower settling velocities than their larger counterparts, leading to longer time spent suspended in air currents. Small pollen grains that stay aloft longer may be dispersed over greater distances than larger pollen grains that may settle out of the air more quickly. However, pollen characteristics of amaranth species observed by Franssen et al. (2001) found that pollen diameter did not vary significantly between monoecious and dioecious species. This is interesting given the fact that monoecious amaranths are generally self-pollinating while dioecious amaranths are obligately outcrossing pollinators (Franssen et al. 2001). However, Franssen points out that pollen morphology is a conserved characteristic and therefore consistent differences in morphology and size between monoecious and

dioecious amaranth pollen is not observed (Franssen et al. 2001).

Flower dehiscence data show that approximately 80% of Palmer amaranth flowers release pollen between 8:00 and 9:00 am, while roughly 20% of flowers dehisce after 9:00 am (Figures 1 and 2). The wind roses shown in Figures 4 through 15 were compiled from weather data taken in the field in the BREEZE ISC GIS PRO software package. The wind vectors in these figures closely resemble the values shown in Table 2 for in-field prevailing wind direction (N = 0, E = 90, S = 180, and W = 270 degrees). However, in the case of the 8/14/2008 wind rose (Figure 36), wind vectors were not tabulated by the modeling software because wind speeds did not exceed 0 km/h during pollen collection.

BREEZE ISC GIS PRO modeling results suggest that the empirically collected data differed significantly from the model output in 66% of cases (Table 3). T-test results indicate that the BREEZE model predictions were not significantly different from the field observations in 33% of cases (Table 3). However, the overall accuracy of the model is uncertain given the number of pollen traps where zero pollen grains were observed (field data) or predicted (model output), which will be referred to as “empty pollen traps”. Table 3 shows the percentage of empty pollen traps out of the 165 total traps for the field observations and for model predictions. Empty pollen trap percentages range from 80% to 91% in the field datasets and 45% to 100% in the model predictions. Given that field datasets have a high percentage of empty pollen traps, model predictions with a high number of empty traps may lead to T-test results that show no significant difference between the field observations and the model predictions. The lack of significant

difference between testing groups may not indicate that the model predictions are an accurate representation of Palmer amaranth pollen dispersal in the field; it may be a result of the large number of empty pollen traps predicted and observed.

Model parameter adjustments were undertaken to determine if the accuracy of the model predictions could be improved (data not shown). These adjustments included transformations of the meteorological data, emission rates, emission factors, average temperature, field observations, and model predictions. T-test results indicate that efforts to improve model efficacy were not successful (data not shown).

Discrepancies between the model predictions and the field observations may have been due to the fact that the BREEZE ISC GIS PRO software was designed to model the concentration of particles in a given volume of air, whereas the data collected in the field measured the amount of pollen grains that settled out of the air onto the pollen trap surface. The high cost of volumetric sampling devices prompted the use of the pollen settling trap method, which allowed for a large number of traps and sample date replicates. Selection of a sampling method taking volumetric measurements in grains/m<sup>3</sup> (rather than grains/view area) would remove the need for the data conversions that were performed in this study to make the model output and the empirical data units compatible.

Future modeling research should include empirical measurements of the plume rise parameter. The model assumption that plume rise was negligible may have led to inaccurate model output data because of incorrect calculation of the effective stack height (2).

Pollen distribution in the field. All correlations between empirical pollen data split by pollen trap height and environmental factors were not significant with the exception of in-field relative humidity ( $R = -0.359$ ,  $p = 0.007$ ) and in-field temperature ( $R = 0.366$ ,  $p = 0.006$ ) in the case of the pollen trap height at two m above crop canopy (Table 4). Also, all correlations between empirical pollen data split by distance from the pollen source and environmental factors were not significant with the exception of 50 m hourly temperature ( $R = -0.258$ ,  $p = 0.024$ ) and 50 m average temperature ( $R = -0.230$ ,  $p = 0.046$ ) (Table 5). No significant correlations were found to exist when data were pooled over all days, trap heights, and distances from the pollen source (Table 6).

Wind roses for the 12 days used in the BREEZE ISC GIS PRO model are shown in Figures 4 through 15. The spatial arrangement of pollen collection traps in the field is outlined in Figure 16. Spatial arrangement of pollen captured for each day is presented in the appendix (Appendix figures 2-20). Data for actual pollen captured at defined intervals from the source are presented in the appendix (Appendix figures 21-39). Eighty-two percent of pollen captured was within 2 m of the source while 5 to 7% was captured 10 to 50 m from then source (Table 7). Seventy-five percent of pollen was captured at canopy level (0.75 m above soil surface) with 10% or less at 1.75, 2.75, or 3.75 m above soil surface (Table 8).

Palmer amaranth pollen grains were found in samples at the farthest extremities of the trap array (Tables 7 and 8) and at the 4.75 m trap height directly above the pollen source on several collection dates (Appendix figures 2-20). Given the Palmer amaranth pollen dispersal distances of 300 m reported in Sosnoskie et al. (2007), these results are not

surprising. Palmer amaranth pollen dispersal was observed 50 m from the source at a height of 3.75 m on August 14, 2009 (Appendix figure 4), despite the fact that no measurable wind was recorded in the field during the time of pollen collection (Table 2). This instance, combined with the lack of correlation between environmental parameters and pollen collection data, suggests that Palmer amaranth pollen dispersion is influenced by additional factors that were not determined by this experiment. This further supports the conclusion that a convective current consisting of heated air rising near the pollen source should be considered as a factor in future research. The pollen trap located the 4.75 m height directly above the pollen source was designed to detect convective currents carrying pollen grains directly upward out of scope of the pollen trap array. On six out of the 19 pollen collection dates, Palmer amaranth pollen grains were observed in the pollen trap 4 m above crop canopy at the center of the pollen source (Table 8) at concentrations up to 1,429 grains/2.5 cm<sup>2</sup>. Figures 17 through 20 show pooled pollen concentrations by distance from the source at a given pollen trap height. Trends in the data for the 0.75, 1.75, and 2.75 m trap heights show that as distance from the pollen source increases, the amount of pollen observed decreases (Figures 17, 18, 19). However, data trends are inconsistent for the 3.75 m trap height (Figure 20), with increases in the number of pollen grains observed from 25 to 50 m from the source on 5 collection dates. These increases at the uppermost pollen trap height indicate that additional pollen movement may be occurring above 3.75 m.

Pollen grains carried upward in convective currents caused by heat fluxes may move high into the planetary boundary layer, the region of turbulent air near the Earth's surface

(Smith et al. 2008). Once suspended in the upper region of the planetary boundary layer, pollen grains have the potential to be carried for long distances in laminar air currents (Aylor et al. 2006; Smith et al. 2008). The remotely piloted aircraft method developed by Gottwald and Tedders (1985), originally designed for fungal spore collection over tree crops, has been applied to measure pollen densities over maize (Aylor et al. 2006). Remotely piloted aircraft have been used to collect fungal, pollen, and wind borne seed samples at a range of altitudes up to 140 m above horseweed (*Conyza canadensis* L.) (Gottwald and Tedders 1985; Shields et. al 2006; Maldonado-Ramirez et al. 2005). The use of remotely piloted aircraft poses challenges, such as in-flight altitude measurements, but it is theoretically able to collect samples at altitudes up to several thousand meters (Gottwald and Tedders 1985). Sampling atmospheric Palmer amaranth pollen in the planetary boundary layer would provide measurements of the height of rising convective currents, but the measurements may no longer be site-specific due to Palmer amaranth pollen released from other locations.

Palmer amaranth pollen viability studies conducted by Sosnoskie et al. (2007) indicate a significant decrease in enzymatic activity 30 min after pollen dehiscence, indicating a loss of pollen viability. However, there is currently no published method to directly determine the viability of species with tri-nuclear pollen, including Palmer amaranth. Due to the inability of this study to rule out long-distance dispersion of Palmer amaranth pollen grains, it is suggested that future research be done to determine a timeline for Palmer amaranth pollen death under a variety of environmental conditions, such as temperature and humidity. A proposed method for establishing this timeline would be to

expose fresh Palmer amaranth pollen grains to temperature, and relative humidity gradients for varying lengths of time before hand-fertilizing receptive female Palmer amaranth flowers. The amount of successful fertilizations that result would reveal how long Palmer amaranth pollen is able to remain viable over time in a range of environmental conditions. Once this timeline has been established, the maximum dispersion distance of viable Palmer amaranth pollen may be more accurately determined.

## Sources of Materials

- <sup>1</sup>HUMPOL, HUII Method of POLLen simulation software package. POLLen-  
LANDscape Calibration Network
- <sup>2</sup>PAPPUS, a trajectory model for wind dispersal of plant diaspores. Philipps-University  
of Marburg, Marburg, Germany.
- <sup>3</sup>POLDISP v 1.0, a free software package to estimate the distribution of pollen dispersal  
distances. Available from <http://poldisp.googlepages.com>.
- <sup>4</sup>BREEZE Industrial Source Complex (ISC) GIS PRO, a short-term, steady-state  
Gaussian plume model to predict dispersion concentrations from non-reactive sources  
according to ISCST3 U.S. EPA regulations. Trinity Consultants, Inc., BREEZE  
Software & Data, 12770 Merit Drive, Suite 900, Dallas, TX 75251.
- <sup>5</sup>Beckman Coulter LS 13 320 electronic particle sizer, a laser diffraction particle size  
analyzer. Beckman Coulter, Inc., 250 S. Kraemer Boulevard, P.O. Box 8000, Brea, CA  
92822-8000.
- <sup>6</sup>SigmaPlot v9, Exact Graphs and Data Analyses. Systat Software, Inc., 225 W  
Washington St., Suite 425, Chicago, IL 60606.

<sup>7</sup>North Carolina State Climate Office CRONOS Database, State Climate Office of North Carolina, NC State University. Available at <http://www.nc-climate.ncsu.edu/cronos/>. Accessed *January 16, 2010*.

<sup>8</sup>Statistical Analysis Systems<sup>®</sup> Software v 9.1.3, SAS Institute Inc., SAS Campus Drive, Cary, NC, 27513.

<sup>9</sup>Paired Student's T test in Microsoft Excel (2007). Microsoft Corporation, 1 Microsoft Way Redmond, WA 98052-8300.

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Table 1. Pollen emission parameters for a glyphosate-susceptible Palmer amaranth population collected from Clayton, NC.

Parameter	Value
Average pollen grains/flower <sup>a</sup>	$2.1 \times 10^4$
Average flowers releasing pollen/d/cm of inflorescence <sup>b</sup>	3
Total cm of inflorescence at pollen source	$7.0 \times 10^3$
Total pollen grains emitted/d <sup>c</sup>	$4.1 \times 10^9$
Pollen grains emitted/plant/d <sup>d</sup>	$1.1 \times 10^7$
Pollen grains emitted/cm inflorescence <sup>e</sup>	$5.9 \times 10^4$

<sup>a</sup>Data are from 49 flowers collected from confirmed glyphosate-susceptible Palmer amaranth plants.

<sup>b</sup>Data are the average of 37 Palmer amaranth plants.

<sup>c</sup>Calculated as the product of average grains/flower, average dehiscing flowers/cm/d, and the total cm of inflorescence at the source.

<sup>d</sup>Calculated as the number of pollen grains emitted/d divided by the total number of plants at the source.

<sup>e</sup>Calculated as the daily total pollen grains emitted divided by the total cm of inflorescence at the source.

Table 2. Relative humidity, dew point, air temperature, prevailing wind, and wind speed for 19 days when Palmer amaranth pollen grain distribution was determined at Goldsboro, NC.<sup>a</sup>

Date	Relative humidity			Dew point		Temperature			Prevailing wind			Wind speed		
	Field	Station		Field	Station	Field	Station		Field	Station		Field	Station	
	Ave.	Hourly	Ave.	Ave.	Hourly	Ave.	Hourly	Ave.	Ave.	Hourly	Ave.	Ave.	Hourly	Ave.
	%			C		C			Degree			km/h		
8/8/08	44	77	89	22	22	36	26	24	327	193	260	2.1	4.3	3.5
8/12/08	90	91	95	22	19	24	20	19	333	235	224	0.8	4.2	4.7
8/14/08	98	53	68	17	13	18	23	21	23	1	101	0	6.8	2.3
8/19/08	94	67	81	23	19	24	25	24	60	319	298	0.3	9.5	9.3
6/19/09	-	69	75	-	21	-	27	26	-	259	272	-	11.3	12.2
6/23/09	-	74	82	-	20	-	25	23	-	11	191	-	9.8	10.6
6/24/09	-	74	81	-	21	-	26	24	-	268	225	-	7.1	9.2
6/26/09	-	70	76	-	22	-	28	26	-	200	194	-	12.2	11.1
7/7/09	-	68	74	-	19	-	25	24	-	117	354	-	11.9	10
7/8/09	89	81	93	22	22	24	25	23	329	255	216	1.8	5.6	7.1
7/10/09	74	64	72	17	16	22	23	22	115	11	12	3.4	11.7	11.7
7/14/09	-	74	86	-	18	-	23	22	-	116	341	-	19.3	15
7/15/09	68	77	90	20	19	23	24	22	247	69	73	2.3	4.8	5.6
7/16/09	73	71	73	21	21	26	27	25	329	190	186	11.6	15.4	15
7/22/09	88	79	88	22	22	25	26	24	215	53	65	1.3	7.1	3.4
7/23/09	91	87	93	23	22	24	25	23	20	191	215	4.2	8.4	7.6
7/24/09	-	86	95	-	22	.	25	23	.	133	150	-	1.3	1.4
7/27/09	86	82	85	24	24	26	27	26	328	154	167	7.7	10.9	11.4
7/30/09	82	75	82	23	22	26	27	26	29	228	221	7.2	10	11.9

<sup>a</sup>Data collected on-site simultaneously with pollen collection. Station weather data collected off-site at the North Carolina State Climate Office at the Cherry Research Farm near Goldsboro, NC. Data from the North Carolina State Climate was substituted from missing observations.

Table 3. Daily deposition rate, percentage of traps containing zero pollen for field observations and model predictions, and paired Student's T-test for Palmer amaranth pollen collection comparing empirical data from eight observations during 2008 and 2009 with estimates provided by the BREEZE ISC GIS PRO software models.<sup>a</sup>

Sample date	Deposition rate	Empty pollen traps		Statistical parameter		
		Field observations <sup>b</sup>	Model predictions <sup>c</sup>	t Stat	P < t	t critical
	— % —	———— % —————				
8/8/08	0.08	85	46	2.73	0.0069	1.97
8/12/08	0.87	81	64	2.31	0.0219	1.97
8/14/08	0.09	90	100	2.71	0.0075	1.97
8/19/08	0.27	80	47	3.61	0.0004	1.97
7/8/09	0.97	90	48	2.56	0.0113	1.97
7/10/09	0.64	81	45	2.53	0.0125	1.97
7/15/09	1.00	91	48	1.44	0.1521	1.97
7/16/09	1.87	82	65	1.66	0.0985	1.97
7/22/09	2.03	88	65	1.51	0.1333	1.97
7/23/09	3.34	84	77	1.40	0.1644	1.97
7/27/09	2.78	91	47	2.54	0.0120	1.97
7/30/09	2.99	85	64	3.27	0.0013	1.97

<sup>a</sup>Hypothesized mean difference = 0, two-tailed  $\alpha = 0.025$ ,  $p \leq 0.025$  indicates significant difference between groups. Daily deposition rates calculated as summed deposition at the source\*100/total pollen grains emitted per day.

<sup>b</sup>Represents the percentage of field observations (165 total pollen traps/d) where zero Palmer amaranth pollen grains/view area were observed.

<sup>c</sup>Represents the percentage of model predictions (165 total pollen traps/d) where zero Palmer amaranth pollen grains/view area were predicted.

Table 4. Correlation coefficients (p-value) and regression coefficients comparing Palmer amaranth pollen observations pooled over all dates and trap distances from the pollen source to trap height.

Parameter	Pollen trap height above soil surface (m)				
	0.75	1.75	2.75	3.75	
<i>Relative humidity</i>					
Field Ave.	R	0.105	0.117	-0.359	-0.009
Field	p-value	0.446	0.393	0.007	0.948
Station Hourly	R	0.01	0.131	-0.016	-0.04
Station	p-value	0.927	0.206	0.874	0.699
Station Ave.	R	-0.015	0.121	0.051	-0.104
Station	p-value	0.884	0.243	0.621	0.318
<i>Dew point</i>					
Field Ave.	R	0.129	0.148	0.023	-0.04
Field	p-value	0.349	0.281	0.869	0.774
Station Hourly	R	0.06	0.1	0.04	-0.015
Station	p-value	0.563	0.334	0.703	0.888
<i>Temperature</i>					
Field Ave.	R	-0.03	-0.062	0.366	-0.019
Field	p-value	0.826	0.653	0.006	0.892
Station Hourly	R	0.074	0.007	0.076	0.02
Station	p-value	0.473	0.945	0.464	0.85
Station Ave.	R	0.097	0.031	0.029	0.039
Station	p-value	0.351	0.767	0.783	0.707
<i>Prevailing wind direction</i>					
Field Ave.	R	-0.047	-0.184	0.147	-0.068
Field	p-value	0.736	0.179	0.285	0.622
Station Hourly	R	0.121	0.068	0.105	0.081
Station	p-value	0.241	0.513	0.313	0.433
Station Ave.	R	0.064	-0.008	0.159	0.198
Station	p-value	0.538	0.941	0.124	0.055

Table 4 Continued.

<i>Wind speed</i>						
Field	Ave.	R	-0.004	0.005	-0.086	0.015
Field		p-value	0.979	0.971	0.532	0.913
Station	Hourly	R	-0.043	-0.185	-0.046	0.054
Station		p-value	0.678	0.072	0.659	0.602
Station	Ave.	R	0.01	-0.133	-0.059	0.057
Station		p-value	0.923	0.2	0.571	0.584

<sup>a</sup>Data collected on-site simultaneously with pollen collection. Station weather data collected off-site at the North Carolina State Climate Office at the Cherry Research Farm near Goldsboro, NC. Data from the North Carolina State Climate was substituted from missing observations.

Table 5. Correlation coefficients (p-value) and regression coefficients comparing Palmer amaranth pollen observations pooled over all dates and trap distances from the pollen source to trap height.

Parameter			Distance from source (m)				
			1	2	10	25	50
<i>Relative humidity</i>							
Field	Ave.	R	0.013	0.09	0.002	0.038	0.044
Field		p-value	0.931	0.561	0.987	0.809	0.778
Station	Hourly	R	0.025	0.035	0.073	-0.02	-0.019
Station		p-value	0.832	0.763	0.53	0.864	0.869
Station	Ave.	R	0.01	0.04	0.059	-0.106	-0.045
		p-value	0.931	0.731	0.615	0.361	0.697
<i>Dew point</i>							
Field	Ave.	R	0.132	0.188	0.137	-0.202	-0.173
Field		p-value	0.392	0.222	0.375	0.189	0.262
Station	Hourly	R	0.082	0.131	0.141	-0.086	-0.207
Station		p-value	0.482	0.258	0.223	0.462	0.073
<i>Temperature</i>							
Field	Ave.	R	-0.044	-0.034	0.206	-0.051	0.028
Field		p-value	0.775	0.825	0.179	0.742	0.858
Station	Hourly	R	0.082	0.199	0.148	0.12	-0.005
Station		p-value	0.479	0.084	0.202	0.301	0.963
Station	Ave.	R	0.072	0.12	0.159	-0.003	-0.039
Station		p-value	0.539	0.303	0.169	0.978	0.74
<i>Prevailing wind direction</i>							
Field	Ave.	R	0.061	0.024	0.039	-0.169	-0.15
Field		p-value	0.694	0.88	0.8	0.273	0.332
Station	Hourly	R	0.088	0.148	0.114	-0.093	-0.258
Station		p-value	0.449	0.202	0.326	0.427	0.024
Station	Ave.	R	0.101	0.156	0.131	-0.055	-0.23
Station		p-value	0.385	0.178	0.258	0.635	0.046

Table 5 Continued.

<i>Wind speed</i>							
Field	Ave.	R	0.01	0.003	0.2	-0.122	-0.154
Field		p-value	0.948	0.984	0.193	0.429	0.318
Station	Hourly	R	-0.071	-0.071	0.049	-0.006	-0.03
Station		p-value	0.545	0.541	0.673	0.961	0.796
Station	Ave.	R	-0.044	0.005	0.103	0.072	-0.013
Station		p-value	0.707	0.963	0.374	0.536	0.913

<sup>a</sup>Data collected on-site simultaneously with pollen collection. Station weather data collected off-site at the North Carolina State Climate Office at the Cherry Research Farm near Goldsboro, NC. Data from the North Carolina State Climate was substituted from missing observations.

Table 6. Correlation coefficients (p-value) and regression coefficient comparing Palmer amaranth pollen observations pooled over date, trap height, and trap distance from source.

Parameter			Pooled Data
<i>Relative humidity</i>			
Field	Ave.	R	0.017
Field		p-value	0.795
Station	Hourly	R	0.052
Station		p-value	0.297
Station	Ave.	R	0.015
Station		p-value	0.764
<i>Dew point</i>			
Field	Ave.	R	0.073
Field		p-value	0.27
Station	Hourly	R	0.086
Station		p-value	0.088
<i>Temperature</i>			
Field	Ave.	R	-0.005
Field		p-value	0.946
Station	Hourly	R	0.032
Station		p-value	0.527
Station	Ave.	R	-0.003
Station		p-value	0.96
<i>Prevailing wind</i>			
Field	Ave.	R	0.01
Field		p-value	0.885
Station	Hourly	R	0.061
Station		p-value	0.227
Station	Ave.	R	0.073
Station		p-value	0.148

Table 6 Continued.

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<i>Wind speed</i>			
Field	Ave.	R	0.106
Field		p-value	0.108
Station	Hourly	R	0.002
Station		p-value	0.975
Station	Ave.	R	0.031
Station		p-value	0.536

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<sup>a</sup>Data collected on-site simultaneously with pollen collection. Station weather data collected off-site at the North Carolina State Climate Office at the Cherry Research Farm near Goldsboro, NC. Data from the North Carolina State Climate was substituted from missing observations.

Table 7: Percentage of total Palmer amaranth pollen collected pooled over trap height.

Sampling date	Percentage of total pollen collected				
	Distance from Source (m)				
	1	2	10	25	50
	%				
8/8/08	75	19	1	2	2
8/12/08	47	10	1	16	25
8/14/08	69	17	0	6	9
8/19/08	56	36	2	1	4
6/19/09	33	32	10	20	6
6/23/09	52	36	7	2	2
6/24/09	83	6	4	4	2
6/26/09	50	45	5	0	0
7/7/09	72	18	1	1	8
7/8/09	51	35	5	2	8
7/10/09	47	10	1	16	25
7/14/09	33	7	53	0	7
7/15/09	38	50	8	0	4
7/16/09	53	29	11	2	4
7/22/09	90	6	0	1	3
7/23/09	60	28	0	8	4
7/24/09	56	31	10	2	0
7/27/09	71	25	2	2	0
7/30/09	72	21	2	3	2
Average <sup>a</sup>	58 a	24 b	7 c	5 c	6 c

<sup>a</sup>Means followed by the same letter are not significantly different according to Fisher's Protected LSD test at  $p < 0.05$ . Data are pooled over all sampling dates and sampling height.

Table 8. Percentage of Palmer amaranth pollen collected pooled over trap distance from source.

Trap height	8/8/08	8/12/08	8/14/08	8/19/08	6/19/09	6/23/09	6/24/09	6/26/09	7/7/09	7/8/09	7/10/09	7/14/09	7/15/09	7/16/09	7/22/09	7/23/09	7/24/09	7/27/09	7/30/09	Average <sup>a</sup>
	%																			
0.75 <sup>b</sup>	51	81	83	84	63	82	87	93	79	80	81	20	77	64	90	72	52	97	84	75 a
1.75	2	10	1	11	12	14	11	8	5	6	10	0	8	13	6	8	46	2	9	10 b
2.75	40	1	9	3	11	5	2	0	0	8	1	73	8	7	1	1	1	2	3	9 b
3.75	7	8	7	1	14	0	0	0	16	6	8	7	8	16	3	19	2	0	4	7 b

<sup>a</sup>Means followed by the same letter are not significantly different according to Fisher's Protected LSD test at  $p < 0.05$ . Data are pooled over all sampling dates and distances from pollen source.

<sup>b</sup>Top of cotton canopy.

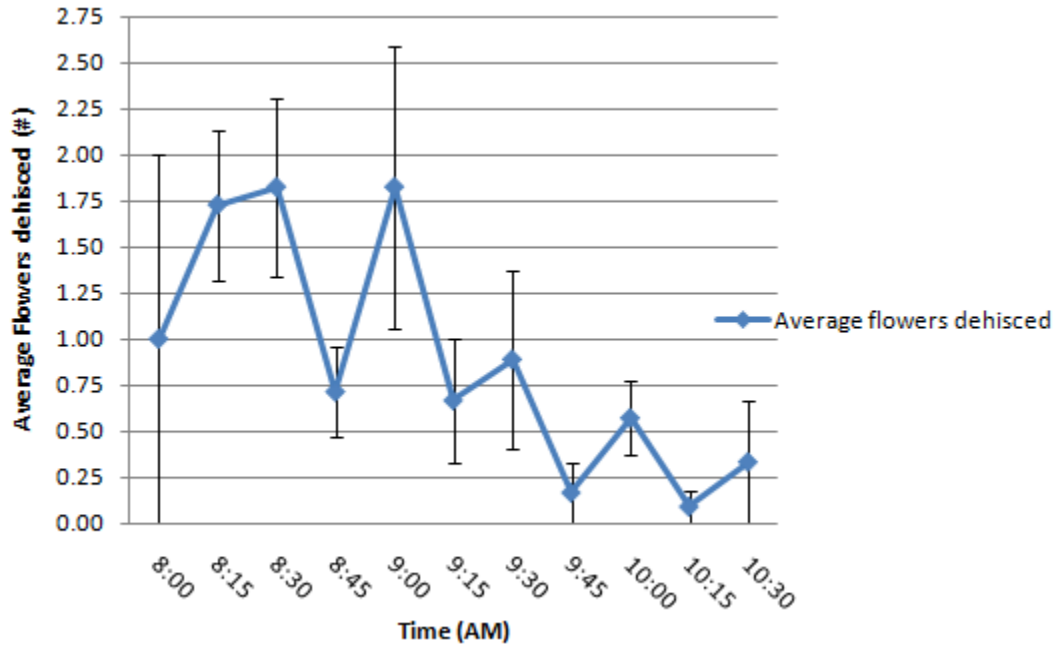


Figure 1. Average North Carolina Palmer amaranth flower dehiscence over time. Data are from 17 observations on four dates in 2007.

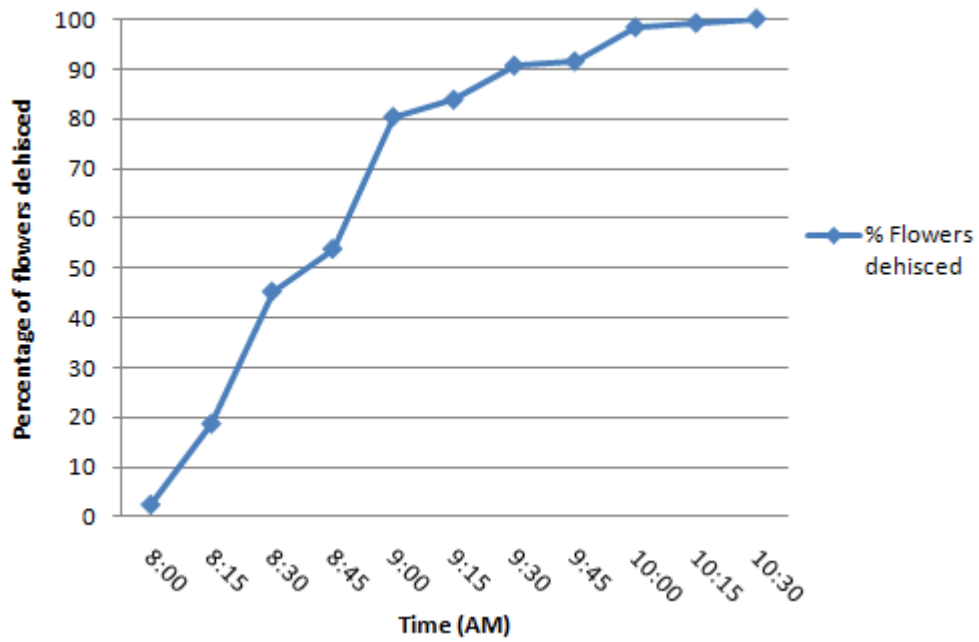


Figure 2. Cumulative percentage of total North Carolina Palmer amaranth flower dehiscence over time. Data are pooled over 17 observations on four dates in 2007.

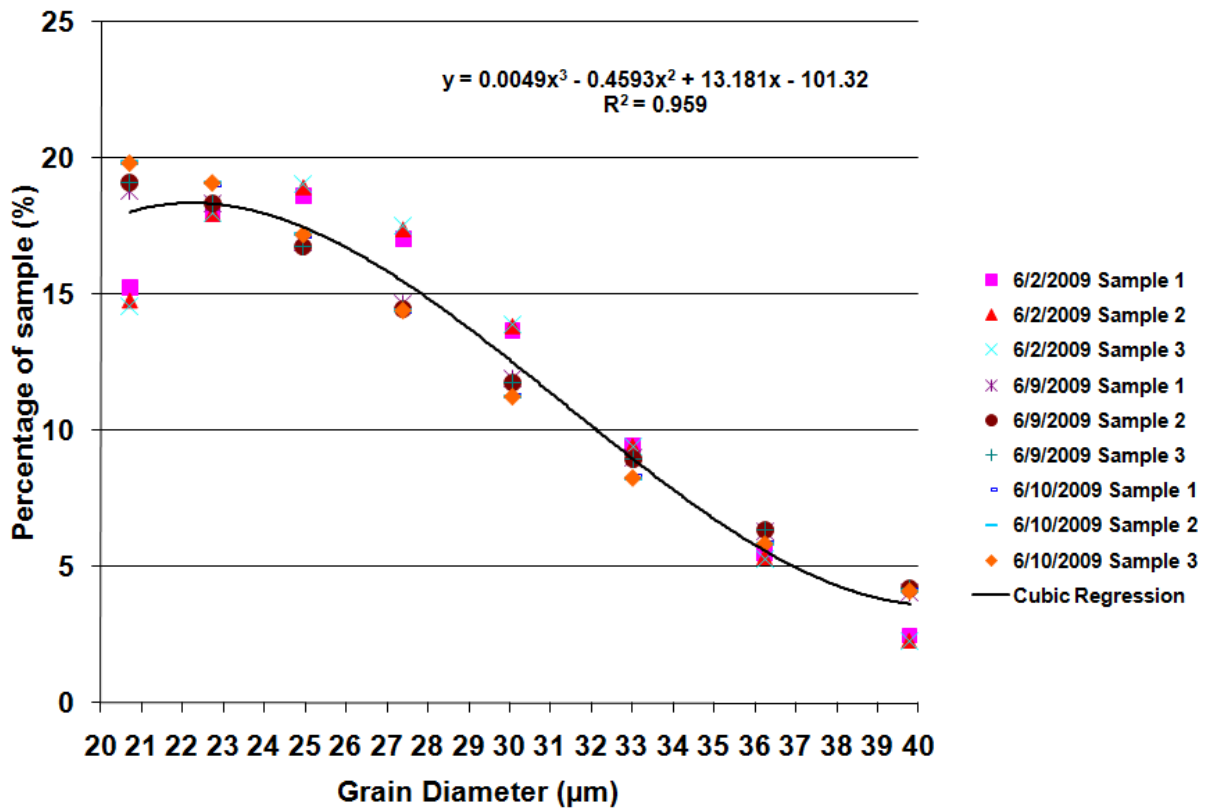


Figure 3. Particle size distribution of North Carolina Palmer amaranth pollen samples collected on three dates in 2009 and measured in triplicate.

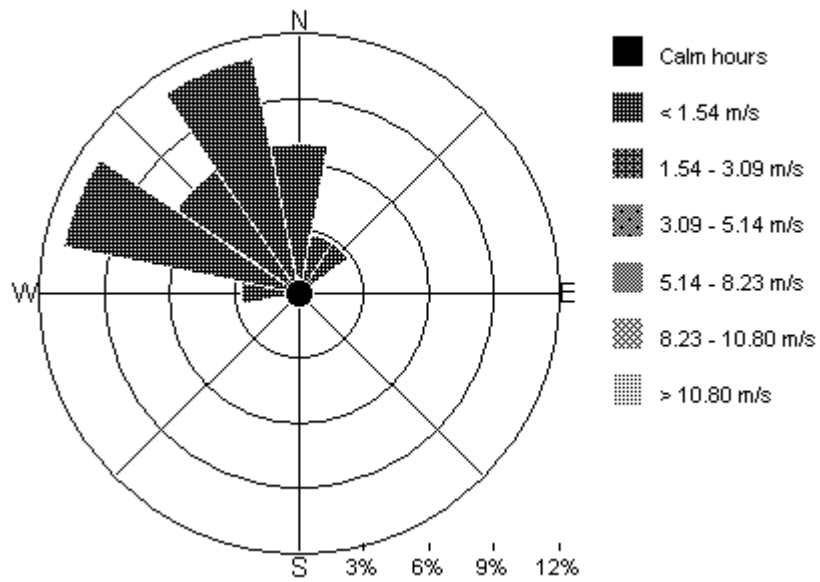


Figure 4. Wind rose based on in-field weather data on 8/08/2008. Wind vectors visually represent wind speed and direction over the two hours of pollen collection. Wind direction represents the direction wind moves toward, whereas the wind vector represents the direction from which the wind originates. The wind vector is therefore a 180 degree reflection of wind direction.

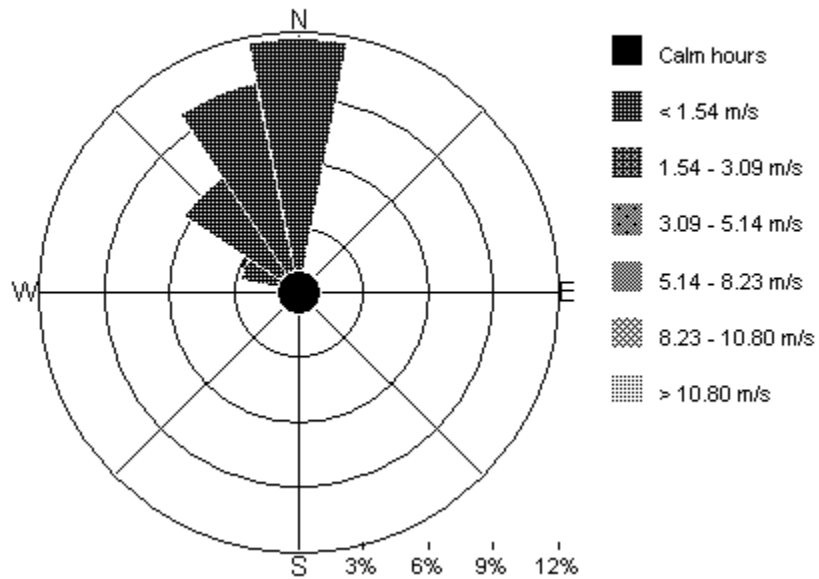


Figure 5. Wind rose based on in-field weather data on 8/12/2008. Vectors visually represent wind speed and direction over the two hours of pollen collection. Wind direction represents the direction wind moves toward, whereas the wind vector represents the direction from which the wind originates. The wind vector is therefore a 180 degree reflection of wind direction.

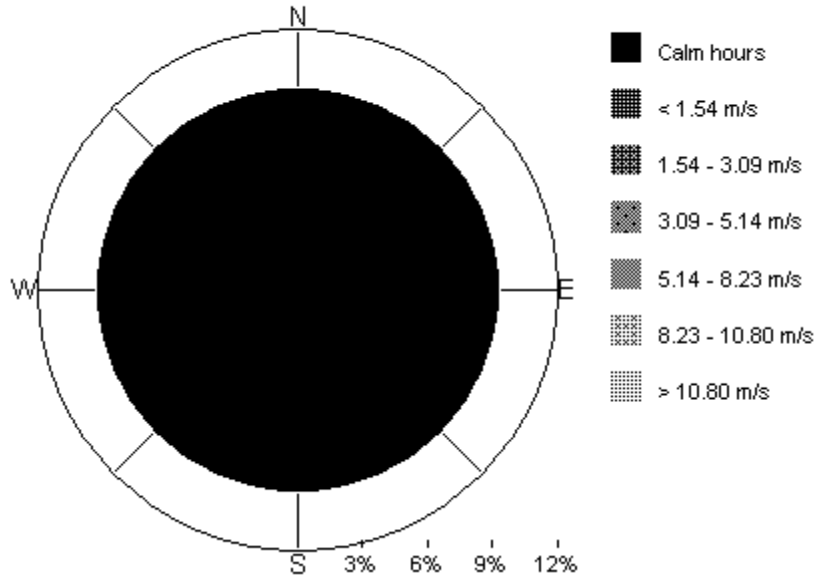


Figure 6. Wind rose based on in-field weather data on 8/14/2008. Vectors visually represent wind speed and direction over the two hours of pollen collection. Wind direction represents the direction wind moves toward, whereas the wind vector represents the direction from which the wind originates. The wind vector is therefore a 180 degree reflection of wind direction.

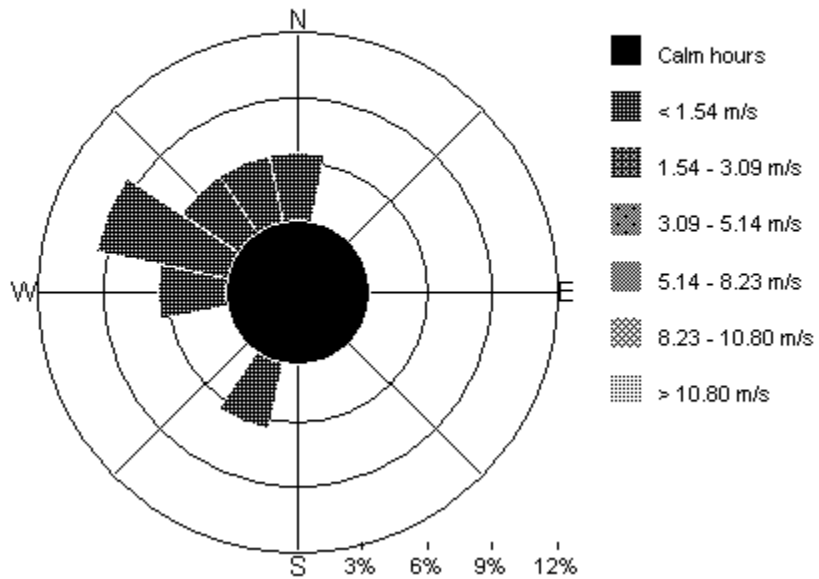


Figure 7. Wind rose based on in-field weather data on 8/19/2008. Vectors visually represent wind speed and direction over the two hours of pollen collection. Wind direction represents the direction wind moves toward, whereas the wind vector represents the direction from which the wind originates. The wind vector is therefore a 180 degree reflection of wind direction.

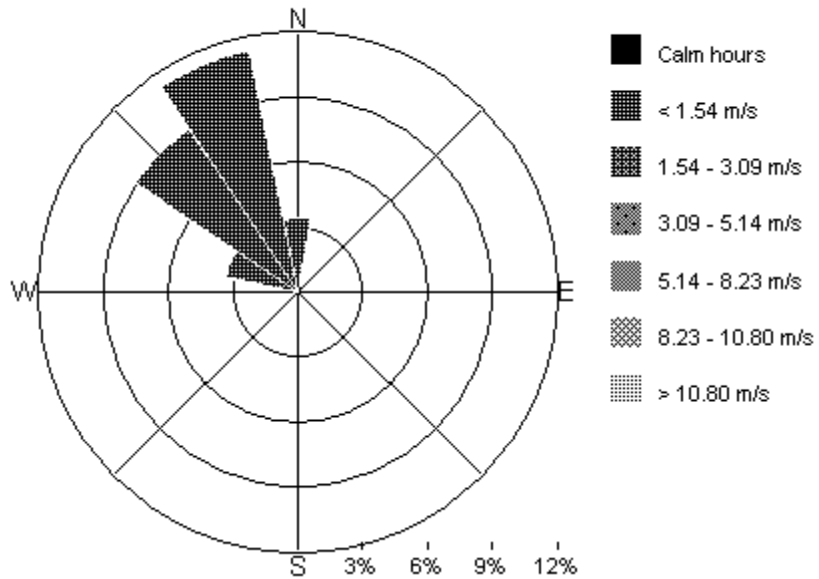


Figure 8. Wind rose based on in-field weather data on 7/08/2009. Vectors visually represent wind speed and direction over the two hours of pollen collection. Wind direction represents the direction wind moves toward, whereas the wind vector represents the direction from which the wind originates. The wind vector is therefore a 180 degree reflection of wind direction.

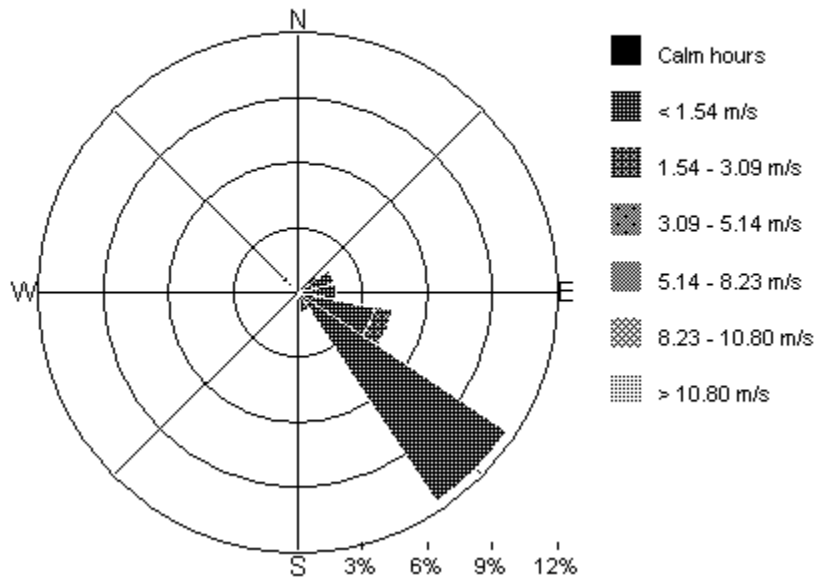


Figure 9. Wind rose based on in-field weather data on 7/10/2009. Vectors visually represent wind speed and direction over the two hours of pollen collection. Wind direction represents the direction wind moves toward, whereas the wind vector represents the direction from which the wind originates. The wind vector is therefore a 180 degree reflection of wind direction.

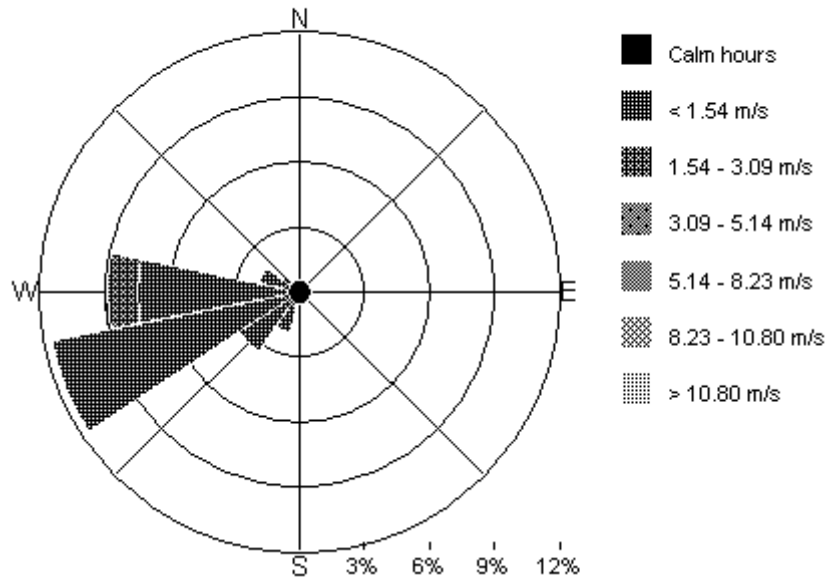


Figure 10. Wind rose based on in-field weather data on 7/15/2009. Vectors visually represent wind speed and direction over the two hours of pollen collection. Wind direction represents the direction wind moves toward, whereas the wind vector represents the direction from which the wind originates. The wind vector is therefore a 180 degree reflection of wind direction.

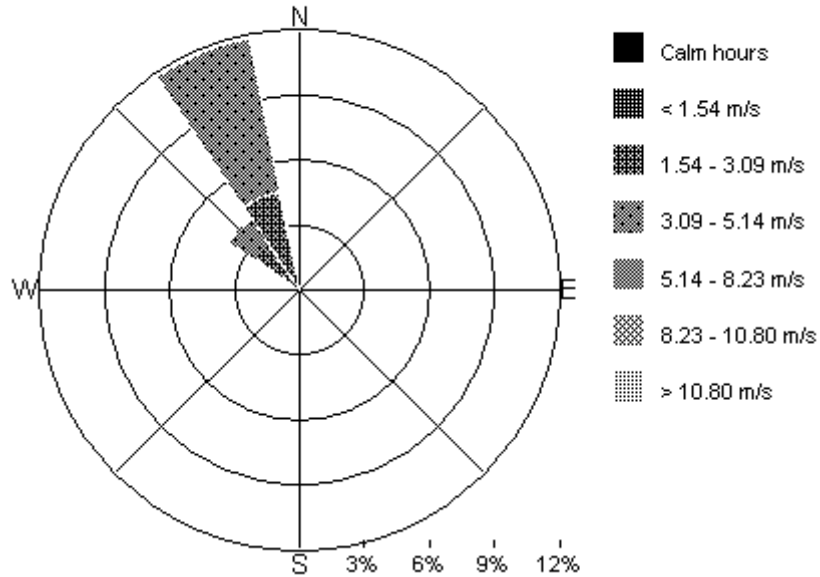


Figure 11. Wind rose based on in-field weather data on 7/16/2009. Vectors visually represent wind speed and direction over the two hours of pollen collection. Wind direction represents the direction wind moves toward, whereas the wind vector represents the direction from which the wind originates. The wind vector is therefore a 180 degree reflection of wind direction.

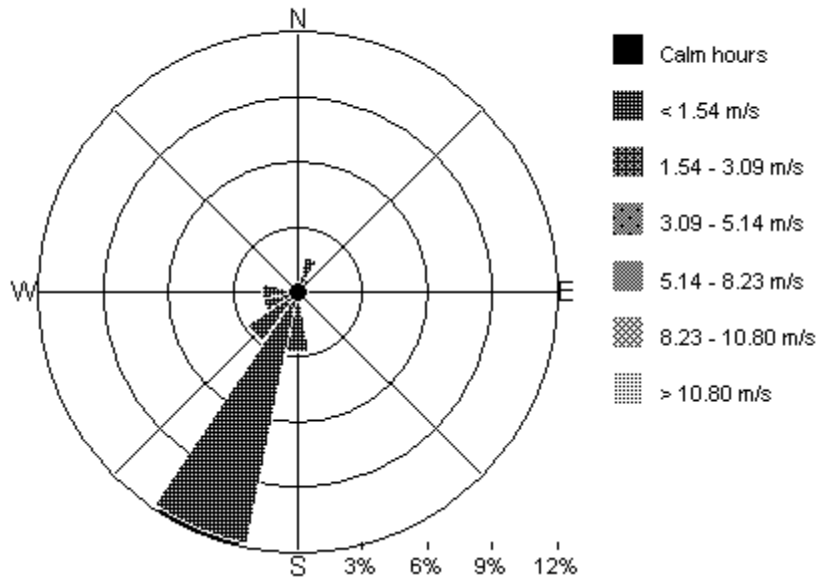


Figure 12. Wind rose based on in-field weather data on 7/22/2009. Vectors visually represent wind speed and direction over the two hours of pollen collection. Wind direction represents the direction wind moves toward, whereas the wind vector represents the direction from which the wind originates. The wind vector is therefore a 180 degree reflection of wind direction.

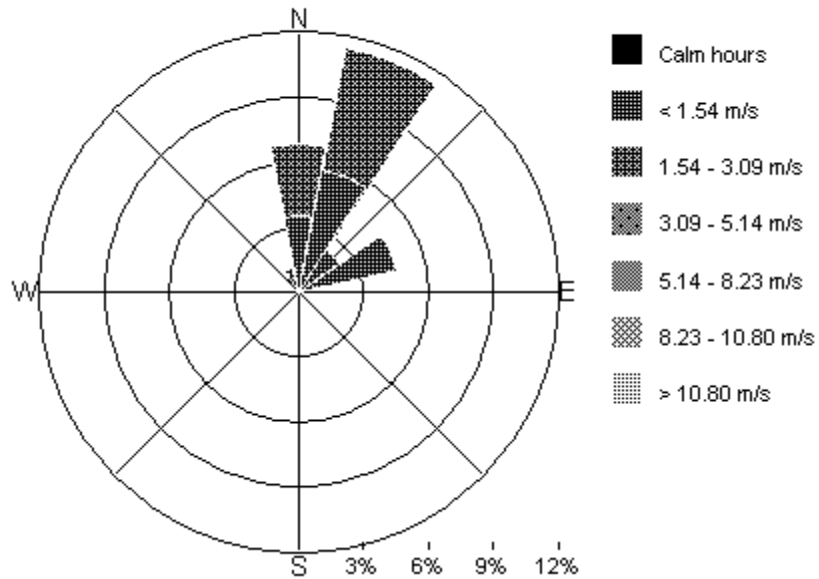


Figure 13. Wind rose based on in-field weather data on 7/23/2009. Vectors visually represent wind speed and direction over the two hours of pollen collection. Wind direction represents the direction wind moves toward, whereas the wind vector represents the direction from which the wind originates. The wind vector is therefore a 180 degree reflection of wind direction.

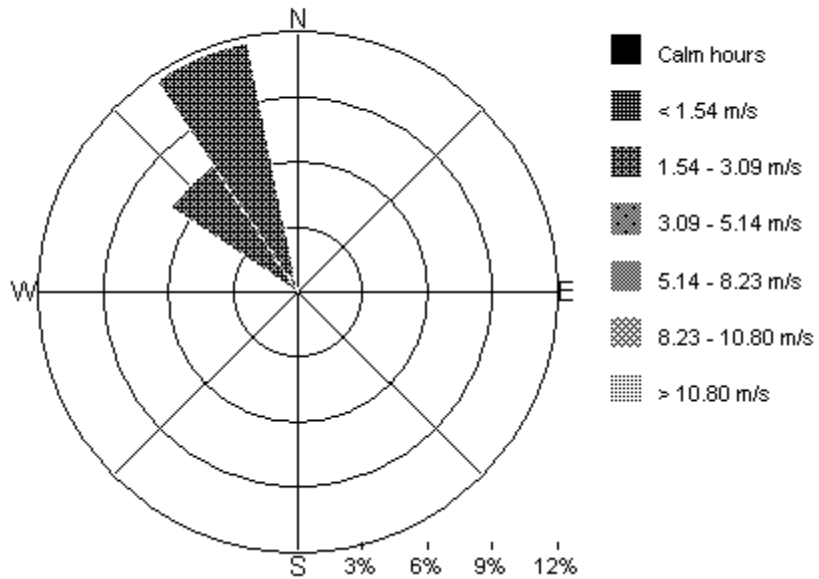


Figure 14. Wind rose based on in-field weather data on 7/27/2009. Vectors visually represent wind speed and direction over the two hours of pollen collection. Wind direction represents the direction wind moves toward, whereas the wind vector represents the direction from which the wind originates. The wind vector is therefore a 180 degree reflection of wind direction.

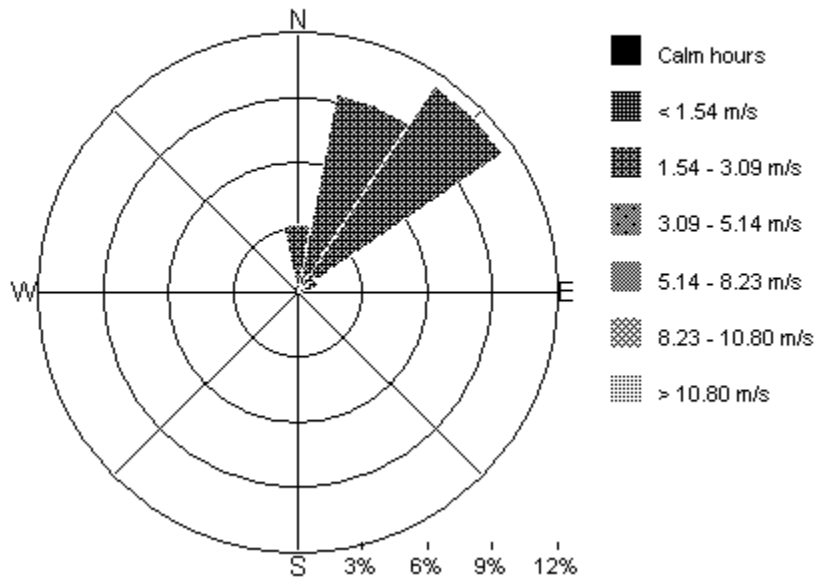


Figure 15 Wind rose based on in-field weather data on 7/30/2009. Vectors visually represent wind speed and direction over the two hours of pollen collection. Wind direction represents the direction wind moves toward, whereas the wind vector represents the direction from which the wind originates. The wind vector is therefore a 180 degree reflection of wind direction.

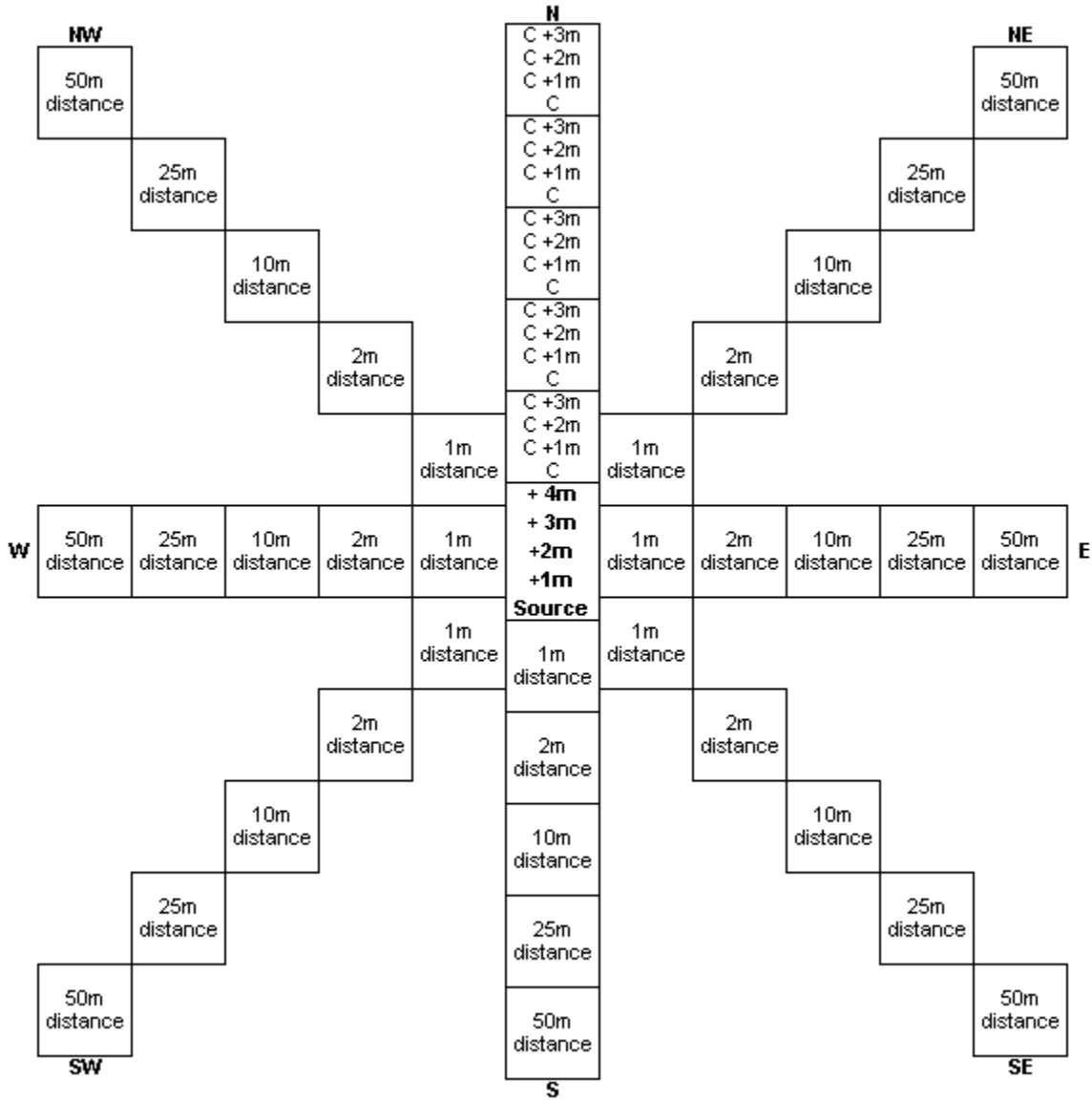


Figure 16. Compass rose configuration key. Blocks are arranged to represent pollen collection sites. Central block represents pollen trap heights at the pollen source. Collection site distance from source is listed in each block with the exception of blocks to the North, which show trap height arrangement within each collection site block. This arrangement is applicable to all collection site blocks. Cardinal and ordinal directions are at the perimeter.

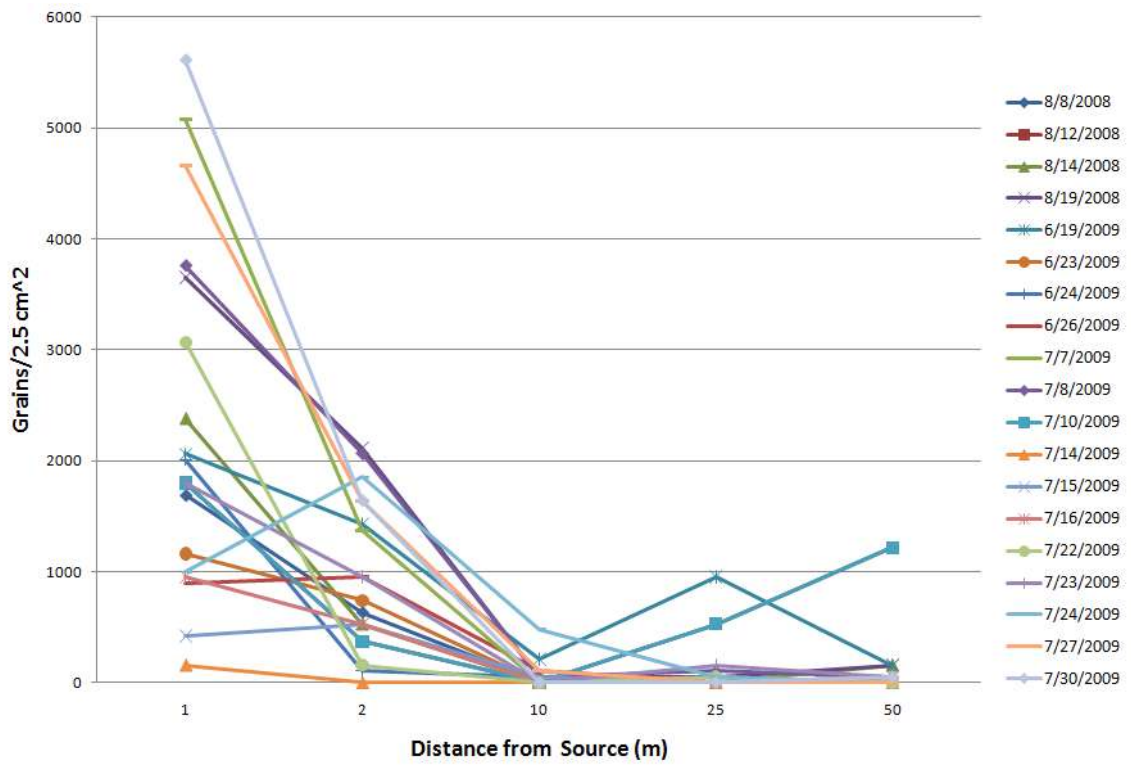


Figure 17. Palmer amaranth pollen totals at canopy trap height (0.75 m). Values are pooled over cardinal and ordinal directions.

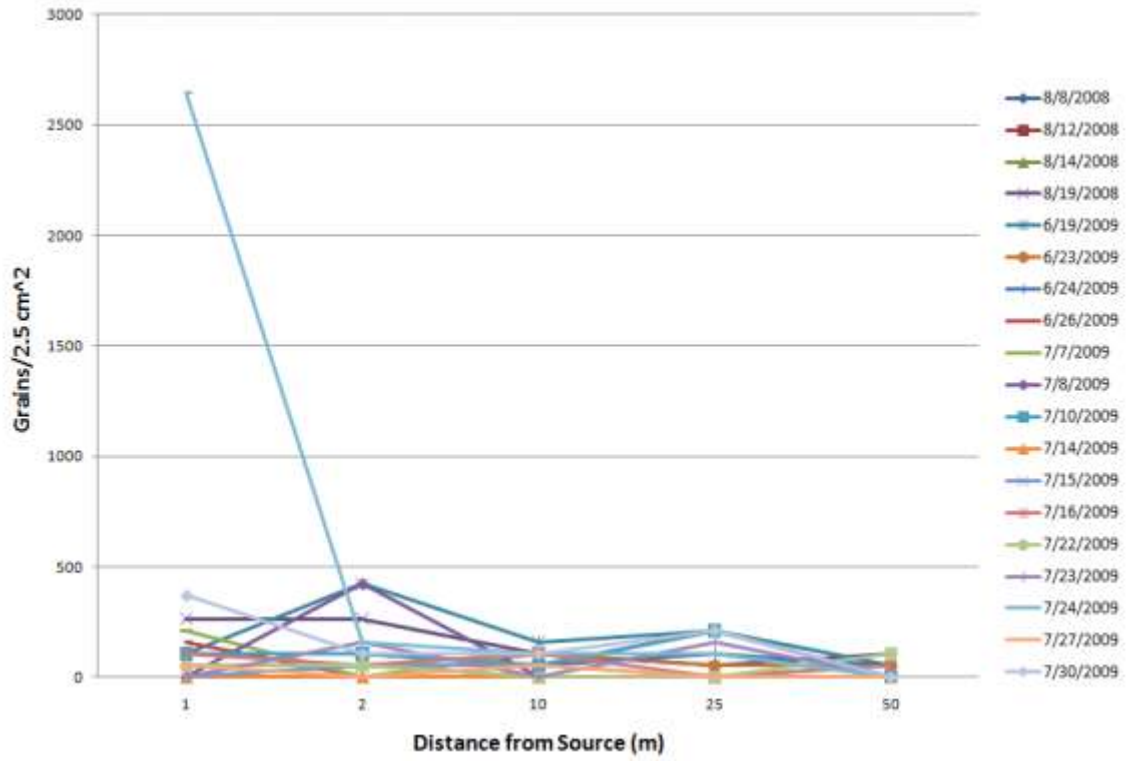


Figure 18. Palmer amaranth pollen totals at 1.75 m above soil surface. Values are pooled over cardinal and ordinal directions.

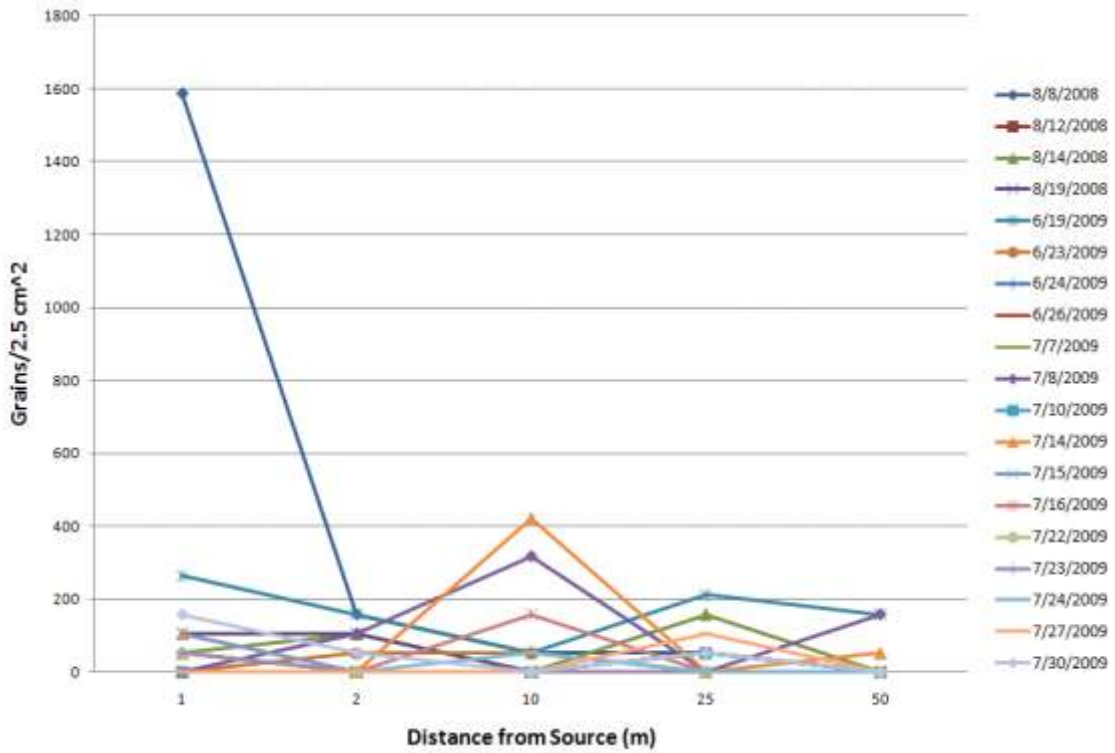


Figure 19. Palmer amaranth pollen totals at 2.75 m above soil surface. Values are pooled over cardinal and ordinal directions.

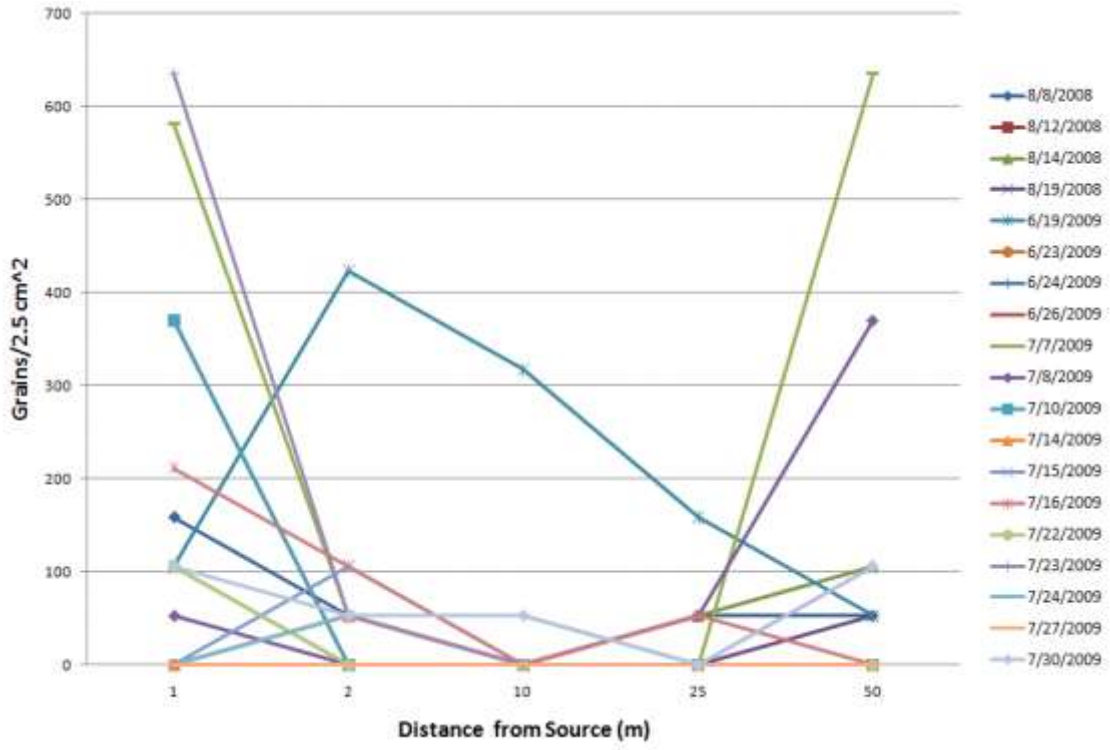
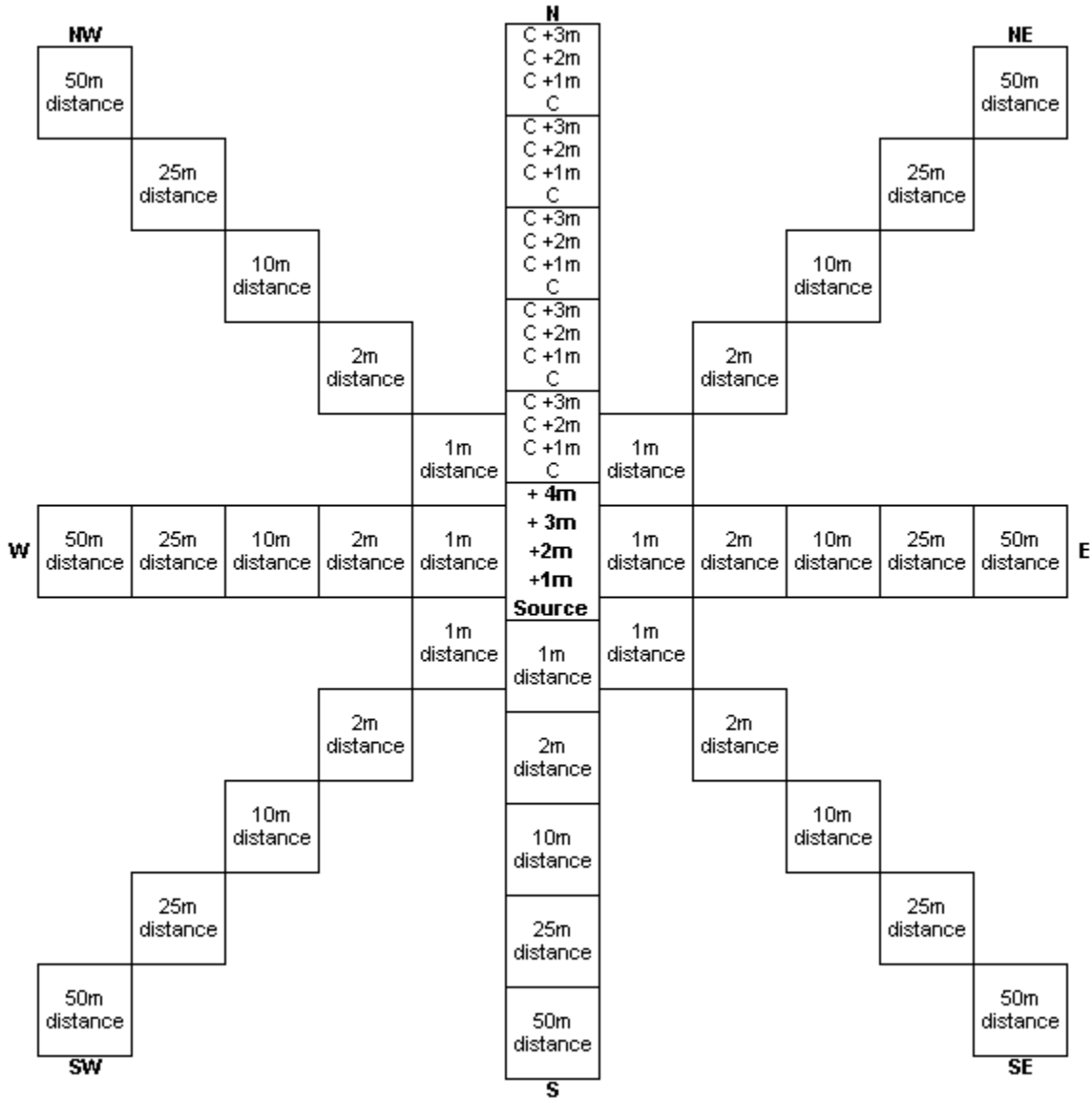


Figure 20. Palmer amaranth pollen totals at 3.75 m above soil surface. Values are pooled over cardinal and ordinal directions.

## APPENDIX 1



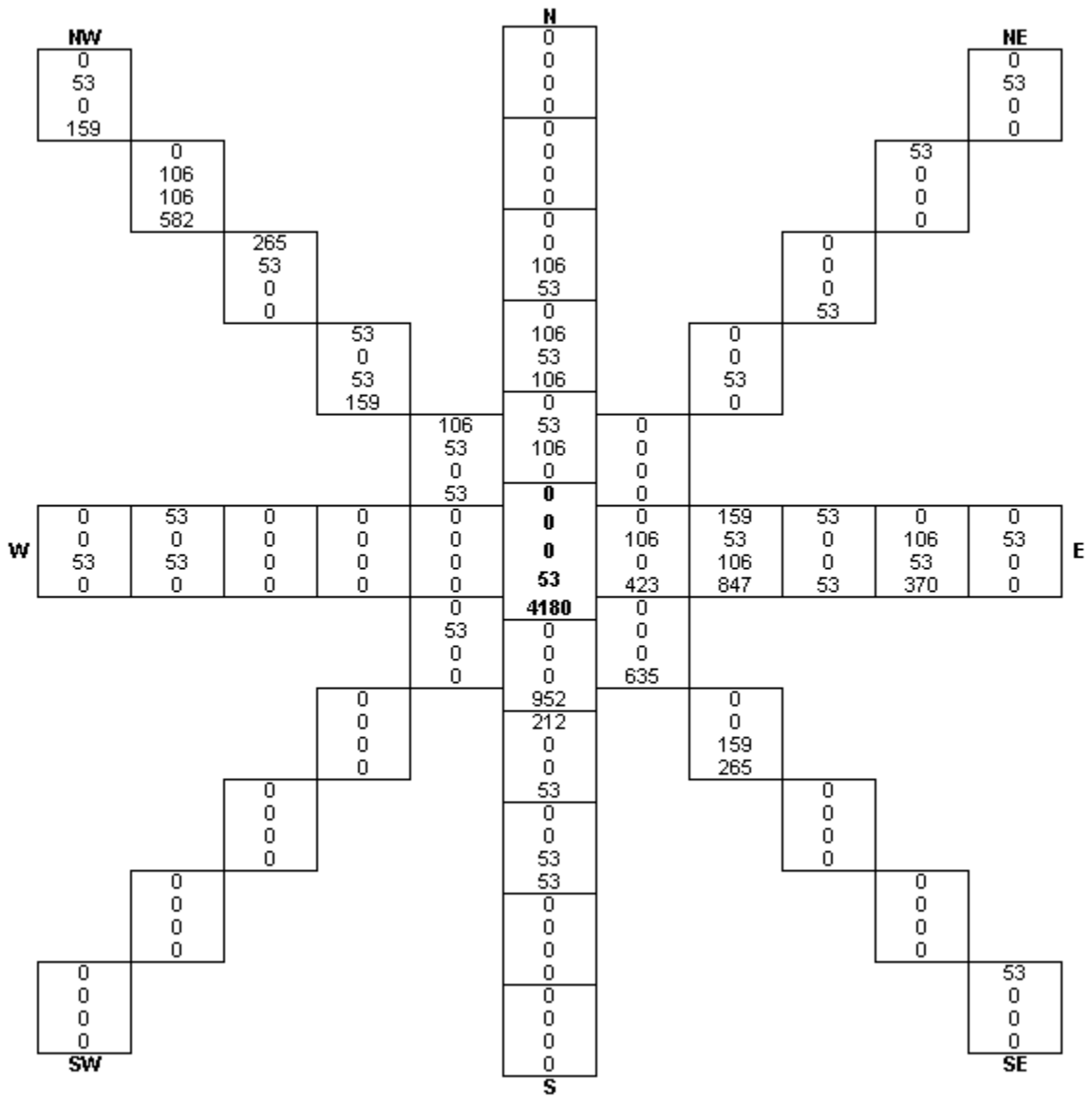
Appendix Figure 1. Compass rose configuration key. Blocks are arranged to represent pollen collection sites. Central block represents pollen trap heights at the pollen source. Collection site distance from source is listed in each block with the exception of blocks to the North, which show trap height arrangement within each collection site block. This arrangement is applicable to all collection site blocks. Cardinal and ordinal directions are at the perimeter.











Appendix Figure 6. Pollen collection data for 6/19/2009. Numbers represent pollen grains per 2.5 square cm. Please refer to Appendix Figure 1 as a key.





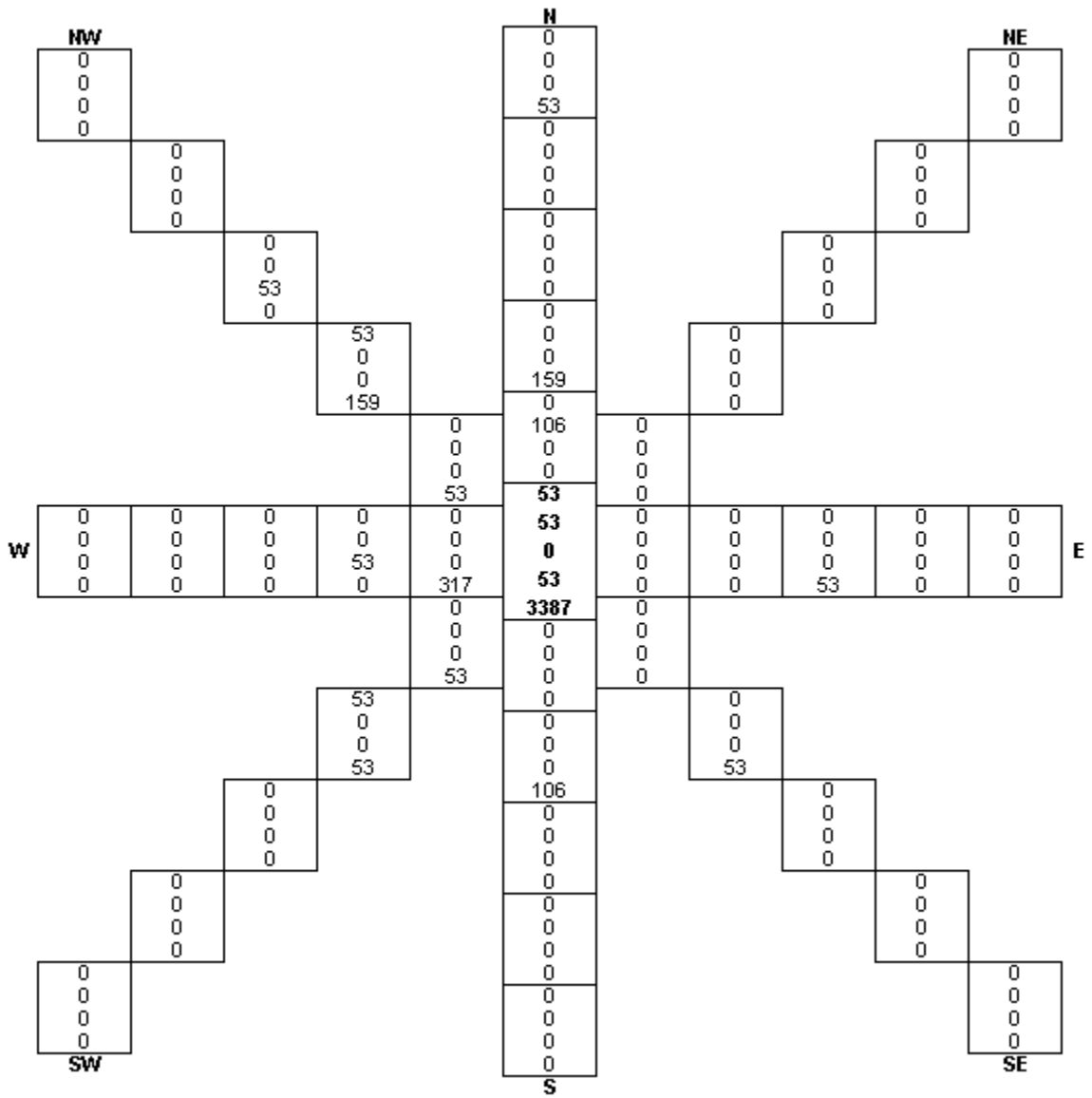












Appendix Figure 14. Pollen collection data for 7/15/2009. Numbers represent pollen grains per 2.5 square cm. Please refer to Appendix Figure 1 as a key.



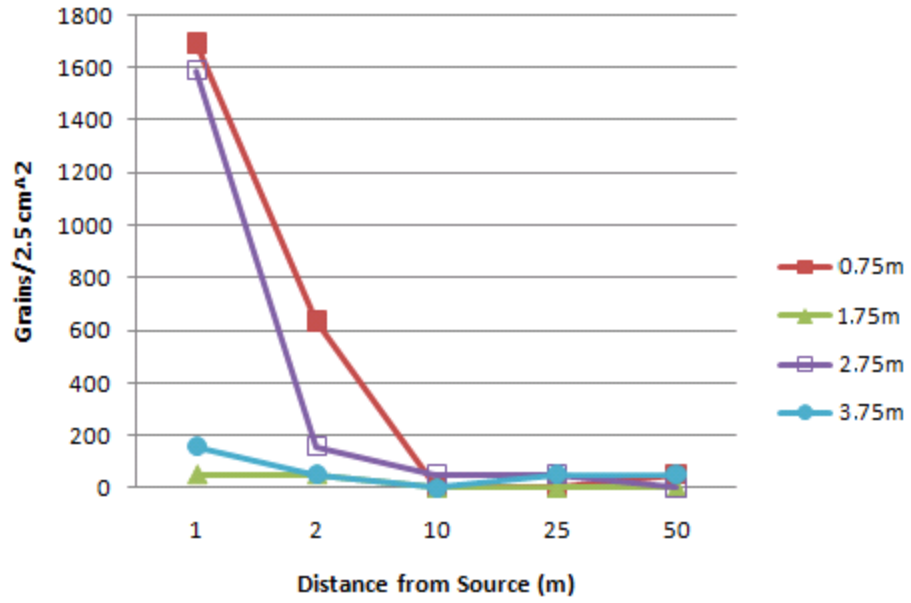




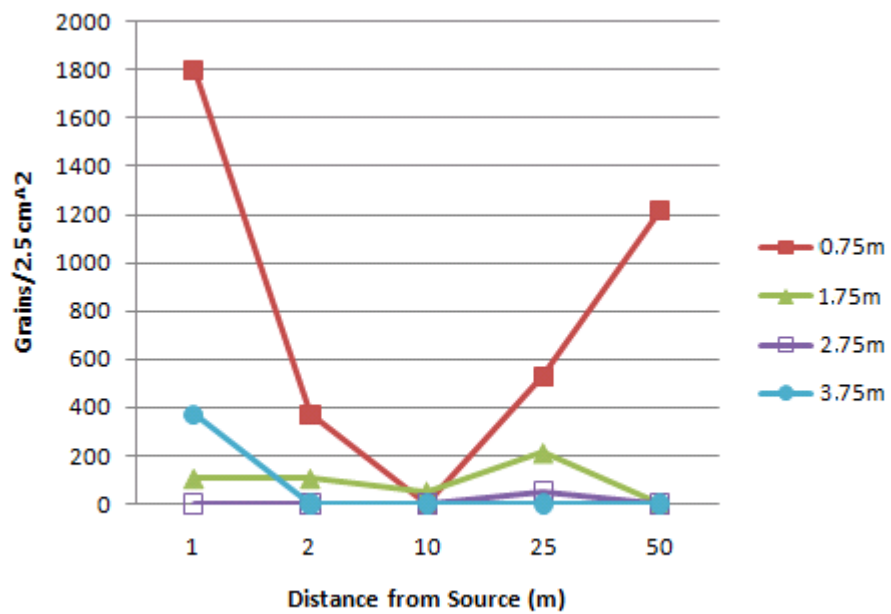




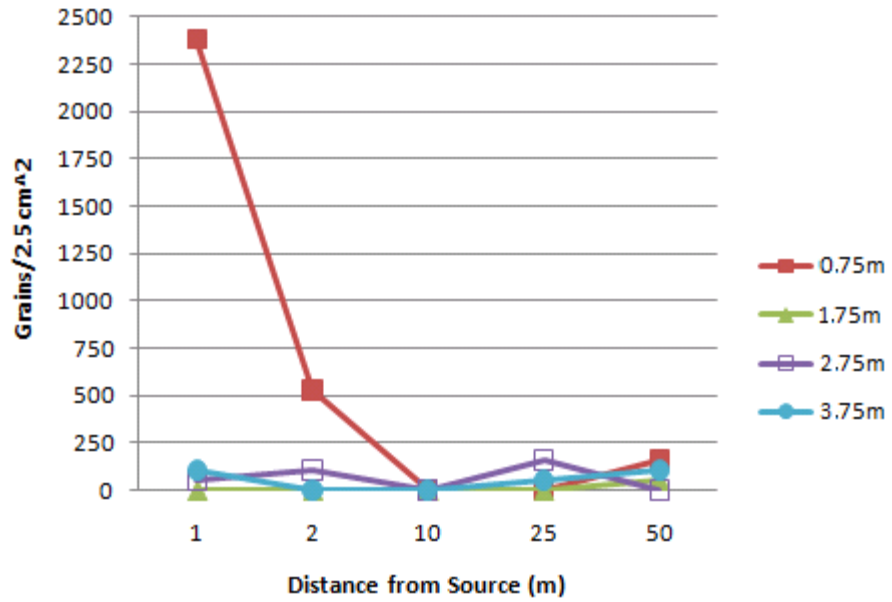




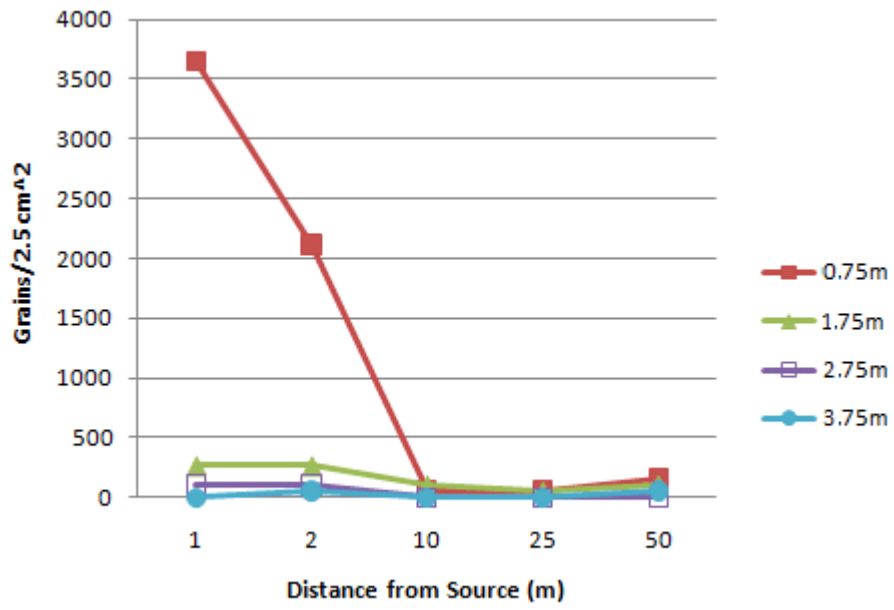
Appendix Figure 21. Amount of pollen captured on 8/08/2008. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



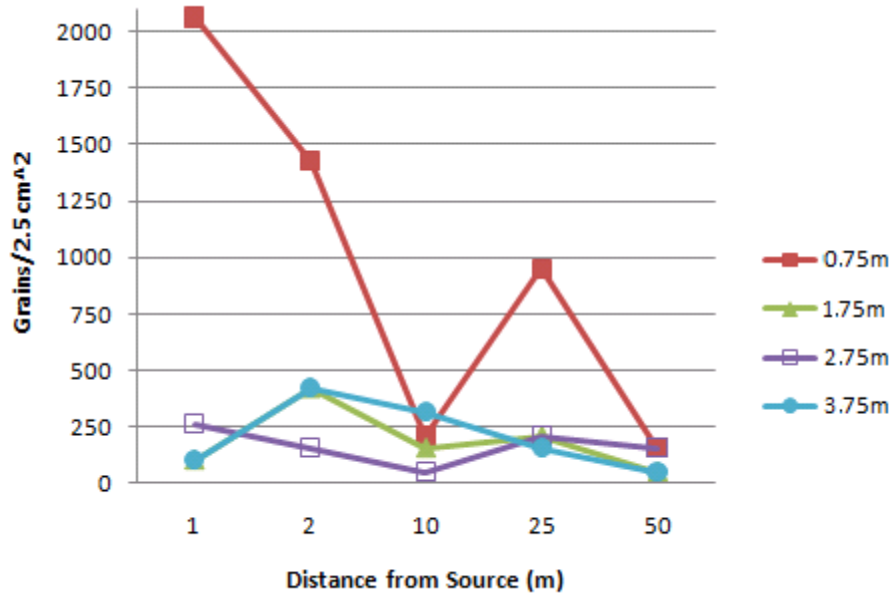
Appendix Figure 22. Amount of pollen captured on 8/12/2008. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



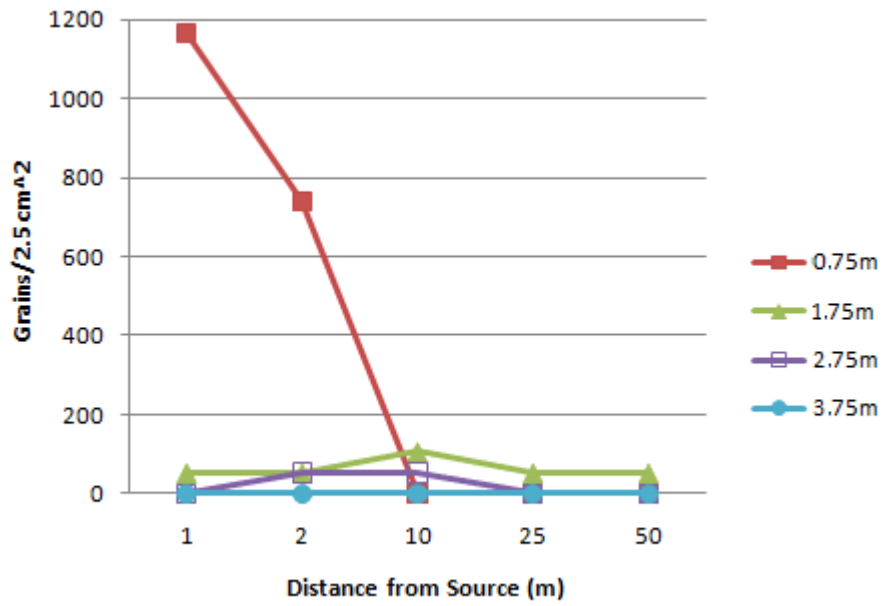
Appendix Figure 23. Amount of pollen captured on 8/14/2008. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



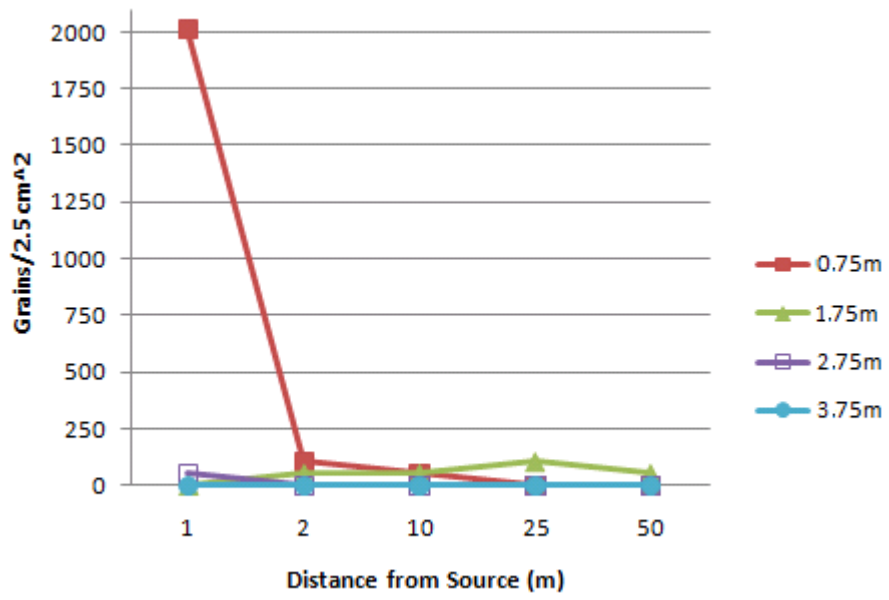
Appendix Figure 24. Amount of pollen captured on 8/19/2008. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



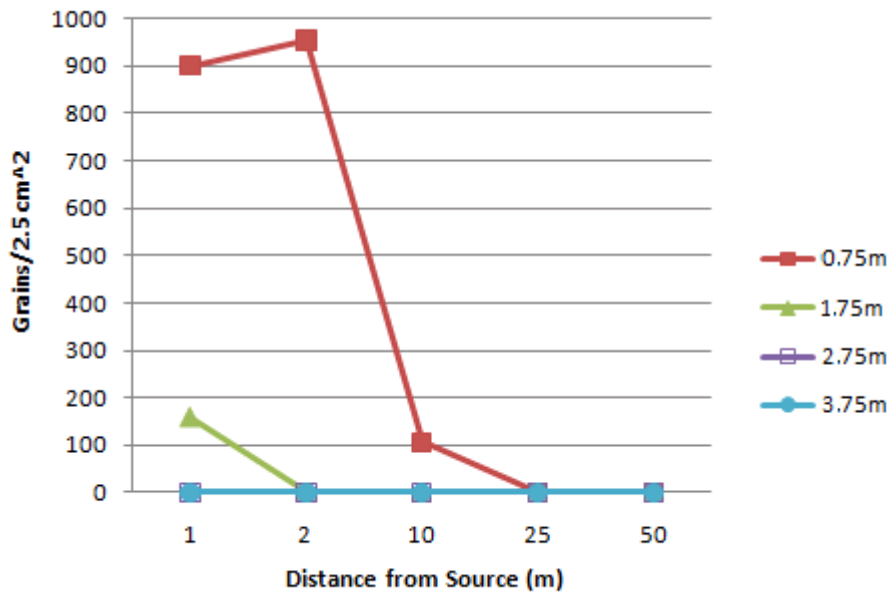
Appendix Figure 25. Amount of pollen captured on 6/19/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



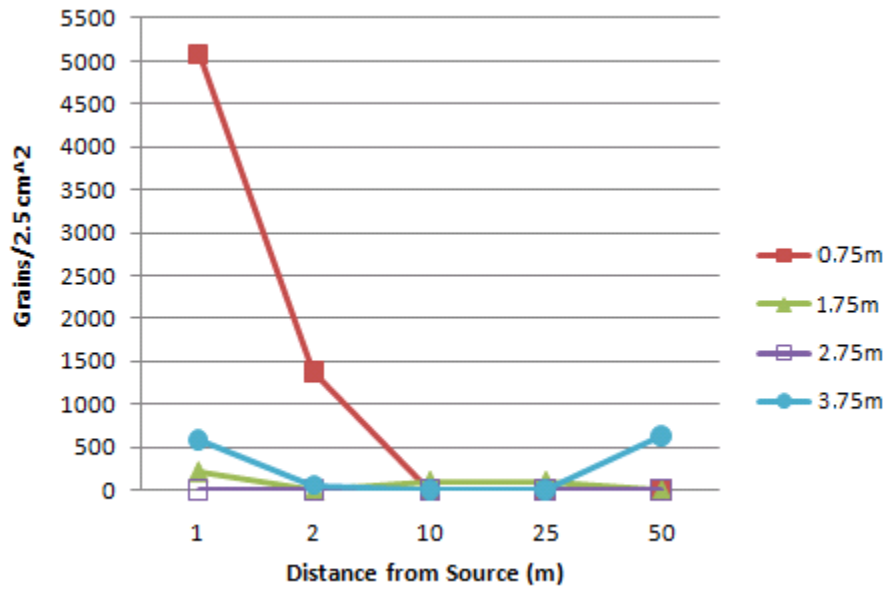
Appendix Figure 26. Amount of pollen captured on 6/23/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



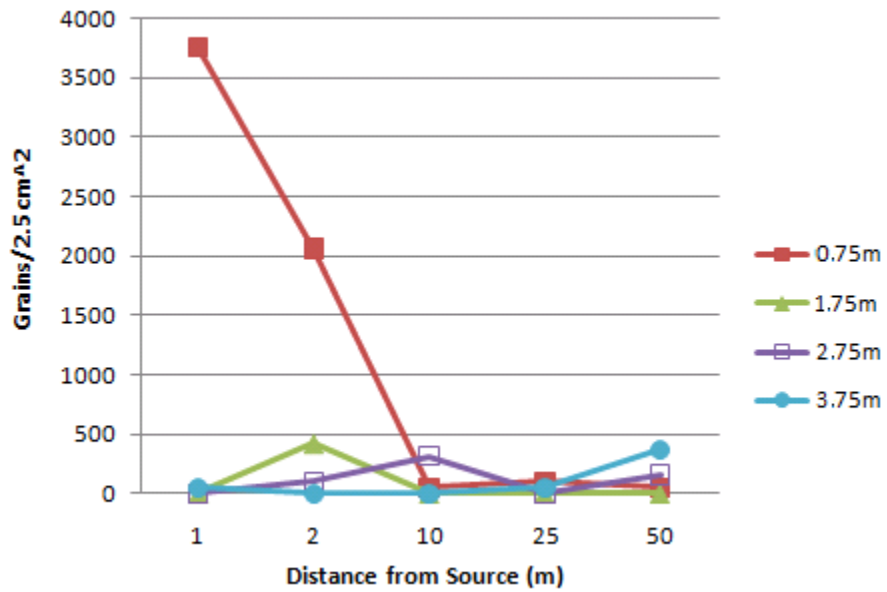
Appendix Figure 27. Amount of pollen captured on 6/24/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



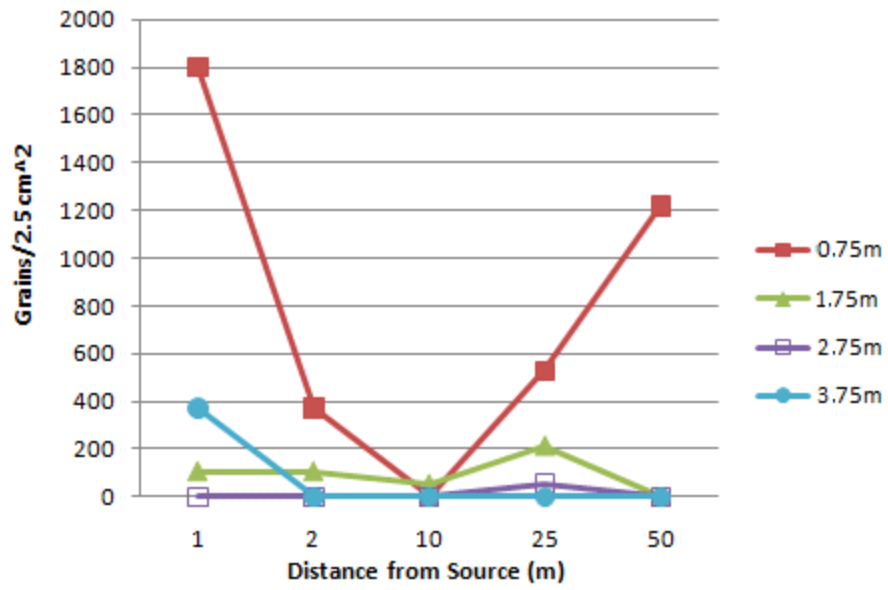
Appendix Figure 28. Amount of pollen captured on 6/26/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



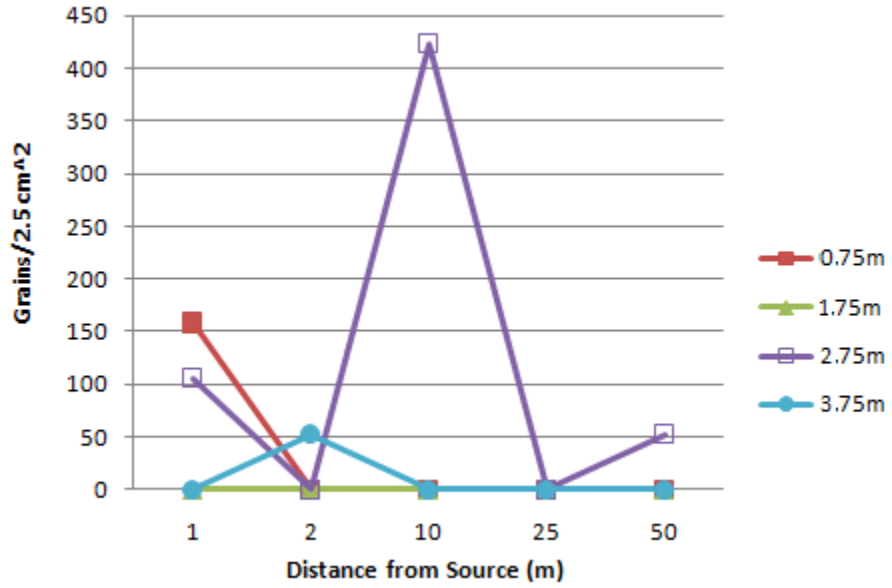
Appendix Figure 29. Amount of pollen captured on 7/7/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



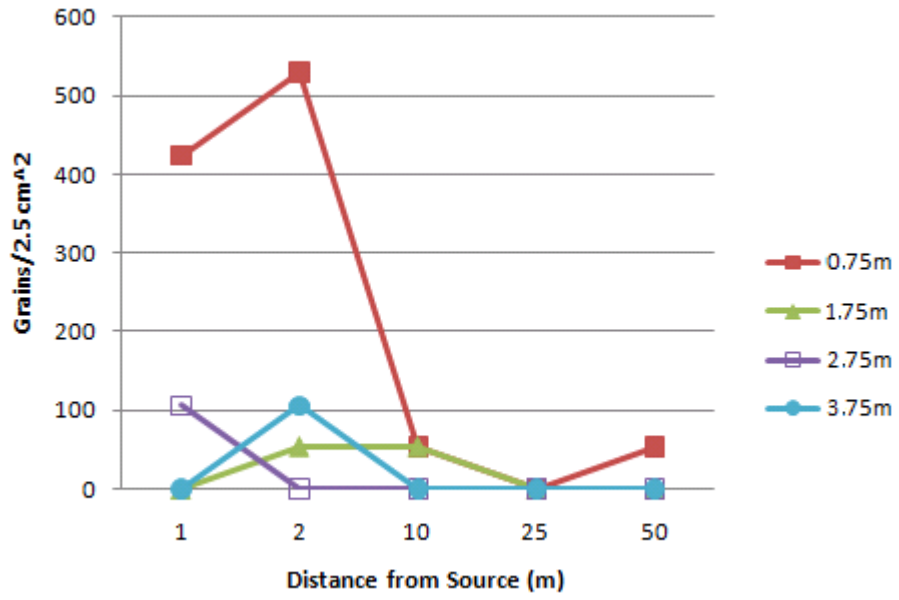
Appendix Figure 30. Amount of pollen captured on 7/8/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



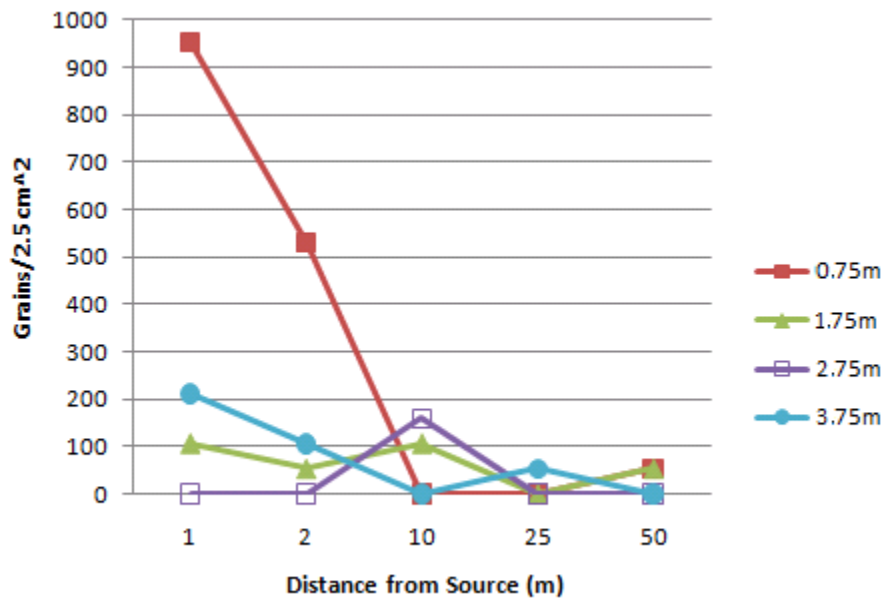
Appendix Figure 31. Amount of pollen captured on 7/10/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



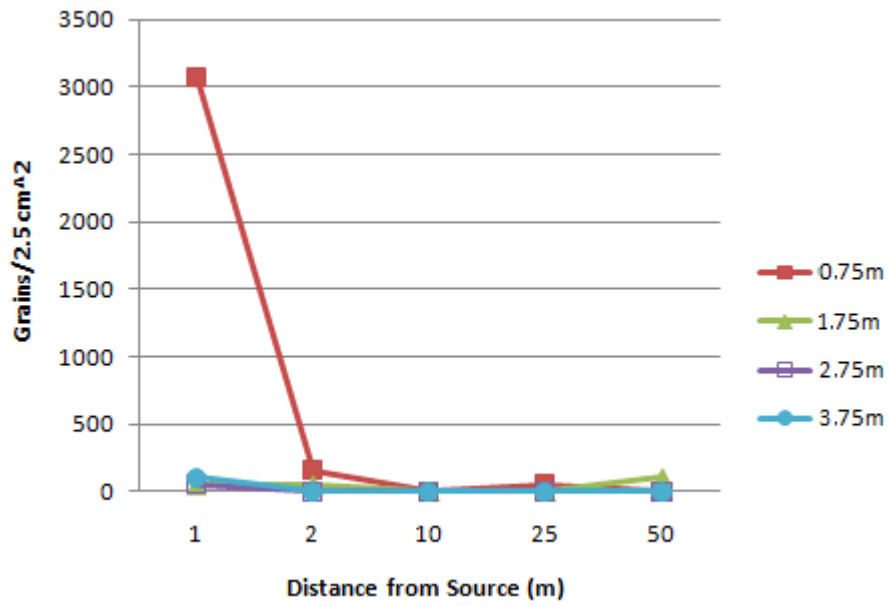
Appendix Figure 32. Amount of pollen captured on 7/14/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



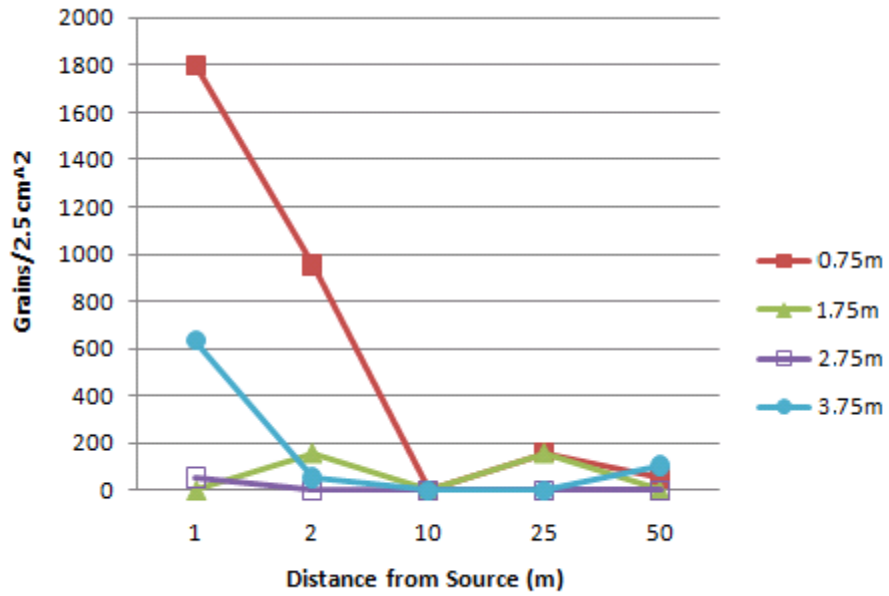
Appendix Figure 33. Amount of pollen captured on 7/15/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



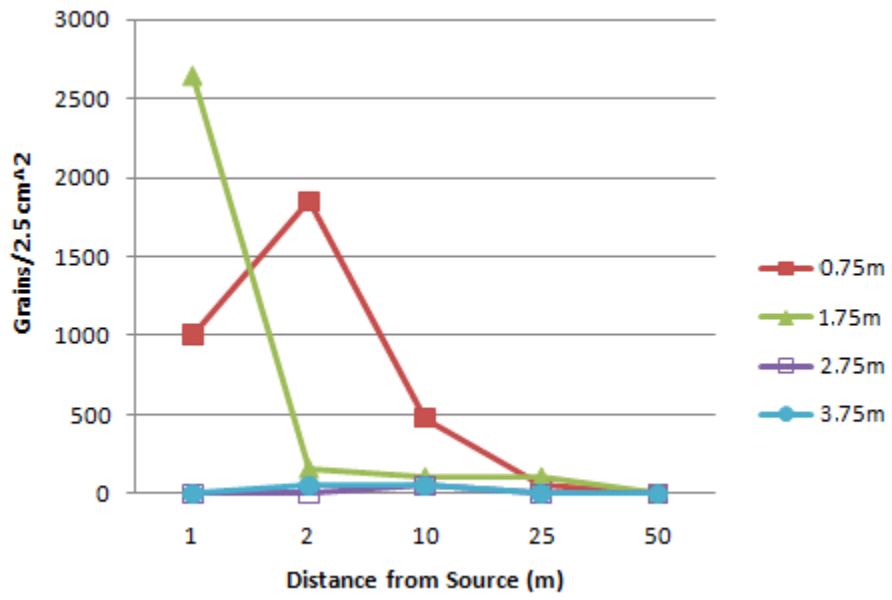
Appendix Figure 34. Amount of pollen captured on 7/16/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



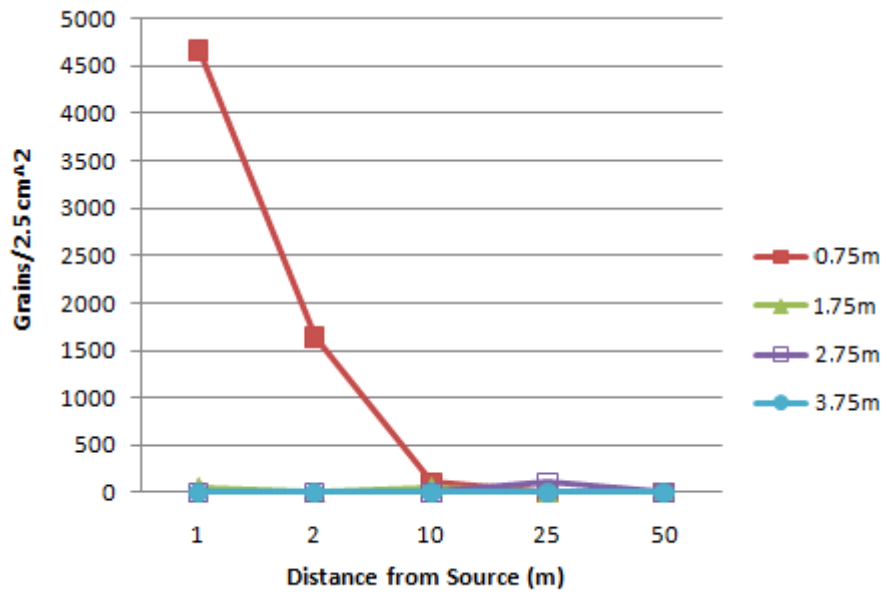
Appendix Figure 35. Amount of pollen captured on 7/18/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



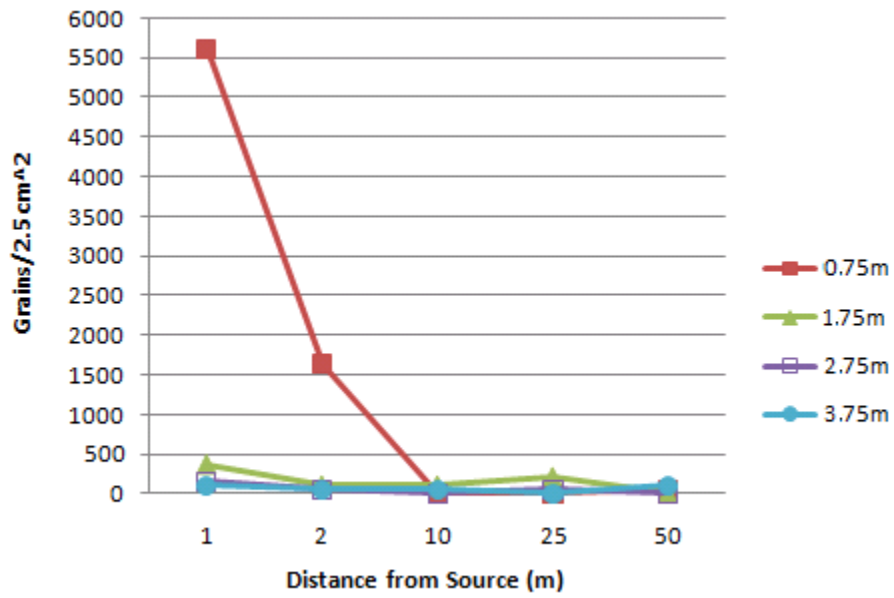
Appendix Figure 36. Amount of pollen captured on 7/23/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



Appendix Figure 37. Amount of pollen captured on 7/24/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



Appendix Figure 38. Amount of pollen captured on 7/27/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.



Appendix Figure 39. Amount of pollen captured on 7/30/2009. Pollen totals at each trap height and distance summed over cardinal and ordinal directions.

## CHAPTER 2

### Emergence and Shading Response Patterns of Solanaceous and Amaranthaceous Weeds

Allison M. Stark, David L. Jordan, Robert J. Richardson, Janet F. Spears, Alan C. York,  
Lingjuan Wang, Michael G. Burton, and Steve T. Hoyle

#### Abstract

Solanaceous and Amaranthaceous weed species are a major concern for corn, cotton, and soybean growers in North Carolina. Understanding germination patterns and other biology-related characteristics of these weeds could improve management. Emergence patterns of apple of Peru, cutleaf groundcherry, eastern black nightshade, and glyphosate-susceptible and resistant Palmer amaranth biotypes were investigated at two locations in North Carolina in corn and cotton (91 cm spacing) and soybean (narrow rows, 35 or 45 cm spacing versus wide rows 71 or 91 cm spacing). A cropping system by weed species interaction was observed in 2007 and 2008 at both locations for cumulative emergence when compared to both total emergence and total seeds planted. For both these comparisons, the main effect of weeks after planting (WAP) was significant at Kinston in 2008 and maximum emergence was reached at 7 WAP when means were pooled over weed species and cropping system. For cumulative emergence over total seeds planted, a significant weed species by WAP interaction for Kinston in 2007 showed that the emergence of apple of Peru and glyphosate-resistant Palmer amaranth was maximized at 1WAP, while cutleaf groundcherry and eastern blacknightshade was maximized at

4WAP and glyphosate-susceptible Palmer amaranth was maximized at 7WAP. For cumulative over total emergence, a significant weed species by WAP interaction was found in Goldsboro in 2007, where maximum emergence of all weed species occurred from 13 to 16 WAP. Goldsboro in 2007 also showed a cropping system by WAP interaction for cumulative over total emergence with maximum emergence being reached in all cropping systems between 13 and 16 WAP. The significance of the third order interaction of cropping system by weed species by WAP was observed for cumulative over total emergence in Goldsboro in 2008 and Kinston in 2007. In both cases, large F-values associated with WAP may be driving the third order interaction. In a second experiment in the greenhouse, ability of these weeds to withstand soybean canopy shading under 25 and 45 cm height was compared. The interaction of weed species by soybean height was significant; weed dry weight was reduced 40 to 81% when planted with the 45 cm tall soybean, whereas dry weight was reduced no more than 14% when planted with 25 cm tall soybean. Cutleaf groundcherry and eastern black nightshade biomass were reduced less by soybean than Palmer amaranth biotypes and apple of Peru when grown with 45 cm soybean.

Nomenclature: Apple of Peru, *Nicandra physalodes* L. Gaertn; corn, *Zea mays* L.; cotton, *Gossypium hirsutum* L.; cutleaf groundcherry, *Physalis angulata* L.; eastern black nightshade, *Solanum ptycanthum* Dunal; glyphosate; Palmer amaranth, *Amaranthus palmeri* S. Wats.; soybean, *Glycine max* L. Merr.

Key Words: Emergence, herbicide resistance, shade tolerance, weed management.

## Introduction

Cutleaf groundcherry, eastern black nightshade, and Palmer amaranth are prevalent in North Carolina and threaten productivity of agricultural production areas. Cutleaf groundcherry is native to North Carolina (USDA 2008). Vasconcellos et al. (1998) determined that cutleaf groundcherry clones grown in shaded conditions exhibited reduced stomatal numbers, thinned leaf lamina, and fragmented leaf vascularization when compared to counterparts in full sun. Stoller and Meyers (1989) reported eastern blacknightshade adaptations to reduced irradiance including lowered respiration rate and increased leaf area, making it well suited to shaded conditions when compared to other broadleaf weeds. Apple of Peru is a relatively new Solanaceous weed in North Carolina. Commonly used soybean herbicides, such as glyphosate and acetolactate synthase (ALS) inhibitors do not provide adequate control of apple of Peru (Doohan and Felix 2004).

Palmer amaranth, one of the top five most troublesome weeds in the southeastern U.S., is an aggressive dioecious summer annual weed with confirmed glyphosate-resistant biotypes distributed in North Carolina, Georgia (Culpepper et al. 2006; Culpepper et al. 2008), Arkansas (Norsworthy et al. 2008), Tennessee (Steckel et al. 2008), New Mexico, Alabama, Mississippi, and Missouri (Heap 2010). Resistance of Palmer amaranth to sulfonylurea, imidazolinone, dinitroaniline, and triazine herbicides has also been recorded (Heap 1997; Gosset et al. 1992; Horak and Peterson 1995). Yield reductions have been documented with as few as two Palmer amaranth plants/m of row in soybean (Klingman and Oliver 1994). Eight Palmer amaranth plants/m of row can result in 78% and 91% loss in yield for soybean and corn, respectively (Bensch et al. 2003; Massinga et al.

2003). Extensive interference in cotton has also been documented (Klingman and Oliver 1994; Massinga et al. 2001). Palmer amaranth is a prolific producer of seeds and grows efficiently at high temperatures (Guo and Al-Khatib 2003; Horak and Loughlin 2000; Hopkins 1999; Keeley et al. 1987). Dispersion of glyphosate-resistance genes via pollen-mediated gene flow can be as far as 300 m resulting in 20% to 40% glyphosate-resistant offspring (Sosnoskie et al. 2009).

Understanding germination patterns and other biological characteristics of Solanaceous and Amaranthaceous weeds may enable farmers to improve management approaches. Weeds emerging early in crop development reduce yields more than late-emerging weeds (Norsworthy et al. 2007; Steckel and Sprague 2004). Herbicides applied postemergence (POST) are generally more effective when applied to small weeds rather than larger weeds (Clayton et al. 2002; Gower et al. 2002; Harker et al. 2004; Johnson and Hoverstad 2002; Klingman et al. 1992; Martin et al. 2001; Wilcut and Swann 1990). Late-emerging weeds are less competitive due to greater crop canopy shading, a factor that can be compounded with the use of narrow row widths to decrease the time needed for canopy closure (Buehring et al. 2002; Norsworthy et al. 2007; Weber et al. 1966; Wells et al. 1993). While late-emerging weeds pose minimal threat to crop yields, seed production from these weeds will augment the weed seed bank, contributing to future infestations. Knowledge of weed emergence timing will allow herbicide applications to be coordinated more effectively.

Moran and Showler (2005) demonstrated that shade stress decreased Palmer amaranth height and mass. Eastern black nightshade seed set was reduced from 50,000 to less than

20,000 by soybean shading (Stoller and Meyers 1989). However, the ability of weeds such as cutleaf groundcherry and eastern black nightshade to physiologically adapt to shaded conditions increases their competitiveness with crops (Crotser et al. 2003; Stoller and Meyers 1989; Vasconcellos et al. 1998). Increasing prevalence of glyphosate-resistant biotypes of Palmer amaranth and occurrence of Solanaceous species poses an important challenge in weed management in North Carolina. Defining the competitive ability of these weeds emerging after crop emergence and comparing weed emergence patterns may contribute to weed management strategies. Therefore, research was conducted to compare emergence patterns of apple of Peru, cutleaf groundcherry, eastern blacknightshade, and Palmer amaranth biotypes in corn, cotton, and soybean and to compare the competitive ability of these weeds emerging after soybean emergence.

## Materials and Methods

Weed emergence experiment. The experiment was conducted in North Carolina during 2007 and 2008 at the Cherry Research Farm near Goldsboro and the Caswell Research Farm near Kinston. Soil at Goldsboro was a Goldsboro loamy sand (fine-loamy, siliceous, subactive, thermic Aquic Paleudults), while soil at Kinston was Kinston loam (fine-loamy, siliceous, semiactive, acid, and thermic Fluvaquentic Endoaquepts) (Soil Service Staff NRCS 2010). Crops were planted in conventionally tilled seedbeds and were not cultivated after planting. Treatments included four cropping systems based on crop and row spacing. Corn and cotton were planted with 91 cm row spacing, while soybean was planted in 35 and 45cm spacing or 71 and 91 cm spacing at Goldsboro and Kinston, respectively. Apple of Peru, cutleaf groundcherry, eastern blacknightshade, and two biotypes of Palmer amaranth were seeded to establish five weed seed planting sites for each crop in each replication. Glyphosate resistant cultivars of corn, cotton, soybean (35 and 45 cm spacings) and soybean (71 and 91 cm spacings) were established at in-row population of 5, 11, 20, and 36 plants/m, respectively. In 2007 for both locations, crop cultivars and planting dates were as follows: Pioneer 31G66<sup>1</sup> corn planted May 15, Asgrow 5905RR<sup>2</sup> soybeans planted June 7, and Stoneville 4357 B2RF<sup>3</sup> cotton planted May 15. In 2008 for both locations, crop cultivars and planting dates were as follows: Pioneer 33V16<sup>1</sup> corn planted May 6, Asgrow 5605RR<sup>2</sup> soybeans planted May 6, and Stoneville 4357 B2RF<sup>3</sup> cotton planted May 6. Emergence data were corrected for planting date differences so that weeks after planting designations are in relation to the crop planting dates for each location-year and may be compared across crops.

Palmer amaranth seed stocks were selected to include one confirmed glyphosate-susceptible and one confirmed glyphosate-resistant biotype from North Carolina (Whitaker 2009). At each weed seed planting site, seeds from a single weed species or biotype were mixed with steam sterilized soil collected from that field location and planted in the uppermost 2.5 cm of soil in a 10 by 10 cm central region of the 30 by 30 cm sheet metal planting enclosure. Metal planting enclosures were constructed from aluminum flashing 20 cm wide buried 10 cm deep in the inter-row space. One hundred seeds were planted per enclosure for each Solanaceous species and 200 seeds were planted per enclosure for each Palmer amaranth biotype.

Plot size for each replicate was 15 by 15 m, divided into four randomly assigned cropping systems with five weed species randomized within each crop. The experimental design was a split plot randomized complete block design with crop species as the whole-plot factor, weed species as the sub-plot factor, weeks after planting as the sub-sub-plot factor, and a single weed seed planting enclosure as the experimental unit. Weed seedlings in each planting enclosure were counted weekly and then hand removed at the soil surface to eliminate seedling competition. Planting enclosures were also cleared of plant debris and seedlings from other species either by hand removal or application of 2% v/v mixture of glyphosate. These measurements were continued until germination had ceased in all planting enclosures and both locations for three consecutive weeks. Weekly emergence data were grouped into time periods three weeks in length and referred to as weeks after planting (WAP). In 2007, the WAP spanned 25 weeks of data collection for a total of nine groups. Data collection began five weeks later in 2008 compared with

2007 due to weather conditions. Data for 2008 has been labeled to coincide with WAP dates from 2007, therefore only spanning 7 through 22 WAP.

Years and locations were not combined in analyses because of large disparities in the yearly weather patterns and field conditions (Soil Survey Staff NRCS 2010). Data for daily soil and air temperature and rainfall for each location during each year are presented in Figures 1 through 4. Separate datasets were constructed in order to understand cumulative emergence in relation to two factors: the total seeds planted in each enclosure and the total number of seedlings that emerged over the course of the experiment in that enclosure. The first dataset is the cumulative emergence as a percentage of the total seeds planted, while the second dataset is the cumulative emergence as a percentage of the total emergence.

Both datasets were subjected to analysis using the MIXED Procedure in SAS<sup>®</sup> Software v. 9.1<sup>4</sup>. Logarithmic regression was performed on cumulative emergence over total seeds planted in SAS v. 9.1 and means were separated using Fisher's Protected LSD at  $p \leq 0.05$ . Regression was not performed for the cumulative over total emergence due to concerns that regression equations would not accurately represent late-season emergence percentages, overestimating emergence as the maximum (100%) was reached. Comparison of means was chosen as a more accurate way to represent the emergence dynamics within the cumulative emergence as a percentage of total emergence dataset. These means were also separated using Fisher's Protected LSD at  $p \leq 0.05$ .

Shading experiment. Soybean canopies were established under greenhouse conditions in the North Carolina State University Method Road facility in Fall 2007 and Spring 2008.

Soybean (cv. USG 7732nRR<sup>5</sup>) was planted six and three weeks before weed seedling transplant in 20 cm diameter, 45 cm deep pots. Pots were filled with a commercial potting media<sup>6</sup> and maintained moist via sub-irrigation. Supplemental lighting was used to give a maximum daytime irradiance of 1200  $\mu\text{mol}$  per  $\text{m}^2\text{s}^{-1}$  photosynthetically active radiation at canopy level with a 12 h photoperiod. Soybean populations were thinned to 2 plants per pot. The experimental design was a split plot randomized complete block design with soybean height as the whole-plot factor and weed species as the split-plot factor arranged in four blocks. Treatments included apple of Peru, cutleaf groundcherry, eastern blacknightshade, and one glyphosate-resistant and one glyphosate-susceptible Palmer amaranth biotype (Whitaker, 2009) grown among soybean height treatments 25 cm and 45 cm tall. Each block also included a negative control treatment where weed species were grown in the absence of shading. In all treatments, four pots containing weeds were staggered between rows of five soybean pots. Weed species rows consisted of a single weed species planted at a density of one seedling per pot for a total of four weed seedlings per row. Treatments were arranged with one row of soybeans between each of the five weed species rows and two rows of soybeans at either end of the treatment. These additional rows of soybeans were used as a buffer intended to eliminate shade overlap between soybean height treatments. Biweekly water soluble fertilizer<sup>7</sup> treatments were applied via sub irrigation at a rate of 1 g/L. By planting weed seedlings at a rate of one seedling per pot with ample sub-irrigation, inter- and intra-specific competition for resources was minimized, isolating the effect of the shading treatments on weed seedling growth. After six weeks of shading, five soybean plants were randomly

selected from each treatment and block to determine stem diameter, runner length, and dry weight measurements. Final height, stem diameter (2.5 cm above soil level), and dry weight measurements for each weed species were also collected at this time. Plants were dried at 60°C for 72 h. Soybean treatment age at the time of harvest was 9 and 12 weeks for 25 and 45 cm tall treatments, respectively. Data were subjected to analysis in SAS Software v 9.1 using the MIXED procedure. Means were separated using Fisher's protected LSD test at  $p \leq 0.05$ .

## Results and Discussion

Emergence dynamics. Comparisons across years and field locations were not made due to disparities in environmental conditions and soil characteristics. When evaluating cumulative emergence of weeds as a percentage of total seeds planted, the main effects of cropping system and weed species were significant at both locations in 2007 and 2008 (Table 1). The interaction of cropping system by weed species was significant for both locations during 2007 and 2008. The main effect of WAP was significant at Kinston during both years but not at Goldsboro during either year. The interaction of weed species by WAP was significant only at Kinston during 2007.

When comparing cumulative emergence over total seeds planted within a cropping system across weed species, emergence in corn was equal (3 to 8%) for all weed species except eastern blacknightshade (1%) in Goldsboro in 2007 (Table 2). Weed emergence in cotton was greatest in cutleaf groundcherry and both Palmer amaranth biotypes. Emergence in soybean was equal for all weed species with the exception of those where zero germination was observed: apple of Peru and eastern blacknightshade in 71 and 35 cm spacing, respectively. In Goldsboro in 2008, weed emergence within cropping system across weed species in corn was greatest for apple of Peru, eastern blacknightshade, and glyphosate-resistant Palmer amaranth. Emergence of eastern blacknightshade in cotton was lowest when compared to all other weed species seeded in that crop. Comparing observations across weed species in soybean reveal that at 71 cm row spacing resulted in greatest emergence of both Palmer amaranth biotypes, whereas 35 cm row spacing glyphosate-susceptible Palmer amaranth alone had the greatest

emergence. In Kinston in 2007, weed emergence within cropping system was greatest for glyphosate-susceptible Palmer amaranth in all cropping systems, glyphosate-resistant Palmer amaranth in corn and soybean, and cutleaf groundcherry in cotton and soybean. Observations from Kinston in 2008 indicate that weed emergence was equal for all crops across all weed species. Investigation of the influence of the main effect of weeks after planting in Kinston in 2008 for the cumulative emergence over total seeds planted is shown in Table 3. When means are pooled over cropping system and weed species, emergence is maximized by 7 WAP in Kinston in 2008.

Means were pooled over cropping system in Kinston in 2007 to examine the weed species by WAP interaction (Table 1) and are located in Table 4. The analysis shows that weed emergence was maximized in apple of Peru and glyphosate-resistant Palmer amaranth at 1WAP, cutleaf groundcherry and eastern blacknightshade emergence were maximized at 4WAP, and glyphosate-susceptible Palmer amaranth emergence was maximized at 7WAP.

In addition to comparing cumulative emergence to the total seeds planted, data were also used to calculate the cumulative emergence as a percentage of the total emergence occurring over the course of the growing season. When evaluating the cumulative over total emergence, the main effects of cropping system and weed species were significant at both locations in 2007 and 2008 (Table 5). The interaction of weed species by cropping system was significant at both locations during 2007 and 2008. The main effect of WAP was also significant at both locations during 2007 and 2008. The interaction of cropping system by WAP was significant in both locations in 2007, but not in 2008. The

interaction of weed species by WAP was significant at Kinston in 2007 as well as during both years at Goldsboro. The third order interaction of weed species by cropping system by weeks after planting was significant in Goldsboro in 2008 and in Kinston in 2007.

Comparing cumulative over total emergence within a cropping system across weed species shows no significant difference between weed species within crop in Goldsboro in 2007 and in Kinston in 2008 (Table 6). Examination of the weed species by WAP interaction in Goldsboro in 2007 is shown in Table 7. Comparing cumulative over total emergence within a weed species across WAP shows that cutleaf groundcherry and glyphosate-susceptible Palmer amaranth emergence was maximized at 13 WAP whereas apple of Peru, eastern blacknightshade, and glyphosate-resistant Palmer amaranth emergence was maximized at 16 WAP. Investigation of the cropping system by WAP interaction (Table 5) in Goldsboro in 2007 shows that within cropping systems over WAP, cumulative over total emergence in corn, cotton, soybean (45 cm spacing), and soybean (91 cm spacing) was maximized at 13, 16, 16, and 13 WAP in Goldsboro in 2007 (Table 8). Means pooled across weed species and cropping systems in Kinston in 2008 indicate that weed emergence was maximized at 16 WAP (Table 9).

The significant third order interaction of weed species by cropping system by WAP in Goldsboro in 2008 and in Kinston in 2007 (Table 5) indicates that these variables do not vary consistently in relation to one another for cumulative over total emergence. The large F-values associated with WAP relative to the lesser F-values associated with cropping system and weed species suggest that the third order interaction may be driven by the WAP factor in both Goldsboro in 2008 and in Kinston in 2007.

Cumulative over total emergence was influenced by weed species, cropping system, and WAP in Goldsboro in 2008 (Table 10). Due to the calculation of the cumulative emergence as a percentage of total emergence for modeling, instances where zero total seedlings emerged result in a denominator of zero cause the variable to approach an infinite value, resulting in omission from analysis. An example is the case of glyphosate-susceptible Palmer amaranth in corn.

Examination of the third order interaction in Goldsboro in 2008 shows apple of Peru emergence was maximized at 16 WAP in all crops (Table 10). Weed emergence in cotton was maximized in cutleaf groundcherry and glyphosate-susceptible Palmer amaranth at 16WAP and in eastern blacknightshade and glyphosate-resistant Palmer amaranth at 13 WAP. Additionally, both Palmer amaranth biotypes maximized emergence at 16WAP in soybean cropping systems. Cutleaf groundcherry and eastern blacknightshade emergence was maximized at 13 WAP in the 35 cm soybean, while the 71 cm soybean spacing showed maximized emergence at 7 and 16 WAP (respectively). Examination of the third order interaction in Kinston in 2007 in Table 11 shows that in cotton and both soybean systems, no emergence was observed in any weed species before 7 WAP, while maximum emergence was achieved by 16 WAP in all cases.

The analysis reveals that emergence dynamics in these location-years are related to cropping system and weed species and are not explained by WAP alone, which is evident by significant second and third order interactions in Tables 1 and 5. In Kinston in 2007, data show that germination was maximized as early as 1WAP and as late as 7 WAP for cumulative emergence as a percentage of total seeds planted (Table 4), while in

Goldsboro in 2007, no weed species reached maximum emergence before the 13 to 16 WAP range (Table 7). Given the plasticity of germination observed in all weed species and cropping systems and the complex interactions seen in the experimental data, it would be prudent to regularly scout fields containing one or more of these weed species from 1 to 16 WAP. After 16 WAP, it may be possible to reduce the frequency of scouting since no significant weed emergence was observed after this time. Basing herbicide application events on these scouting observations will allow for herbicides to be timed soon after large cohorts of weed seedlings emerge, but before they become too large or produce seed. Overall, this research suggests that several herbicide applications may be needed to control emergence of Solanaceous and Amaranthaceous weeds in corn, cotton, and varying soybean cropping systems. Herbicide applications timing is crucial to effectively manage weed populations and avoid yield losses. Research has shown that yield losses in corn are more closely linked to timing of Palmer amaranth emergence than the number of plants that emerge (Massinga et al. 2001). Just a few large Palmer amaranth individuals can damage cotton harvesting equipment, leading to additional time and money spent on labor to repair equipment or remove large weeds (Morgan et al. 2001).

While no statistically significant increase in emergence was observed after 16 WAP in this study, this finding does not diminish the importance of late-season weed management. Even though late emerging weeds may not damage crop yields, they can contribute to the soil seed bank and add to future weed infestations. Herbicide applications to control late-season weeds are effective at reducing weed density (Johnson

and Hoverstad 2002), preventing seed rain from augmenting the soil seedbank.

Shading experiment. Data were pooled across the four blocks in each replicate and the four weed pots of the same species in each soybean height treatment. For the evaluation of percent reduction of weed dry weight, stem diameter, and height as influenced by soybean shading, the main effect of soybean height was significant for all variables (Table 12). The interaction of run and soybean height was significant for weed dry weight. The main effect of weed species was also significant for weed dry weight. Investigation of the effect of soybean height on percent reduction of weed stem diameter indicates that weed stem diameter was reduced by the 45 cm soybean height when compared to the 25 cm soybean height (94% versus 10% reduction) (Table 13). When comparing percent reduction across soybean height treatments, weed height was also reduced by the 45 cm soybean height group when compared to the 25 cm soybean height group (93% versus 9% reduction). Forty-five cm tall soybeans likely had greater influence than the 25 cm tall soybeans due the fact that larger soybean close canopy earlier and have larger total leaf area, leading to greater sunlight interception (Wells 1993).

When comparing weed dry weight reduction within soybean height treatments among weed species, weed dry weight was reduced 40 to 81% when planted with the 45 cm tall soybeans, whereas dry weight was reduced no more than 14% when planted with 25 cm tall soybeans (Table 14). When planted with the 45 cm soybean height, cutleaf groundcherry and eastern blacknightshade biomass were reduced less than apple of Peru and Palmer amaranth (40% to 46% versus 70% to 81%, respectively). These results are

reasonable given the documented ability of cutleaf groundcherry and eastern blacknightshade to physiologically adapt to shaded conditions (Stoller and Meyers 1989; Vasconcellos et al. 1998).

Collectively, results from these experiments suggest that emergence patterns of apple of Peru, cutleaf groundcherry, eastern black nightshade, and glyphosate-resistant and susceptible Palmer amaranth can vary depending on crop species and edaphic and environmental conditions. Cutleaf groundcherry and eastern black nightshade appeared to be affected less by shading when compared with apple of Peru or the two Palmer amaranth biotypes compared in this study, suggesting that these species may have a greater chance of tolerating shade from soybean and possibly other crops which may enhance long term viability in crop environments.

## Sources of Materials

- <sup>1</sup> Pioneer Hi-Bred International, Inc., PO Box 1000, Johnston, IA 50131-0184.
- <sup>2</sup> Asgrow ®, Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO 63167.
- <sup>3</sup> Stoneville ®, Bayer CropScience LP, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709.
- <sup>4</sup> Statistical Analysis Systems® Software v 9.1.3, SAS Institute Inc., SAS Campus Drive, Cary, NC, 27513.
- <sup>5</sup> Georgia Seed Development Commission, 2420 S. Milledge Ave., Athens, GA, 30605.
- <sup>6</sup> Fafard 2 Mix, Conrad Fafard, Inc., P.O. Box 790, Agawam, Mass., 01001-0790.
- <sup>7</sup> Peters Professional Water Soluble Fertilizer, Scotts-Sierra Horticultural Products Co., 1411 Scottslawn Rd., Marysville, OH, 43041.

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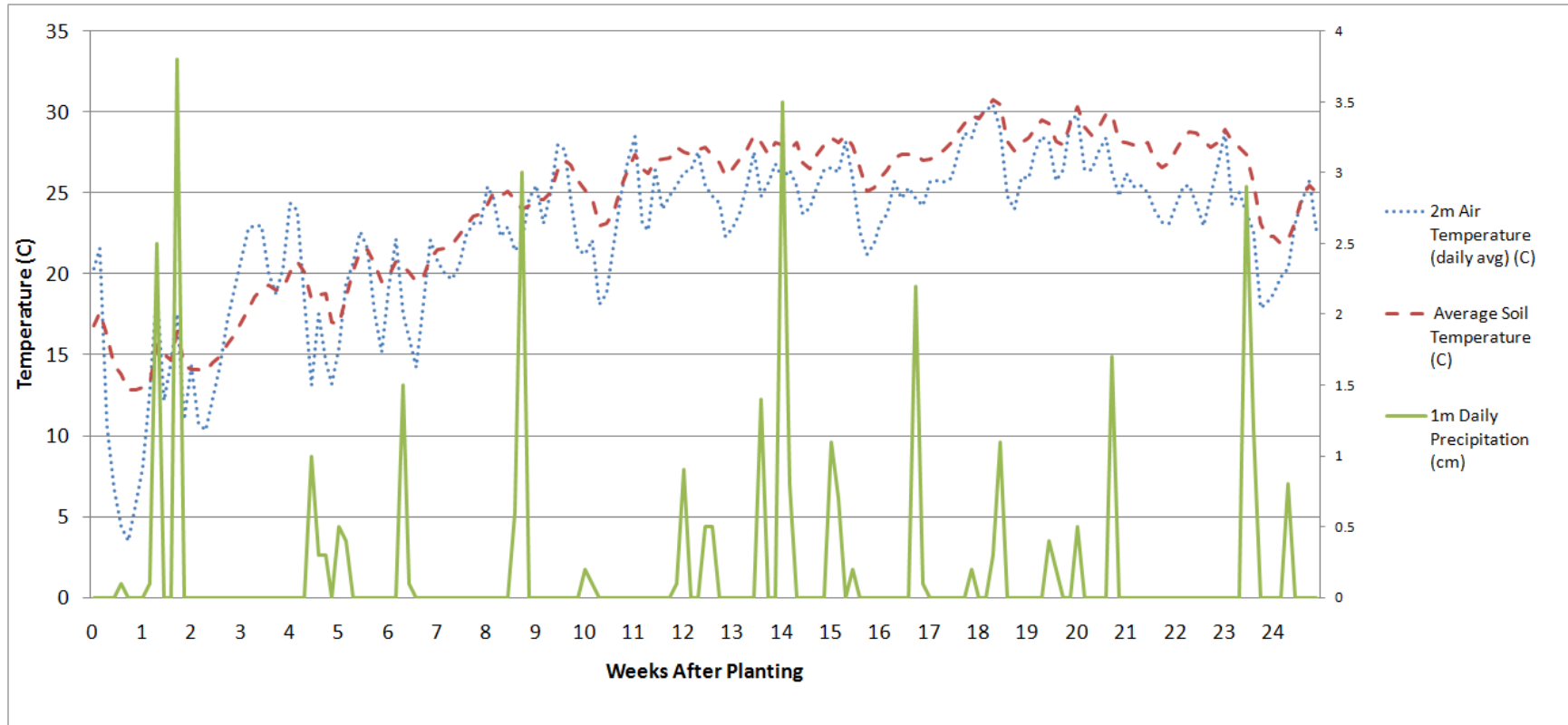


Figure 1. Goldsboro 2007; NC State Climate Office data for average daily air temperature, soil temperature, and precipitation at the Cherry Research Farm, Goldsboro, NC.

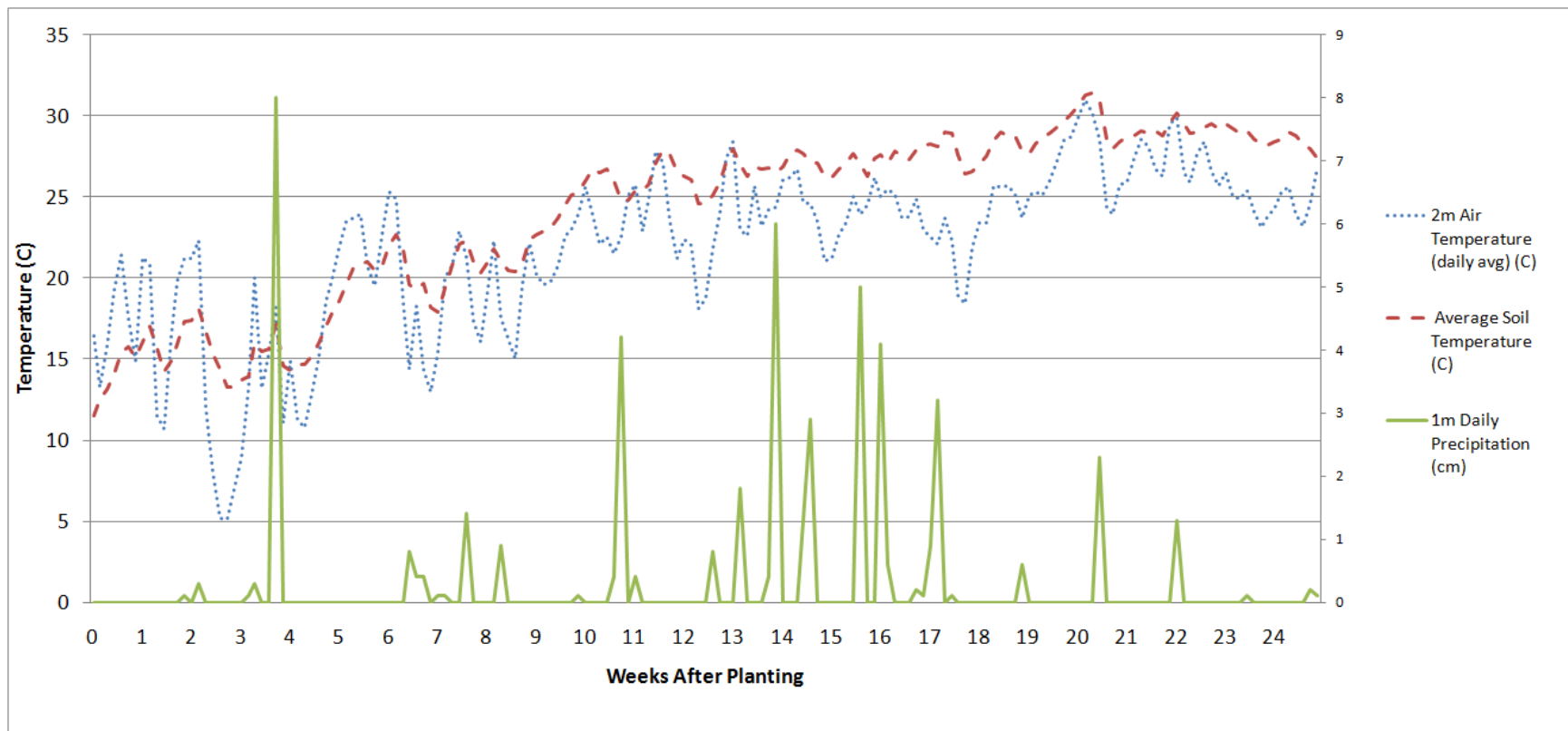


Figure 2. Kinston 2007; NC State Climate Office data for average daily air temperature, soil temperature, and precipitation at the Caswell Research Farm, Kinston, NC.

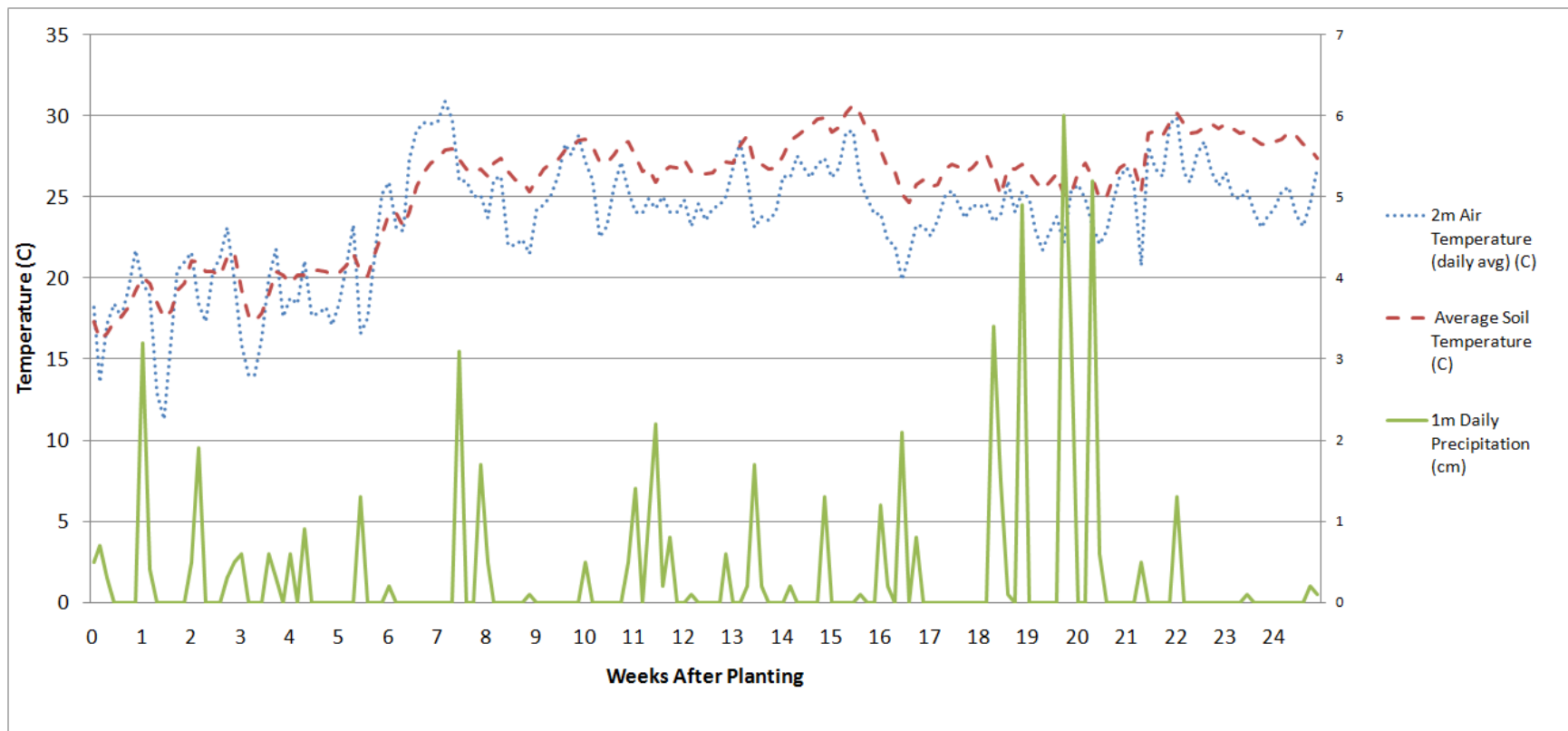


Figure 3. Goldsboro 2008; NC State Climate Office data for average daily air temperature, soil temperature, and precipitation at the Cherry Research Farm, Goldsboro, NC.

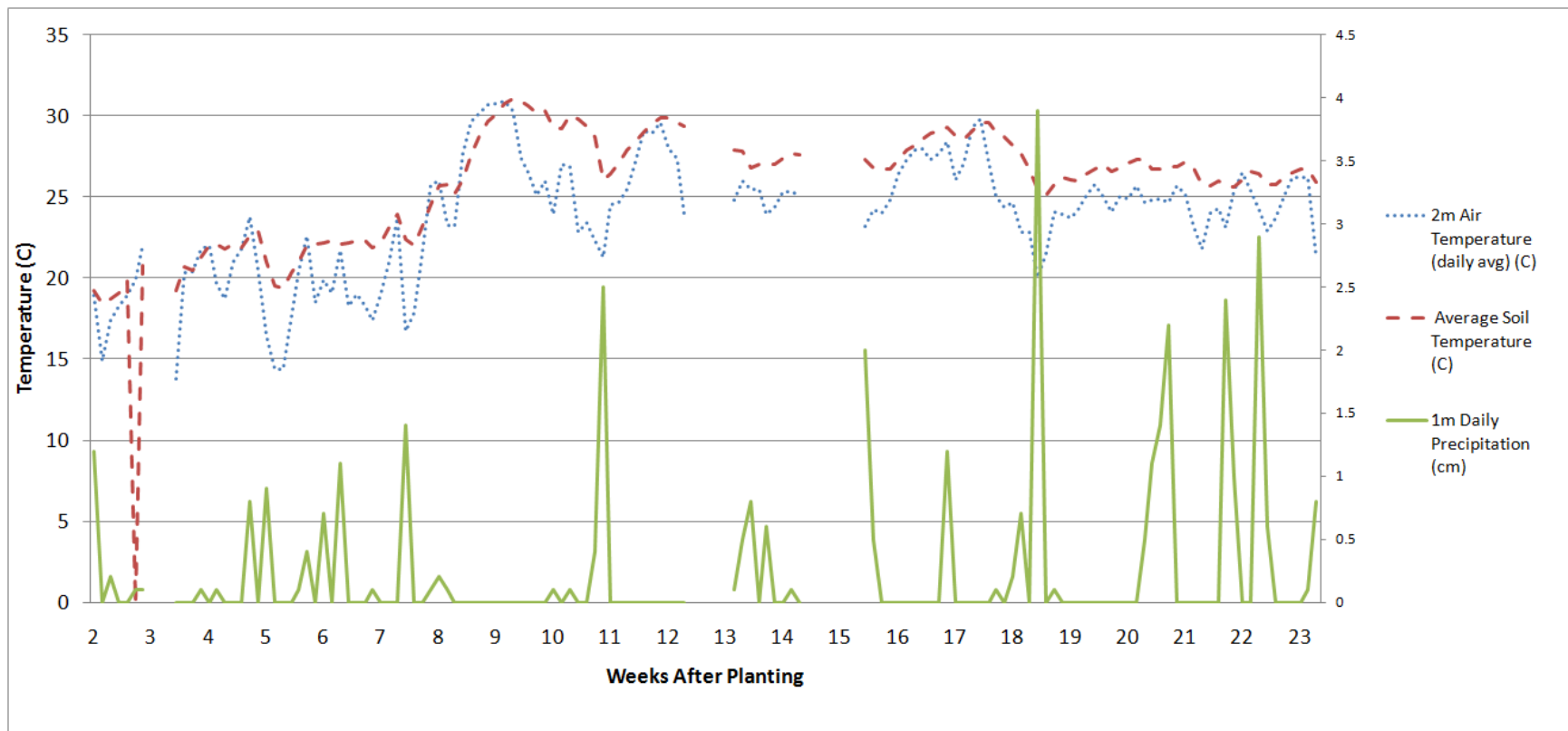


Figure 4. Kinston 2008; NC State Climate Office data for average daily air temperature, soil temperature, and precipitation at the Caswell Research Farm, Kinston, NC. Gaps within series denote missing data.

Table 1. Analysis of variance for cumulative emergence of weeds as a percentage of total seeds planted as influenced by weed species, cropping system, and weeks after planting for Goldsboro and Kinston during 2007 and 2008.<sup>a</sup>

Model Effect	Goldsboro				Kinston			
	2007		2008		2007		2008	
	F value	P > F	F value	P > F	F value	P > F	F value	P > F
Cropping system (Crop)	14.2	<0.0001	5.6	0.0010	8.8	<0.0001	9.7	<0.0001
Weed species	17.8	<0.0001	37.5	<0.0001	491.9	<0.0001	4.4	0.0019
Crop*Weed species	3.1	0.0007	6.3	<0.0001	34.5	<0.0001	5.8	<0.0001
Weeks after planting (WAP)	0.3	0.9711	0.3	0.8986	17.9	<0.0001	6.7	<0.0001
Crop*WAP	0.1	0.9999	0.1	0.9999	1.2	0.3035	0.4	0.9814
Weed species*WAP	0.4	0.9962	0.1	0.9999	3.3	<0.0001	0.9	0.5597
Weed species*Crop*WAP	0.1	0.9999	0.1	0.9999	0.4	0.9999	0.4	0.9999

<sup>a</sup> Values calculated using Proc Mixed.  $\alpha = 0.05$ ,  $p \leq 0.05$  indicates significance.

Table 2. Cumulative emergence of weeds as a percentage of total seeds planted as influenced by the interaction of cropping system and weed species at Goldsboro and Kinston during 2007 and 2008. <sup>a</sup>

Crop	Row spacing cm	Weed species					LSD (0.05)	CV (%)
		Apple of Peru	Cutleaf groundcherry	Eastern blacknightshade	Palmer amaranth			
					glyphosate resistant	glyphosate susceptible		
		%						
<i>Goldsboro, 2007</i>								
Corn	91	3	8	1	4	3	6	120
Cotton	91	0	6	0	1	1	5	227
Soybean	71	0	4	1	1	1	4	208
Soybean	35	1	1	0	1	1	1	165
<i>Goldsboro, 2008</i>								
Corn	91	18	0	10	13	0	8	71
Cotton	91	10	19	7	19	29	20	84

Table 2 Continued.

Soybean	71	6	4	3	16	20	10	71
Soybean	35	4	8	3	14	33	9	50
<i>Kinston, 2007</i>								
Corn	91	10	25	22	27	38	11	31
Cotton	91	6	64	7	35	42	34	79
Soybean	45	8	60	9	44	37	32	72
Soybean	91	5	65	3	46	40	33	73
<i>Kinston, 2008</i>								
Corn	91	7	12	11	5	4	8	75
Cotton	91	9	11	8	10	16	11	72
Soybean	45	6	12	8	13	17	13	86
Soybean	91	20	10	6	19	20	18	82

<sup>a</sup> LSD at  $p \leq 0.05$  designed to compare means within a cropping system and row width.

Table 3. Cumulative emergence of weed species as a percentage of total seeds planted pooled over weed species and cropping system for Kinston in 2008. <sup>a</sup>

	Weeks after planting						LSD (0.05)	CV (%)
	7	10	13	16	19	22		
	% —————							
Pooled mean	8	8	8	14	14	14	6	88

<sup>a</sup> LSD at  $p \leq 0.05$  designed to compare means pooled over cropping system and weed species.

Table 4. Cumulative emergence of weeds as a percentage of total seeds planted as influenced by weed species and weeks after planting in Kinston in 2007. <sup>a</sup>

Weed species	Weeks after planting									LSD (0.05)	CV (%)
	1	4	7	10	13	16	19	22	25		
	%										
<i>Kinston, 2007</i>											
Apple of Peru	6	9	10	10	11	11	11	11	11	5	34
Cutleaf groundcherry	2	28	28	28	28	29	29	29	29	6	16
Eastern blacknightshade	2	24	24	24	24	24	24	24	24	11	36
Palmer amaranth (resistant)	21	27	27	27	27	27	27	27	27	11	30
Palmer amaranth (susceptible)	8	10	46	48	48	48	48	48	48	17	30

<sup>a</sup>LSD at  $p \leq 0.05$  designed to compare means within a weed species.

Table 5. Analysis of variance for cumulative emergence of weeds as a percentage of total emergence as influenced by species, cropping system, and weeks after planting for Goldsboro and Kinston during 2007 and 2008.<sup>a</sup>

Model effect	Goldsboro				Kinston			
	2007		2008		2007		2008	
	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F	F Value	Pr > F
Cropping system (Crop)	47.3	<.0001	4.2	0.0061	260.0	<.0001	6.9	0.0002
Weed species	8.0	<.0001	37.5	<.0001	45.7	<.0001	5.7	0.0002
Crop*Weed species	2.5	0.0043	11.1	<.0001	1.9	0.0345	3.0	0.0004
Weeks after planting (WAP)	299.4	<.0001	50.8	<.0001	1293.7	<.0001	41.2	<.0001
Crop*WAP	11.7	<.0001	1.0	0.4352	70.7	<.0001	1.4	0.1438
Weed species*WAP	2.0	0.0022	8.2	<.0001	16.3	<.0001	1.3	0.1596
Weed species*Crop*WAP	1.2	0.1100	2.6	<.0001	4.6	<.0001	0.7	0.9605

<sup>a</sup> Values calculated using Proc Mixed.  $\alpha = 0.05$ ,  $p \leq 0.05$  indicates significance.

Table 6. Cumulative emergence of weeds as a percentage of total emergence as influenced by weed species and cropping system for Goldsboro in 2007 and Kinston in 2008. <sup>a</sup>

Crop	Row spacing cm	Weed species					LSD (0.05)	CV (%)
		Apple of Peru	Cutleaf groundcherry	Eastern blacknightshade	Palmer amaranth			
					glyphosate resistant	glyphosate susceptible		
<i>Goldsboro, 2007</i>								
Corn	91	59	72	78	64	78	58	60
Cotton	91	44	54	50	47	56	72	100
Soybean	35	28	52	44	48	51	70	104
Soybean	71	56	56	100	66	56	70	86
<i>Kinston, 2008</i>								
Corn	91	82	88	100	92	99	23	18
Cotton	91	80	96	94	90	70	37	31
Soybean	45	90	90	90	77	77	40	33
Soybean	91	87	88	82	68	70	46	41

<sup>a</sup> LSD at  $p \leq 0.05$  designed to compare means within a cropping system and row width.

Table 7. Cumulative emergence of weeds as a percentage of total emergence as influenced by weeks after planting and weed species during Goldsboro in 2007. <sup>a</sup>

Weed species	Weeks after planting									LSD (0.05)	CV (%)
	1	4	7	10	13	16	19	22	25		
	%										
<i>Goldsboro, 2007</i>											
Apple of Peru	0	5	24	24	46	88	88	88	100	40	55
Cutleaf groundcherry	0	3	18	18	87	100	100	100	100	27	32
Eastern blacknightshade	0	0	14	14	29	100	100	100	100	34	47
Palmer amaranth (resistant)	0	7	18	18	52	97	100	100	100	35	45
Palmer amaranth (susceptible)	0	17	24	24	84	99	99	99	100	34	40

<sup>a</sup> LSD at  $p \leq 0.05$  designed to compare means within a weed species.

Table 8. Cumulative emergence of weeds as a percentage of total emergence as influenced by cropping system and weeks after planting in Goldsboro in 2007. <sup>a</sup>

Crop	Row spacing	Weeks after planting									LSD (0.05)	CV (%)
		1	4	7	10	13	16	19	22	25		
	cm	%										
<i>Goldsboro, 2007</i>												
Corn	91	0	21	65	65	79	96	96	96	100	34	35
Cotton	91	0	0	0	0	56	100	100	100	100	24	33
Soybean	45	0	0	0	0	39	95	97	97	100	24	36
Soybean	91	0	7	7	7	98	100	100	100	100	17	21

<sup>a</sup> LSD at  $p \leq 0.05$  designed to compare means within a cropping system and row width.

Table 9. Cumulative emergence of weed species as a percentage of total emergence pooled over weed species and cropping system for Kinston in 2008. <sup>a</sup>

	Weeks after planting						LSD (0.05)	CV (%)
	7	10	13	16	19	22		
	% —————							
Pooled mean	69	69	76	100	100	100	15	28

<sup>a</sup> LSD at  $p \leq 0.05$  designed to compare means pooled over cropping system and weed species.

Table 10. Cumulative emergence of weeds as a percentage of total emergence as influenced by weed species, cropping system, and weeks after planting in Goldsboro in 2008. <sup>a</sup>

Crop	Row spacing	Weed species	Weeks after planting						LSD (0.05)	CV (%)
			7	10	13	16	19	22		
	cm		%							
Corn	91	Apple of Peru	82	84	91	100	100	100	2	5
		Cutleaf groundcherry	0	0	0	100	100	100	.	.
		Eastern blacknightshade	87	87	90	97	98	100	7	15
		Palmer amaranth (resistant)	89	89	91	96	100	100	4	8
		Palmer amaranth (susceptible)	.	.	.	.	.	.	.	.
		LSD (0.05)	7	7	6	3	1	0		
		CV (%)	18	18	13	5	2	0		
Cotton	91	Apple of Peru	27	27	32	100	100	100	7	22
		Cutleaf groundcherry	97	97	97	100	100	100	2	4
		Eastern blacknightshade	70	70	100	100	100	100	14	31

Table 10 Continued.

		Palmer amaranth (resistant)	81	81	96	100	100	100	7	14
		Palmer amaranth (susceptible)	92	92	93	100	100	100	2	5
		LSD (0.05)	24	24	8	0	0	0		
		CV (%)	35	35	11	0	0	0		
Soybean	35	Apple of Peru	33	33	71	100	100	100	12	32
		Cutleaf groundcherry	94	94	100	100	100	100	4	7
		Eastern blacknightshade	83	83	100	100	100	100	7	14
		Palmer amaranth (resistant)	96	96	97	100	100	100	2	4
		Palmer amaranth (susceptible)	95	95	95	100	100	100	2	4
		LSD (0.05)	9	9	6	0	0	0		
		CV (%)	21	21	14	0	0	0		
Soybean	71	Apple of Peru	31	31	33	100	100	100	15	47
		Cutleaf groundcherry	100	100	100	100	100	100	0	0
		Eastern blacknightshade	87	87	92	100	100	100	6	12

Table 10 Continued.

Palmer amaranth (resistant)	85	85	93	100	100	100	3	6
Palmer amaranth (susceptible)	96	96	96	100	100	100	1	2
LSD (0.05)	10	10	11	0	0	0		
CV (%)	26	26	27	0	0	0		

<sup>a</sup> LSD at  $p \leq 0.05$  designed to compare means within cropping system and weed species across weeks after planting as well as within cropping system and weeks after planting across weed species.

Table 11. Cumulative emergence of weeds as a percentage of total emergence as influenced by weed species, cropping system, and weeks after planting in Kinston in 2007. <sup>a</sup>

Crop	Row spacing cm	Weed species	Weeks after planting									LSD (0.05)	CV (%)
			1	4	7	10	13	16	19	22	25		
			%										
Corn	91	Apple of Peru	52	79	88	88	100	100	100	100	100	6	14
		Cutleaf groundcherry	6	94	94	95	96	99	100	100	100	3	7
		Eastern blacknightshade	6	100	100	100	100	100	100	100	100	1	2
		Palmer amaranth (resistant)	78	98	100	100	100	100	100	100	100	1	2
		Palmer amaranth (susceptible)	88	99	100	100	100	100	100	100	100	1	2
		LSD (0.05)	5	7	4	4	1	0	0	0	0		
		CV (%)	0	15	8	7	3	1	0	0	0		
Cotton	91	Apple of Peru	0	0	25	80	97	97	100	100	100	6	17
		Cutleaf groundcherry	0	0	40	97	99	100	100	100	100	4	10
		Eastern blacknightshade	0	0	21	61	98	100	100	100	100	9	29

Table 11 Continued.

		Palmer amaranth (resistant)	0	0	70	99	100	100	100	100	100	4	11
		Palmer amaranth (susceptible)	0	0	93	99	100	100	100	100	100	0	1
		LSD (0.05)	0	0	10	13	1	1	0	0	0		
		CV (%)	.	.	41	29	3	2	0	0	0		
Soybean	45	Apple of Peru	0	0	19	72	100	100	100	100	100	5	14
		Cutleaf groundcherry	0	0	51	99	100	100	100	100	100	3	8
		Eastern blacknightshade	0	0	34	65	100	100	100	100	100	9	27
		Palmer amaranth (resistant)	0	0	89	99	100	100	100	100	100	1	3
		Palmer amaranth (susceptible)	0	0	92	99	100	100	100	100	100	1	2
		LSD (0.05)	0	0	9	11	0	0	0	0	0		
		CV (%)	.	.	31	26	0	0	0	0	0		
Soybean	91	Apple of Peru	0	0	38	82	100	100	100	100	100	6	16
		Cutleaf groundcherry	0	0	61	96	99	99	100	100	100	4	10
		Eastern blacknightshade	0	0	8	64	100	100	100	100	100	5	16

Table 11 Continued.

Palmer amaranth (resistant)	0	0	87	100	100	100	100	100	100	1	2
Palmer amaranth (susceptible)	0	0	94	99	100	100	100	100	100	1	1
LSD (0.05)	0	0	9	7	0	0	0	0	0		
CV (%)	.	.	30	16	1	1	0	0	0		

<sup>a</sup> LSD at  $p \leq 0.05$  designed to compare means within cropping system and weed species across weeks after planting as well as within cropping system and weeks after planting across weed species.

Table 12. Analysis of variance for percent reduction of dry weight, stem diameter, and height of weeds as influenced by soybean size. <sup>a</sup>

Treatment factor	Percent reduction		
	Dry weight	Stem diameter	Height
	p-value		
Replication	0.0676	0.0540	0.1669
Soybean height	0.0002	<0.0001	<0.0001
Replication *Soybean height	0.0430	0.3904	0.6019
Weed species	0.0230	0.6236	0.3671
Replication *Weed species	0.8511	0.7059	0.8517
Soybean height*Weed species	0.0554	0.6552	0.7738
Replication *Soybean height*Weed species	0.8102	0.2772	0.8894
CV (95%)	69	49	59

<sup>a</sup> Values calculated using Proc Mixed and pooled over Fall 2007 and Spring 2008 and analyzed with proper error terms,  $\alpha = 0.05$ .

Table 13. Stem diameter and height reduction values for weeds grown among each soybean height group. <sup>a</sup>

Soybean height (cm)	Reduction	
	Stem diameter	Height
	————— % —————	
25	10	9
45	94	93
P > F	< 0.0001	< 0.0001

<sup>a</sup> Data are pooled over experiments and weed species and analyzed with Proc Mixed,  $\alpha = 0.05$ .

Table 14. Dry weight reduction by soybean height. <sup>a</sup>

Weed species	Weed dry weight reduction by soybean height (cm)	
	25	45
	————— % —————	
Apple of Peru	0 a	81 a
Cutleaf groundcherry	6 a	40 b
Eastern blacknightshade	3 a	46 b
Palmer amaranth (resistant)	14 a	80 a
Palmer amaranth (susceptible)	7 a	70 a

<sup>a</sup> Means within shading regimes followed by the same letter are not significantly different ( $p \leq 0.05$ ) according to Fisher's Protected LSD Test. Data are pooled over experiments.

## APPENDIX 2

Appendix Table 1. Cumulative emergence of weeds as a percentage of total seeds planted as influenced by weed species, cropping system, and time after planting in Goldsboro in 2007. <sup>a</sup>

Crop	Row spacing cm	Weed species	Weeks after planting									LSD (0.05)	CV (%)	Regression equation	R <sup>2</sup>	p-value	
			1	4	7	10	13	16	19	22	25						
			%														
Corn	91	Apple of Peru	0	1	3	3	3	3	3	3	4	2	92	$y = 0.018 * \log \{ x * \exp (-0.001/0.018) \}$	0.27	0.0012	
		Cutleaf groundcherry	0	1	7	7	11	11	11	11	11	4	71	$y = 0.02 * \log \{ x * \exp (0.033/0.02) \}$	0.39	<.0001	
		Eastern blacknightshade	0	0	1	1	1	1	1	1	1	2	227	$y = 0.006 * \log \{ x * \exp (0.001/0.006) \}$	0.05	0.1917	
		Palmer amaranth (resistant)	0	1	4	4	4	5	5	5	5	4	163	$y = 0.02 * \log \{ x * \exp (0.008/0.02) \}$	0.09	0.0827	
		Palmer amaranth (susceptible)	0	2	3	3	3	4	4	4	4	2	108	$y = 0.012 * \log \{ x * \exp (0.013/0.012) \}$	0.14	0.0227	
		LSD (0.05)	0	1	1	1	1	2	2	2	2						
		CV (%)	.	174	116	116	103	102	102	102	99						

Appendix Table 1 Continued.

Cotton	91	Apple of Peru	0	0	0	0	0	1	1	1	1	0	173	$y = 0.004 * \log \{ x * \exp (-0.004/0.004) \}$	0.21	0.0050
		Cutleaf groundcherry	0	0	0	0	10	11	11	11	11	4	103	$y = 0.022 * \log \{ x * \exp (0.037/0.022) \}$	0.35	0.0001
		Eastern blacknightshade	0	0	0	0	0	1	1	1	1	0	168	$y = 0.004 * \log \{ x * \exp (-0.004/0.004) \}$	0.21	0.0050
		Palmer amaranth (resistant)	0	0	0	0	0	1	1	1	1	0	62	$y = 0.009 * \log \{ x * \exp (-0.009/0.009) \}$	0.50	<.0001
		Palmer amaranth (susceptible)	0	0	0	0	1	1	1	1	1	1	135	$y = 0.011 * \log \{ x * \exp (-0.01/0.011) \}$	0.25	0.0018
		LSD (0.05)	0	0	0	0	1	1	1	1	1					
		CV (%)	.	.	.	.	177	128	128	128	128					
Soybean	35	Apple of Peru	0	0	0	0	0	0	0	0	1	0	317	$y = 0.003 * \log \{ x * \exp (-0.003/0.003) \}$	0.21	0.0050
		Cutleaf groundcherry	0	0	0	0	5	6	6	6	6	3	139	$y = 0.017 * \log \{ x * \exp (0.028/0.017) \}$	0.35	0.0001

Appendix Table 1 Continued.

	Eastern blacknightshade	0	0	0	0	0	1	1	1	1	0	60	$y = 0.011 * \log \{ x * \exp (-0.011/0.011) \}$	0.21	0.0050	
	Palmer amaranth (resistant)	0	0	0	0	1	1	1	1	1	0	89	$y = 0.012 * \log \{ x * \exp (-0.011/0.012) \}$	0.50	<.0001	
	Palmer amaranth (susceptible)	0	0	0	0	2	2	2	2	2	1	112	$y = 0.02 * \log \{ x * \exp (-0.018/0.02) \}$	0.25	0.0018	
	LSD (0.05)	0	0	0	0	1	1	1	1	1						
	CV (%)	.	.	.	.	181	134	132	132	130						
Soybean	71	Apple of Peru	0	0	0	0	1	1	1	1	1	155	$y = 0.009 * \log \{ x * \exp (-0.008/0.009) \}$	0.09	0.0721	
		Cutleaf groundcherry	0	0	0	0	2	2	2	2	2	1	96	$y = 0.004 * \log \{ x * \exp (0.006/0.004) \}$	0.25	0.0018
		Eastern blacknightshade	0	0	0	0	0	0	0	0	0	.	$y = 0 * \log \{ x * \exp (0/0) \}$	0.48	<.0001	
		Palmer amaranth (resistant)	0	1	1	1	1	1	1	1	1	186	$y = 0.003 * \log \{ x * \exp (0.002/0.003) \}$	0.43	<.0001	

Appendix Table 1 Continued.

Palmer amaranth (susceptible)	0	0	0	0	1	1	1	1	1	1	123	$y = 0.01 * \log \{ x * \exp(-0.009/0.01) \}$	0.34	0.0002
LSD (0.05)	0	0	0	0	1	1	1	1	1					
CV (%)	.	447	447	447	112	116	116	116	116					

<sup>a</sup> LSD at  $p \leq 0.05$  designed to compare means within cropping system and weed species across time after planting as well as within cropping system and time after planting across weed species.

Appendix Table 2. Cumulative emergence of weeds as a percentage of total seeds planted as influenced by weed species, cropping system, and time after planting in Goldsboro 2008. <sup>a</sup>

Crop	Row spacing cm	Weed species	Weeks after planting						LSD (0.05)	CV (%)	Regression equation	R <sup>2</sup>	p-value
			7	10	13	16	19	22					
			————— % —————										
Corn	91	Apple of Peru	16	17	18	20	20	20	7	71	$y = 0.043 * \log \{ x * \exp (0.112/0.043) \}$	0.02	0.5540
		Cutleaf groundcherry	0	0	0	1	1	1	1	283	$y = 0.006 * \log \{ x * \exp (0.01/0.006) \}$	0.11	0.1207
		Eastern blacknightshade	9	9	9	10	11	11	3	62	$y = 0.023 * \log \{ x * \exp (0.059/0.023) \}$	0.02	0.4896
		Palmer amaranth (resistant)	12	12	12	13	14	14	2	24	$y = 0.021 * \log \{ x * \exp (0.092/0.021) \}$	0.06	0.2347
		Palmer amaranth (susceptible)	0	0	0	0	0	0	0	.	$y = 0 * \log \{ x * \exp (0/0) \}$	.	.
		LSD (0.05)	3	3	3	4	4	4					

Appendix Table 2 Continued.

		CV (%)	79	79	79	81	80	80					
Cotton	91	Apple of Peru	4	4	5	16	16	16	3	63	$y = 0.154 * \log \{ x * \exp (-0.151/0.154) \}$	0.40	0.0009
		Cutleaf groundcherry	19	19	19	20	20	20	11	0	$y = 0.122 * \log \{ x * \exp (0.205/0.122) \}$	0.00	0.8751
		Eastern blacknightshade	7	7	8	8	8	8	3	0	$y = 0.012 * \log \{ x * \exp (0.054/0.012) \}$	0.01	0.6994
		Palmer amaranth (resistant)	18	18	18	20	20	20	9	0	$y = 0.026 * \log \{ x * \exp (0.148/0.026) \}$	0.00	0.7892
		Palmer amaranth (susceptible)	28	28	29	30	30	30	10	0	$y = 0.021 * \log \{ x * \exp (0.257/0.021) \}$	0.00	0.8529
		LSD (0.05)	8	8	8	8	8	8					
		CV (%)	99	99	96	88	88	88					

Appendix Table 2 Continued.

Soybean	35	Apple of Peru	4	4	5	8	8	8	4	131	$y = 0.045 * \log \{ x * \exp (-0.015/0.045) \}$	0.05	0.3071
		Cutleaf groundcherry	4	4	5	5	5	5	2	71	$y = 0.017 * \log \{ x * \exp (0.029/0.017) \}$	0.00	0.8616
		Eastern blacknightshade	3	3	3	3	3	3	2	142	$y = 0.003 * \log \{ x * \exp (0.022/0.003) \}$	0.00	0.8848
		Palmer amaranth (resistant)	16	16	16	17	17	17	2	24	$y = 0.008 * \log \{ x * \exp (0.149/0.008) \}$	0.01	0.7162
		Palmer amaranth (susceptible)	20	20	20	21	21	21	7	72	$y = 0.01 * \log \{ x * \exp (0.188/0.01) \}$	0.00	0.9067
		LSD (0.05)	4	4	4	4	4	4					
		CV (%)	83	83	80	79	79	79					
Soybean	71	Apple of Peru	3	3	3	5	5	5	2	108	$y = 0.026 * \log \{ x * \exp (-0.007/0.026) \}$	0.06	0.2428
		Cutleaf groundcherry	8	8	8	8	8	8	1	38	$y = 0.016 * \log \{ x * \exp (0.027/0.016) \}$	0.00	1.0000

Appendix Table 2 Continued.

Eastern blacknightshade	3	3	3	3	3	3	1	47	$y = 0.006 * \log \{ x * \exp (0.018/0.006) \}$	0.03	0.3949
Palmer amaranth (resistant)	13	13	14	15	15	15	5	68	$y = 0.023 * \log \{ x * \exp (0.103/0.023) \}$	0.01	0.6671
Palmer amaranth (susceptible)	33	33	33	34	34	34	6	33	$y = 0.016 * \log \{ x * \exp (0.307/0.016) \}$	0.00	0.7958
LSD (0.05)	3	3	3	4	4	4					
CV (%)	58	58	57	55	55	56					

<sup>a</sup> LSD at  $p < 0.05$  designed to compare means within cropping system and weed species across time after planting as well as within cropping system and time after planting across weed species.

Appendix Table 3. Cumulative emergence of weeds as a percentage of total seeds planted as influenced by weed species, cropping system, and time after planting in Kinston 2007. <sup>a</sup>

Crop	Row spacing cm	Weed species	Weeks after planting									LSD (0.05)	CV (%)	Regression equation	R <sup>2</sup>	p-value
			1	4	7	10	13	16	19	22	25					
Corn	91	Apple of Peru	6	9	10	10	11	11	11	11	11	2	34	$y = 0.012 * \log \{ x * \exp (0.083/0.012) \}$	0.19	0.0076
		Cutleaf groundcherry	2	28	28	28	28	29	29	29	29	3	16	$y = 0.014 * \log \{ x * \exp (0.023/0.014) \}$	0.53	<.0001
		Eastern blacknightshade	2	24	24	24	24	24	24	24	24	.	36	$y = 0 * \log \{ x * \exp (0.24/0) \}$	0.29	0.0007
		Palmer amaranth (resistant)	21	27	27	27	27	27	27	27	27	6	30	$y = 0.004 * \log \{ x * \exp (0.266/0.004) \}$	0.04	0.2389
		Palmer amaranth (susceptible)	34	38	38	38	38	38	38	38	38	6	19	$y = 0.002 * \log \{ x * \exp (0.379/0.002) \}$	0.03	0.3059
		LSD (0.05)	3	5	5	5	5	5	5	5	5					

Appendix Table 3 Continued.

		CV (%)	34	27	27	26	26	25	25	25	25					
Cotton	91	Apple of Peru	0	0	2	7	8	8	9	9	9	1	34	$y = 0.061 * \log \{ x * \exp (-0.034/0.061) \}$	0.71	<.0001
		Cutleaf groundcherry	0	0	37	87	90	91	91	91	91	9	19	$y = 0.071 * \log \{ x * \exp (0.119/0.071) \}$	0.78	<.0001
		Eastern blacknightshade	0	0	6	9	10	11	11	11	11	9	163	$y = 0.066 * \log \{ x * \exp (-0.022/0.066) \}$	0.12	0.0362
		Palmer amaranth (resistant)	0	0	36	46	47	47	47	47	47	14	53	$y = 0.257 * \log \{ x * \exp (-0.018/0.257) \}$	0.46	<.0001
		Palmer amaranth (susceptible)	0	0	51	54	55	55	55	55	55	6	1	$y = 0.277 * \log \{ x * \exp (0.03/0.277) \}$	0.68	<.0001
		LSD (0.05)	0	0	11	10	10	10	10	10	10					
		CV (%)	.	.	56	33	31	32	32	32	32					
Soybean	45	Apple of Peru	0	0	0	0	0	50	50	50	100	.	24	$y = 0.091 * \log \{ x * \exp (-0.056/0.091) \}$	0.77	<.0001

Appendix Table 3 Continued.

		Cutleaf groundcherry	0	0	0	0	68	100	100	100	100	14	31	$y = 0.085 * \log \{ x * \exp (0.142/0.085) \}$	0.68	<.0001
		Eastern blacknightshade	0	0	0	0	0	100	100	100	100	5	76	$y = 0.087 * \log \{ x * \exp (-0.036/0.087) \}$	0.38	<.0001
		Palmer amaranth (resistant)	0	0	0	0	40	90	100	100	100	2	5	$y = 0.297 * \log \{ x * \exp (0.016/0.297) \}$	0.76	<.0001
		Palmer amaranth (susceptible)	0	0	0	0	57	100	100	100	100	7	26	$y = 0.245 * \log \{ x * \exp (0.024/0.245) \}$	0.64	<.0001
		LSD (0.05)	0	0	9	8	8	8	8	8	8					
		CV (%)	.	.	42	27	26	26	26	26	26					
Soybean	91	Apple of Peru	0	0	0	0	100	100	100	100	100	3	70	$y = 0.054 * \log \{ x * \exp (-0.028/0.054) \}$	0.44	<.0001
		Cutleaf groundcherry	0	0	0	0	100	100	100	100	100	10	20	$y = 0.079 * \log \{ x * \exp (0.133/0.079) \}$	0.77	<.0001
		Eastern blacknightshade	0	0	0	0	0	0	0	0	0	.	81	$y = 0.04 * \log \{ x * \exp (-0.029/0.04) \}$	0.42	<.0001

Appendix Table 3 Continued.

Palmer amaranth (resistant)	0	33	33	33	92	92	100	100	100	5	14	$y = 0.315 * \log \{ x * \exp (0.012/0.315) \}$	0.73	<.0001
Palmer amaranth (susceptible)	0	0	0	0	100	100	100	100	100	5	17	$y = 0.26 * \log \{ x * \exp (0.03/0.26) \}$	0.69	<.0001
LSD (0.05)	0	0	6	6	7	7	7	7	7					
CV (%)	.	.	24	21	21	21	21	21	21					

<sup>a</sup> LSD at  $p < 0.05$  designed to compare means within cropping system and weed species across time after planting as well as within cropping system and time after planting across weed species.

Appendix Table 4. Cumulative emergence of weeds as a percentage of total seeds planted as influenced by weed species, cropping system, and time after planting in Kinston 2008. <sup>a</sup>

Crop	Row spacing cm	Weed species	Weeks after planting						LSD (0.05)	CV (%)	Regression equation	R <sup>2</sup>	p-value
			7	10	13	16	19	22					
Corn	91	Apple of Peru	5	5	6	8	8	8	5	140	$y = 0.038 * \log \{ x * \exp (0.004/0.038) \}$	0.02	0.4700
		Cutleaf groundcherry	9	9	11	14	14	14	2	40	$y = 0.026 * \log \{ x * \exp (0.044/0.026) \}$	0.18	0.0386
		Eastern blacknightshade	11	11	11	11	11	11	5	85	$y = 0 * \log \{ x * \exp (0.108/0) \}$	0.00	1.0000
		Palmer amaranth (resistant)	5	5	5	6	6	6	2	60	$y = 0.013 * \log \{ x * \exp (0.031/0.013) \}$	0.02	0.4690
		Palmer amaranth (susceptible)	4	4	4	4	4	4	1	28	$y = 0.002 * \log \{ x * \exp (0.039/0.002) \}$	0.003	0.8082
		LSD (0.05)	3	3	3	4	4	4					

Appendix Table 4 Continued.

		CV (%)	85	85	75	83	83	83					
Cotton	91	Apple of Peru	7	7	8	11	11	11	4	89	$y = 0.048 * \log \{ x * \exp (0.012/0.048) \}$	0.05	0.3012
		Cutleaf groundcherry	11	11	11	12	12	12	1	20	$y = 0.012 * \log \{ x * \exp (0.021/0.012) \}$	0.04	0.3275
		Eastern blacknightshade	7	7	7	8	8	8	3	73	$y = 0.022 * \log \{ x * \exp (0.038/0.022) \}$	0.02	0.4707
		Palmer amaranth (resistant)	7	7	7	13	13	13	4	87	$y = 0.077 * \log \{ x * \exp (-0.028/0.077) \}$	0.10	0.1297
		Palmer amaranth (susceptible)	7	7	8	25	25	25	5	57	$y = 0.229 * \log \{ x * \exp (-0.215/0.229) \}$	0.41	0.0008
		LSD (0.05)	2	2	2	5	5	5					
		CV (%)	60	60	53	67	67	67					

Appendix Table 4 Continued.

Soybean	45	Apple of Peru	5	5	5	6	6	6	1	50	$y = 0.112 * \log \{ x * \exp (0.021/0.112) \}$	0.09	0.1585
		Cutleaf groundcherry	9	9	9	14	14	14	3	47	$y = 0.04 * \log \{ x * \exp (0.067/0.04) \}$	0.14	0.0728
		Eastern blacknightshade	7	7	9	9	9	9	4	93	$y = 0.038 * \log \{ x * \exp (-0.007/0.038) \}$	0.01	0.0048
		Palmer amaranth (resistant)	7	7	7	18	18	18	6	99	$y = 0.255 * \log \{ x * \exp (-0.228/0.255) \}$	0.16	0.0133
		Palmer amaranth (susceptible)	9	9	9	26	26	26	7	79	$y = 0.308 * \log \{ x * \exp (-0.306/0.308) \}$	0.25	0.0138
		LSD (0.05)	3	3	3	6	6	6					
		CV (%)	70	70	64	84	84	84					
Soybean	91	Apple of Peru	16	16	18	25	25	25	8	82	$y = 0.112 * \log \{ x * \exp (0.021/0.112) \}$	0.06	0.2438
		Cutleaf groundcherry	10	10	10	10	10	10	4	73	$y = 0.04 * \log \{ x * \exp (0.067/0.04) \}$	0.00	0.9362

Appendix Table 4 Continued.

Eastern blacknightshade	4	4	5	7	7	7	1	51	$y = 0.038 * \log \{ x * \exp (-0.007/0.038) \}$	0.20	0.0286
Palmer amaranth (resistant)	9	9	10	29	29	29	5	51	$y = 0.255 * \log \{ x * \exp (-0.228/0.255) \}$	0.43	0.0005
Palmer amaranth (susceptible)	8	8	9	32	32	32	7	69	$y = 0.308 * \log \{ x * \exp (-0.306/0.308) \}$	0.37	0.0018
LSD (0.05)	3	3	4	7	7	7					
CV (%)	70	70	70	70	70	70					

<sup>a</sup> LSD at  $p < 0.05$  designed to compare means within cropping system and weed species across time after planting as well as within cropping system and time after planting across weed species.

Appendix Table 5. Cumulative emergence of weeds as a percentage of total emergence as influenced by weed species, cropping system, and time after planting in Goldsboro in 2007. <sup>a</sup>

Crop	Row spacing	Weed species	Weeks after planting									LSD (0.05)	CV (%)
			1	4	7	10	13	16	19	22	25		
	cm		%										
Corn	91	Apple of Peru	0	11	54	54	54	86	86	86	100	51	92
		Cutleaf groundcherry	0	10	68	68	100	100	100	100	100	22	71
		Eastern blacknightshade	0	0	0	0	0	0	0	0	0	.	227
		Palmer amaranth (resistant)	0	9	46	46	72	100	100	100	100	51	163
		Palmer amaranth (susceptible)	0	59	85	85	85	96	96	96	100	24	108
		LSD (0.05)	0	4	11	11	9	2	2	2	0		
		CV (%)	.	174	116	116	103	102	102	102	99		
Cotton	91	Apple of Peru	0	0	0	0	0	1	100	100	100	0	173
		Cutleaf groundcherry	0	0	0	0	10	11	100	100	100	19	103
		Eastern blacknightshade	0	0	0	0	0	1	100	100	100	40	168
		Palmer amaranth (resistant)	0	0	0	0	0	1	100	100	100	28	62

Appendix Table 5 Continued.

		Palmer amaranth (susceptible)	0	0	0	0	1	1	100	100	100	0	135
		LSD (0.05)	0	0	0	0	3	3	0	0	0		
		CV (%)	.	.	.	.	177	128	0	0	0		
Soybean	35	Apple of Peru	0	0	0	0	0	50	50	50	100	.	317
		Cutleaf groundcherry	0	0	0	0	68	100	100	100	100	26	139
		Eastern blacknightshade	0	0	0	0	0	100	100	100	100	0	60
		Palmer amaranth (resistant)	0	0	0	0	40	90	100	100	100	30	89
		Palmer amaranth (susceptible)	0	0	0	0	57	100	100	100	100	29	112
		LSD (0.05)	0	0	0	0	32	18	0	0	0	0	
		CV (%)	.	.	.	.	108	11	0	0	0	0	
Soybean	71	Apple of Peru	0	0	0	0	100	100	100	100	100	0	155
		Cutleaf groundcherry	0	0	0	0	100	100	100	100	100	0	96
		Eastern blacknightshade	0	0	0	0	0	0	0	0	0	.	.
		Palmer amaranth (resistant)	0	33	33	33	92	92	100	100	100	46	186

Appendix Table 5 Continued.

Palmer amaranth (susceptible)	0	0	0	0	100	100	100	100	100	0	123
LSD (0.05)	0	14	14	14	4	4	0	0	0		
CV (%)	.	289	289	289	112	5	0	0	0		

<sup>a</sup> LSD at  $p \leq 0.05$  designed to compare means within cropping system and weed species across time after planting as well as within cropping system and time after planting across weed species.

Appendix Table 6. Cumulative emergence of weeds as a percentage of total emergence as influenced by weed species, cropping system, and time after planting in Kinston 2008.<sup>a</sup>

Crop	Row spacing	Weed species	Weeks after planting						LSD (0.05)	CV (%)
			7	10	13	16	19	22		
	cm		%							
Corn	91	Apple of Peru	56	56	82	100	100	100	15	37
		Cutleaf groundcherry	70	70	88	100	100	100	8	18
		Eastern blacknightshade	100	100	100	100	100	100	0	0
		Palmer amaranth (resistant)	83	83	88	100	100	100	4	10
		Palmer amaranth (susceptible)	97	97	97	100	100	100	2	4
		LSD (0.05)	22	22	11	0	0	0		
		CV (%)	28	28	13	0	0	0		
Cotton	91	Apple of Peru	52	52	74	100	100	100	12	30
		Cutleaf groundcherry	90	90	98	100	100	100	3	6
		Eastern blacknightshade	88	88	91	100	100	100	8	17
		Palmer amaranth (resistant)	78	78	81	100	100	100	13	29

Appendix Table 6 Continued.

		Palmer amaranth (susceptible)	40	40	42	100	100	100	15	41
		LSD (0.05)	29	29	29	0	0	0		
		CV (%)	45	45	40	0	0	0		
Soybean	45	Apple of Peru	78	78	84	100	100	100	11	24
		Cutleaf groundcherry	80	80	80	100	100	100	14	32
		Eastern blacknightshade	69	69	100	100	100	100	13	30
		Palmer amaranth (resistant)	54	54	54	100	100	100	12	30
		Palmer amaranth (susceptible)	53	53	53	100	100	100	12	32
		LSD (0.05)	34	34	31	0	0	0		
		CV (%)	55	55	45	0	0	0		
Soybean	91	Apple of Peru	71	71	81	100	100	100	6	13
		Cutleaf groundcherry	75	75	75	100	100	100	18	40
		Eastern blacknightshade	62	62	71	100	100	100	16	39
		Palmer amaranth (resistant)	36	36	38	100	100	100	5	16

Appendix Table 6 Continued.

Palmer amaranth (susceptible)	40	40	40	100	100	100	15	43
LSD (0.05)	18	18	19	0	0	0		
CV (%)	65	65	61	0	0	0		

<sup>a</sup> LSD at  $p < 0.05$  designed to compare means within cropping system and weed species across time after planting as well as within cropping system and time after planting across weed species.