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Weed Biology and Competition

Influence of Palmer Amaranth (*Amaranthus palmeri*) on the Critical Period for Weed Control in Plasticulture-Grown Tomato

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Field studies were conducted in 1996, 1997, and 1998 at Clinton, NC, to determine the influence of Palmer amaranth establishment and removal periods on the yield and quality of plasticulture-grown 'Mountain Spring' fresh market tomato. Treatments consisted of 14 Palmer amaranth establishment and removal periods. Half of the treatments were weed removal treatments (REM), in which Palmer amaranth was sowed at the time tomato transplanting and allowed to remain in the field for 0 (weed-free all season), 2, 3, 4, 6, 8, or 10 wk after transplanting (WAT). The second set of the treatments, weed establishment treatments (EST), consisted of sowing Palmer amaranth 0 (weedy all season), 2, 3, 4, 6, 8, or 10 WAT and allowing it to grow in competition with tomato the remainder of the season. Tomato shoot dry weight was reduced 23, 7, and 11 g plant^{-1} for each week Palmer amaranth removal was delayed from 0 to 10 WAT in 1996, 1997, and 1998, respectively. Marketable tomato yield ranged from 87,000 to 41,000 kg ha^{-1} for REM of 0 to 10 WAT and 28,000 to 88,000 kg ha^{-1} for EST of 0 to 6 WAT. Percentage of jumbo, large, medium, and cull tomato yields ranged from 49 to 33%, 22 to 31%, 2 to 6%, and 9 to 11%, respectively, for REM of 0 to 10 WAT and 30 to 49%, 38 to 22%, 3 to 2%, and 12 to 9%, respectively, for EST of 0 to 6 WAT. To avoid losses of marketable tomato yield and percentage of jumbo tomato fruit yield, tomato plots must remain free of Palmer amaranth between 3 and 6 WAT. Observed reduction in marketable tomato yield was likely due to competition for light as Palmer amaranth plants exceeded the tomato plant canopy 6 WAT and remained taller than tomato plants for the remainder of the growing season.
Nomenclature: Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; tomato, *Lycopersicon esculentum* L. 'Mountain Spring'.
Key words: Interspecific competition, intraspecific competition, light, marketable yields, weed-free period.

En 1996, 1997 y 1998, se realizaron estudios de campo en Clinton, North Carolina, para determinar la influencia del establecimiento y momento de remoción de *Amaranthus palmeri* en el rendimiento y la calidad del tomate para el mercado fresco 'Mountain Spring' producido con cobertura plástica. Los tratamientos consistieron en 14 períodos de establecimiento y remoción de *A. palmeri*. La mitad de los tratamientos fueron de remoción de la maleza (REM), en los cuales se sembró *A. palmeri* al momento del trasplante del tomate y se mantuvo en el campo por 0 (libre de malezas a lo largo de toda la temporada), 2, 3, 4, 6, 8 ó 10 semanas después del trasplante (WAT). El segundo grupo de tratamientos, establecimiento de la maleza (EST), consistió en la siembra de *A. palmeri* a 0 (enmalezado durante toda la temporada), 2, 3, 4, 6, 8 ó 10 WAT y permitiéndole crecer en competencia con el tomate durante el resto de la temporada. El peso seco de la parte aérea del tomate se redujo 23, 7 y 11 g planta^{-1} por cada semana que se retrasó la remoción de *A. palmeri* desde 0 a 10 WAT en 1996, 1997 y 1998, respectivamente. El rendimiento de tomate comercializable varió entre 87,000 a 41,000 kg ha^{-1} para REM de 0 a 10 WAT y 28,000 a 88,000 kg ha^{-1} para EST de 0 a 6 WAT. El porcentaje del rendimiento de tomates "jumbo", grande, mediano y de rechazo varió de 49 a 33%, 22 a 31%, 2 a 6% y 9 a 11%, respectivamente para REM de 0 a 10 WAT y 30 a 49%, 38 a 22%, 3 a 2% y 12 a 9%, respectivamente para EST de 0 a 6 WAT. Para evitar pérdidas de rendimiento de tomate comercializable y de porcentaje de rendimiento de fruta jumbo, las parcelas de tomate deben permanecer libres de *A. palmeri* entre 3 y 6 WAT. Las reducciones en el rendimiento de tomate comercializable se debieron probablemente a la competencia por luz, ya que las plantas de *A. palmeri* sobrepasaron el dosel de las plantas de tomate a 6 WAT y se mantuvieron más altas que las plantas de tomate por el resto de la temporada de crecimiento.

Most fresh market tomato growers in the southeastern United States utilize a plasticulture production system to achieve earlier harvests and increased yields of high quality fruit (Brown et al. 1991; Kemble 2012; Wein and Minotti 1987). Use of black polyethylene mulch inhibits sunlight penetration and therefore prevents germination and growth of most weeds. However, weeds can grow from the openings in the mulch where tomato transplants are planted. Increased weed–crop competition can occur because these weeds are in close proximity to the crop (Monks and Oliver 1988; Pike et al. 1990). Competition from weeds emerging in tomato holes is likely to become more common due to the phase out of methyl bromide, traditionally used for pest control in plasticulture production systems (USEPA 2008). Currently growers rely upon pretransplant and postdirected herbicide applications and hand-removal of weeds within the tomato planting holes.

Palmer amaranth is a troublesome annual weed in North Carolina tomato production (Webster 2010) and has become

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increasingly troublesome in the South since the 1970s (Webster and Coble 1997). Palmer amaranth competes effectively with crops for resources due to its rapid, erect growth (Horak and Loughin 2000; Monks and Oliver 1988; Sellers et al. 2003). Its use of C_4 photosynthesis results in a lower CO_2 compensation point and greater photosynthetic rate, growth rate, and water use efficiency (Black et al. 1969; Horak and Loughin 2000; Massinga et al. 2003). Documented interactions between Palmer amaranth and horticultural crops are limited to bell pepper (*Capsicum annuum* L.) (Norsworthy et al. 2008) and sweetpotato (*Ipomoea batatas* L. Lam.) (Meyers et al. 2010). Palmer amaranth reduced bell pepper fruit set and was predicted to be the same height as the bell pepper canopy (20 cm) at 287 growing degree days (base 10 C) (Norsworthy et al. 2008).

The competitive ability of a plant is determined by the space it is able to occupy at the beginning of the season, the rate at which it is able to expand within its space, and its ability for capturing a limiting resource (Spitters and Van Berg 1982). The plasticulture production system provides an environment with continuous water, nutrients, and warm temperatures. Under plentiful water and nutrient supply conditions, such as those in a plasticulture system, early research showed light was the primary resource determining the outcome of crop–weed interactions (Blackman and Black 1959; Donald 1958; Stahler 1948). Spitters and Aerts (1983) also reported the greatest competition in mixed species canopies would be for light under plentiful water and nutrient conditions. Effects of reduced light on tomato include flower inhibition (Atherton and Harris 1986; Calvert 1959; Kinet 1977) and decreased assimilates to fruits, resulting in smaller fruits with lower sugar content (Ho and Hewitt 1986; Kinet and Peet 1997).

In a high-value crop such as fresh market tomato, a near zero weed threshold is usually employed. However, investigating the nature of competitive interactions between weeds and transplanted tomato in a plasticulture system will provide valuable information on crop–weed relationships and for managing weeds in this production system. The objective of this study was to determine the critical period for Palmer amaranth control in fresh market, plasticulture-grown tomato.

Materials and Methods

Field studies were conducted in 1996, 1997, and 1998 at the Horticultural Crops Research Station near Clinton, NC (35°1′N, 78°16′W; 48 m above sea level). Soil in 1996 was an Orangeburg loamy sand (fine loamy, siliceous, thermic, Typic Paleaudult) with 0.2% humic matter and pH 6.1. Soil in 1997 and 1998 was a Norfolk loamy sand (fine loamy, siliceous, thermic, Typic Paleaudult) with 0.3% humic matter and pH 5.4 and 5.5, respectively.

Two weeks prior to transplanting, planting beds (15 cm high and 90 cm wide on 1.5-m centers) were formed, injected with methyl bromide (98%) at 392 kg ha^{-1}, and covered with black polyethylene mulch in a single operation. In the same operation, drip tape was placed 3 to 5 cm deep beneath the mulch to allow for fertigation. One day prior to transplanting, 10-cm-diam planting holes were punched 0.6 m apart through the black polyethylene mulch in the center of the beds. Six-week-old (approximately 20 to 25 cm tall) ‘Mountain Spring’ tomato plants, a fresh market cultivar, were transplanted in the field on April 22, April 19, and April 28 in 1996, 1997, and 1998, respectively. Plots consisted of seven tomato plants in 1996 and six tomato plants in 1997 and 1998. Plasticulture production practices and drip fertigation schedules followed those currently recommended by Kemble (2012). Row middles were maintained weed-free throughout the growing season with use of paraquat (Gramoxone Extra®, 200 g ai L^{-1}, Syngenta Crop Protection, Inc., Greensboro, NC) at 530 g ai ha^{-1}.

The study consisted of 14 treatments using the removal and establishment methods described by Oliver (1988) to determine the critical period for weed control (CPWC). In EST treatments, plots were maintained weed-free for 0 (weedy all season), 2, 3, 4, 6, 8, or 10 WAT, at which time Palmer amaranth seed were sowed in the tomato planting hole and resulting plants were allowed to remain for the remainder of the growing season. In the REM treatments, Palmer amaranth was sowed into the tomato transplanting hole immediately following transplanting and were allowed to grow for 0 (weed-free all season), 2, 3, 4, 6, 8, or 10 WAT, at which time Palmer amaranth plants were hand-removed and the plot maintained weed-free for the remainder of the growing season. EST times of 8 and 10 WAT were excluded in 1997 and 1998 because tomato canopies at this stage prohibited Palmer amaranth seedling growth in 1996. Inclusion of these treatments in at least one more year would have confirmed this suspicion. However, the authors cannot be certain that the tomato canopy would have prohibited Palmer amaranth seedling growth in 1997 and 1998.

To determine the influence of weed density on CPWC, EST and REM treatments were duplicated utilizing one of two Palmer amaranth densities: one or three plants per tomato planting hole. Weeds were thinned to two to three plants above treatment density per tomato planting hole at the cotyledon stage and thinned again to a final density by 2 wk after sowing. Weed densities were maintained throughout the growing season by hand-removing undesired weeds weekly. To compare the effect of intraspecific Palmer amaranth and interspecific Palmer amaranth–tomato interactions, additional treatments consisted of Palmer amaranth at the aforementioned EST, REM, and densities, but in the absence of tomato plants. However, monoculture stands of Palmer amaranth were not grown in 1998. The experimental design was a randomized complete block with four replications. Therefore, the entire treatment set consisted of 14 removal or establishment timings (REM or EST) by two Palmer amaranth densities by two competitive environments (i.e., Palmer amaranth alone or in mixture with tomato) by four replications.

Tomato and Palmer amaranth plant heights were recorded at the time of weed removal for REM treatments. After heights of the crop and weeds were recorded in REM treatments, aboveground biomass of weeds was taken by cutting the stems at ground level. The weeds were then hand-chopped, bagged, oven-dried at 60 C for 72 h, and weighed. Upon final tomato fruit harvest, tomato shoots from both

Table 1. Effect of Palmer amaranth removal (REM) treatments on 'Mountain Spring' tomato plant height at Clinton, NC.[a]

Treatment	Tomato plant height			
	4 WAT[c]	6 WAT	8 WAT	10 WAT
	cm			
With Palmer amaranth[b]	38	58	68	70
Weed-free	37	54	71	77
LSD (0.05)	NS	NS	NS	6

[a] Data pooled over 1996, 1997, and 1998.

[b] Data pooled over Palmer amaranth densities of one and three plants per tomato planting hole.

[c] Abbreviations: WAT, weeks after transplanting; NS, not significant.

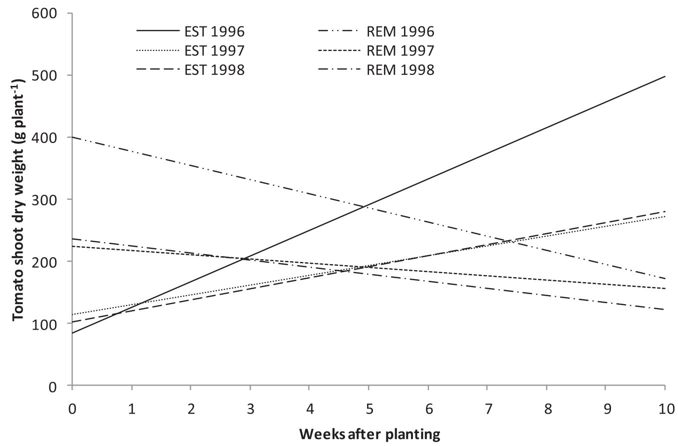

Figure 1. Relationship between Palmer amaranth removal (REM) or establishment (EST) regimes and tomato shoot dry weight at Clinton, NC, in 1996, 1997, and 1998. Lines represent predicted values. 1996: EST = 41.3x + 83.4, R^2 = 0.97; REM = –22.6x + 398.3, R^2 = 0.97. 1997: EST = 15.9x + 112.9, R^2 = 0.95; REM = –6.8x + 223.9, R^2 = 0.77. 1998: EST = 17.8x + 100.8, R^2 = 0.94; REM = –11.3x + 235, R^2 = 0.87.

EST and REM treatments were collected from a single tomato plant per plot in 1996 and two tomato plants per plot in 1997 and 1998. Any remaining small tomato fruit were removed, and tomato shoot biomass was determined as described above for Palmer amaranth shoot biomass. Additionally, end-of-season weed dry weight was collected from Palmer amaranth–tomato mixed culture treatments.

Vine-ripened tomato fruit meeting a minimum color classification of "breakers" to "turning" (USDA 1997) were hand-harvested once weekly for 5 wk in 1997 and 6 wk in 1996 and 1998. Tomato fruit were graded according to USDA standards (1997) into jumbo (≥ 8.8 cm in diam), extra large (7.3 to 8.8 cm), large (6.4 to 7.3 cm), medium (5.0 to 6.4 cm), and cull (< 5 cm orcontaining damage or defects as defined by USDA grading standards). In 1996 fruit was harvested from all the tomato plants in each plot. However, in 1997 and 1998 fruit were harvested from four tomato plants from the center of the plot to negate the influence of an "end of row" effect in which tomato plants at the end of a plot were subjected to less interference from adjacent tomato plants within the same plot.

Data were subjected to an ANOVA by SAS Proc Mixed (SAS/STAT Version 6, SAS Institute, Cary, NC). Separate models were used for EST and REM treatments. Fixed as well as main effects were EST or REM treatment, Palmer amaranth density, and competitive environment (with regard to Palmer amaranth shoot dry weight). Location and replication were treated as random effects. Means of significant main effects were compared using LSD ($P = 0.05$) tests. Data for tomato plant height, shoot dry weight, and yield by grade were subjected to regression analysis against EST and REM treatments by SAS Proc Mixed to determine best fit models. Least squares means generated by SAS Proc Mixed were used to estimate coefficients for linear and quadratic models via SAS Proc GLM.

Results and Discussion

Tomato and Palmer Amaranth Plant Height. Tomato and Palmer amaranth plant height data were influenced by REM. There was no Palmer amaranth density by REM interaction nor was there a year by REM interaction. Therefore, data for tomato and Palmer amaranth plant height were combined across densities and years. Tomato plant height, recorded immediately before REM treatments were employed 4, 6, 8, and 10 WAT, were compared with the weed-free check (REM = 0 WAT) (Table 1). Height of tomato plants from REM treatments were similar to the weed-free check 4, 6, and 8 WAT. However, tomato plants from plots with a REM of 10 WAT were shorter (70 cm) compared with tomato plants in plots that were maintained weed-free for the entire growing season (77 cm). Observed Palmer amaranth heights were 27, 82, 145, and 200 cm immediately prior to the implementation of REM treatments 4, 6, 8, and 10 WAT, respectively (data not shown). In REM treatments, tomatoes were taller than Palmer amaranth at 4 WAT. However, by 6 WAT and later, Palmer amaranth plants had grown well above the tomato canopy and remained taller than the tomato plants for the remainder of the growing season in weedy check plots.

Tomato Plant Shoot Dry Weight. ANOVA indicated significant EST and REM treatment effects influencing tomato plant shoot dry weight. However, Palmer amaranth density did not influence tomato plant shoot dry weight. Due to a lack of Palmer amaranth density by EST and REM interaction, data for the effect of EST and REM on tomato plant shoot weight were analyzed across Palmer amaranth densities. Due to year by EST and REM interaction, tomato plant shoot dry weight data were analyzed by year for EST and REM. In each year tomato shoot dry weight displayed a linear response to Palmer amaranth REM and EST treatments (Figure 1). Tomato shoot dry weight displayed a positive linear response to EST treatments, indicating that tomato shoot dry weight increased with delayed Palmer amaranth establishment. Conversely, tomato shoot dry weight displayed a negative linear response to REM treatments, indicating that tomato shoot dry weight decreased when Palmer amaranth removal is delayed. Weed-free (REM = 0 WAT) tomato plant shoot dry weights were 398, 224, and 235 g plant^{-1} in 1996, 1997, and 1998, respectively. REM treatment slope estimates show tomato shoot dry weight was decreased by 23, 7, and 11 g plant^{-1} for each week Palmer amaranth removal was delayed

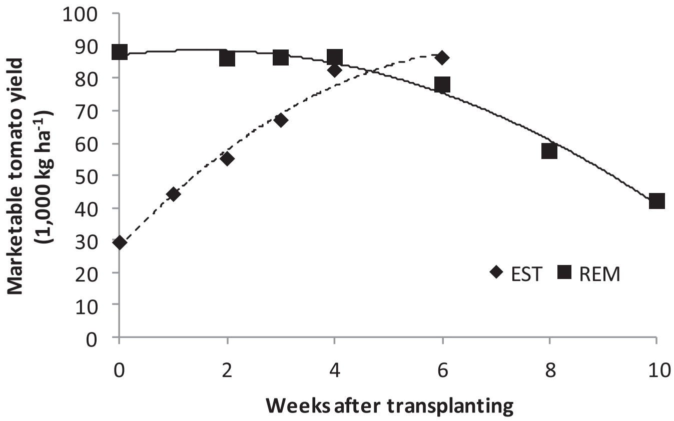

Figure 2. Relationship between weed removal (REM) or establishment (EST) regimes and marketable tomato yield at Clinton, NC, across 1996, 1997, and 1998. Points represent observed mean data. Lines represent predicted values. EST $= 1{,}000x\ (-1.23x^2 + 17.34x + 28.05)$; R^2=0.98. REM $= 1{,}000x\ (-0.66x^2 + 2.03x + 87.16)$; R^2=0.98.

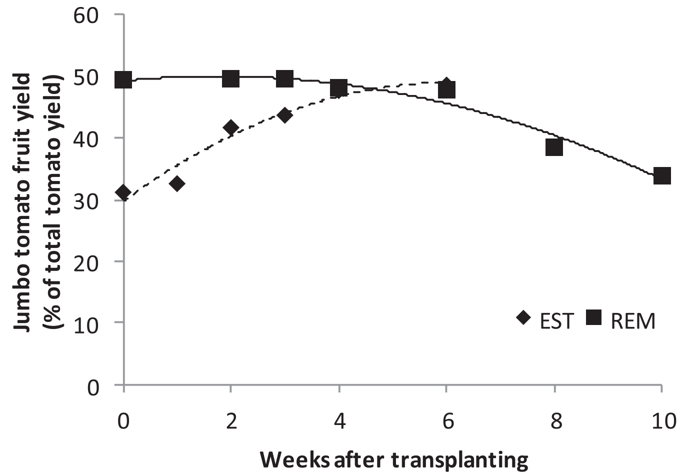

Figure 3. Relationship between weed removal (REM) or establishment (EST) regimes and jumbo fruit tomato yield as a percentage of total tomato yield at Clinton across 1996, 1997, and 1998. Points represent observed mean data. Lines represent predicted values. EST $= -0.52x^2 + 6.35x + 29.75$; R^2=0.95. REM $= -0.25x^2 + 0.90x + 49.28$; R^2=0.96.

from 0 to 10 WAT in 1996, 1997, and 1998, respectively. According to predicted EST responses, to achieve the same tomato plant shoot dry weights observed in the weed-free plots, establishment of Palmer amaranth would have needed to be delayed until 7.6, 7, and 7.5 WAT in 1996, 1997, and 1998, respectively. The reduction of tomato shoot dry weight in the presence of Palmer amaranth indicates the existence of competition between tomato and Palmer amaranth.

Palmer Amaranth Shoot Dry Weight. Palmer amaranth shoot dry weight data displayed an interaction between treatment and year and were therefore analyzed separately by year. Across all EST and REM treatments, Palmer amaranth density greatly influenced Palmer amaranth biomass. Palmer amaranth shoot dry weight was 440 and 210 g plant^{-1} in 1996 and 1997, respectively when thinned to one Palmer amaranth plant per tomato planting hole (data not shown). When Palmer amaranth plants were thinned to three plants per tomato planting hole, individual Palmer amaranth shoot dry biomass was reduced to 230 and 80 g plant^{-1} (data not shown). These data suggest the presence of intraspecific competition from increasing Palmer amaranth density. When grown in the presence of tomato, Palmer amaranth shoot dry biomass was decreased compared with Palmer amaranth grown in monoculture (data not shown). Palmer amaranth shoot dry weight in monoculture plots (across Palmer amaranth densities) was 440 and 220 g plant^{-1} in 1996 and 1997, respectively. Shoot dry biomass was reduced to 230 and 72 g plant^{-1} when grown with tomato in 1996 and 1997, respectively.

Tomato Yield. Tomato fruit weight by grade as a percentage of all grades was tested for EST and REM treatment effects. Due to a lack of year by Palmer amaranth density, EST, and REM interactions, data were combined across all 3 yr. Marketable tomato yield displayed a quadratic relationship to both EST and REM (Figure 2). Marketable tomato yield ranged from 87,000 to 41,000 kg ha^{-1} for REM of 0 to 10 WAT and 28,000 to 88,000 kg ha^{-1} for EST of 0 to 6 WAT. The reduction in marketable tomato yield resulting from season-long competition with Palmer amaranth was twice as great as the 30% yield reduction reported by Mohammed and Sweet (1978) for one redroot pigweed (*Amaranthus retroflexus* L.) per 3 m of seeded tomato row in bare-ground production, but similar to the naturally occurring pigweed interference in transplanted bare-ground tomato production (Qasem 1992). The reduction in marketable tomato yield is likely due to competition between Palmer amaranth and tomato for light as Palmer amaranth height exceeded that of tomato at 6 WAT.

The effect of Palmer amaranth EST and REM on the percentage of jumbo tomato yield was fit to quadratic regression equations. Percentage of jumbo tomato yield ranged from 49 to 33% for REM of 0 to 10 WAT (Figure 3). Jumbo yield percentage ranged from to 30 to 49% for EST of 0 to 6 WAT.

The effect of Palmer amaranth EST and REM on extra-large tomato yield as a percentage of total yield could not be fit to a regression model (data not shown). Extra-large tomato fruit comprised 26% of total tomato yield in plots that remained weed-free throughout the growing season. Percentage of tomato fruit (by weight) that were extra-large fruit ranged from 27 to 30% for EST treatments and 26 to 30% for REM treatments (data not shown).

The influence of EST and REM on large, medium, and cull tomato fruit yield as a percentage of total tomato fruit yield differed from trends observed for marketable fruit yield and percentage of jumbo fruit yield. Marketable and jumbo percentage yields were the greatest in plots that remained weed-free through the entire growing season. Conversely, these plots yielded the lowest percentage of large, medium, and cull tomato yield. Percentage of large tomato yield was fit to a quadratic relationship with both EST and REM (Figure 4). Large tomato percentage yield ranged from 38 to 22% for EST of 0 to 6 WAT and 22 to 31% for REM of 0 to 10 WAT. Medium tomato yield percentage ranged from 3 to 2% for EST of 0 to 6 WAT and 2 to 6% for REM of 0 to 10 WAT (Figure 5).

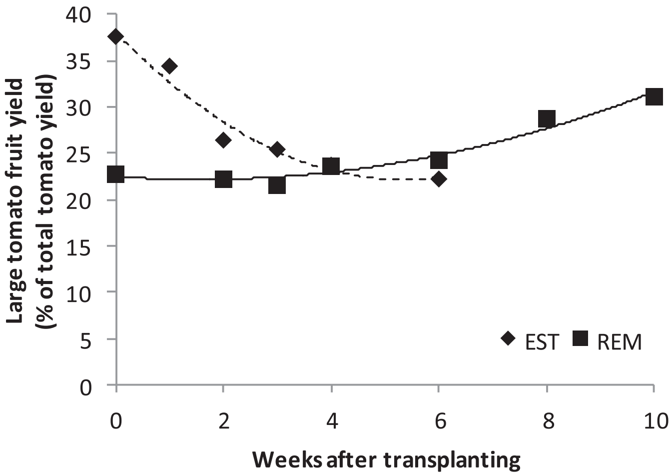

Figure 4. Relationship between weed removal (REM) or establishment (EST) regimes and large tomato fruit yield as a percentage of total tomato yield at Clinton across 1996, 1997, and 1998. Points represent observed mean data. Lines represent predicted values. EST = $0.56x^2$ - 5.99x + 38.07; R^2=0.96. REM = $0.13x^2$ - 0.41x + 22.45; R^2=0.96.

The effect of Palmer amaranth EST and REM treatments on the percentage of cull tomato yield differed from one another (Table 2) in that Palmer amaranth EST treatments displayed a negative linear relationship and REM displayed a quadratic relationship with the percentage of tomato yield graded as cull. Percentage of cull tomato yield ranged from 12 to 9% from EST of 0 (weedy the entire season) to 6 WAT. Percentage of cull tomato yield ranged from 9 to 11% from REM of 0 (weed-free the entire season) to 10 WAT.

Spitters and Van Berg (1982) indicated that the critical factors that determine the competitive ability of a plant include capture of space at the beginning of the season, the rate at which the plant is able to grow and expand within this space, and its competitive advantage for some limiting resource. Tomato has the early season advantage over weeds for space as a result of being transplanted. When grown together, it is apparent that early established Palmer amaranth are able to occupy space at a faster rate than tomato, thus utilizing the resources contained within the space to the detriment of the tomato. The result is reduced marketable yield and increased smaller fruit yield which demand less of a premium than larger tomatoes. The data obtained from this study suggest that transplanted, plasticulture-grown tomato must remain Palmer amaranth–free between 3 and 6 WAT in order to maintain marketable and percentage of jumbo tomato fruit yields similar to the weed-free check. A delay in weed removal will result in lower total marketable yield and smaller, less marketable fruit.

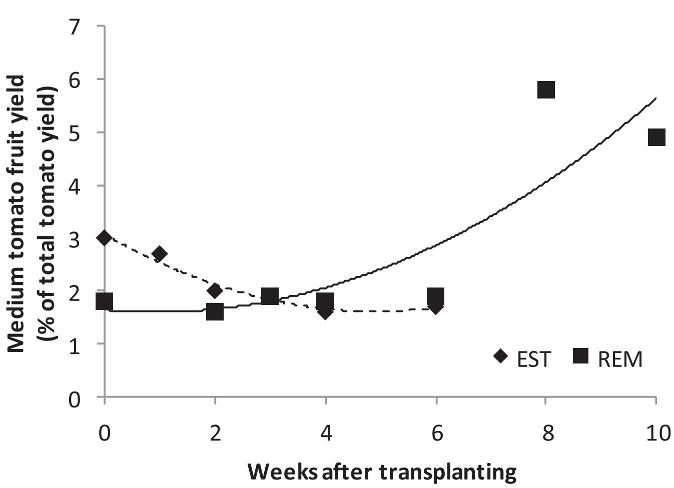

Figure 5. Relationship between weed removal (REM) or establishment (EST) regimes and medium tomato fruit yield as a percentage of total tomato yield at Clinton across 1996, 1997, and 1998. Points represent observed mean data. Lines represent predicted values. EST = $0.06x^2$ – 0.60x + 3.07; R^2=0.97. REM = $0.05x^2$ - 0.09x + 1.64; R^2=0.74.

Table 2. Effect of Palmer amaranth establishment (EST) and removal (REM) on percentage 'Mountain Spring' tomato fruit yield graded as cull at Clinton, NC.[a]

Parameter	Regression equation	R^2
Percentage of cull tomato yield (EST)	$-0.47x + 11.69$	0.67
Percentage of cull tomato yield (REM)	$-0.03x^2 + 0.54x + 9.01$	0.99

[a] Data pooled over 1996, 1997, and 1998.

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