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Growth Analysis of Cotton in Competition with Velvetleaf (*Abutilon theophrasti*)

Xiaoyan Ma, Jinyan Yang, Hanwen Wu, Weili Jiang, Yajie Ma, and Yan Ma*

Field experiments were conducted in 2013 and 2014 to determine the influence of velvetleaf densities of 0, 0.125, 0.25, 0.5, 1, 2, 4, and 8 plants m^{-1} of row on cotton growth and yield. The relationship between velvetleaf density and seed cotton yield was described by the hyperbolic decay regression model, which estimated that a density of 0.44 to 0.48 velvetleaf m^{-1} of row would result in a seed cotton yield loss of 50%. Velvetleaf remained taller and thicker than cotton throughout the growing season. Both cotton height and stem diameter reduced with increasing velvetleaf density. Moreover, velvetleaf interference delayed cotton maturity, especially at velvetleaf densities of 1 to 8 plants m^{-1} of row, and cotton boll number and weight, seed numbers per boll, and lint percentage were also reduced. Fiber quality was not influenced by weed density when analyzed over 2 yr; however, fiber length uniformity and micronaire were adversely affected in 2014. Velvetleaf intraspecific competition resulted in density-dependent effects on weed biomass, ranging from 97 to 204 g $plant^{-1}$ dry weight. Velvetleaf seed production per plant or per square meter was indicated by a logarithmic response. At a density of 1 plant m^{-1} of cotton row, velvetleaf produced approximately 20,000 seeds m^{-2}. The adverse impact of velvetleaf on cotton growth and development identified in this study have indicated the need for effective management of this species when the weed density is greater than 0.25 to 0.5 plant m^{-1} of row and before the weed seed maturity.

Nomenclature: Velvetleaf, *Abutilon theophrasti* Medik. ABUTH; cotton, *Gossypium hirsutum* L.
Key words: Fiber properties, productive growth, seed cotton yield, seed production, weed biomass.

Experimentos de campo fueron realizados en 2013 y 2014 para determinar la influencia de densidades de *Abutilon theophrasti* de 0, 0.125, 0.25, 0.5, 1, 2, 4, y 8 plantas m^{-1} de hilera en el crecimiento y el rendimiento del algodón. La relación entre la densidad de *A. theophrasti* y el rendimiento de semilla de algodón fue descrita con un modelo de regresión hiperbólico decreciente, el cual estimó que una densidad de 0.44 a 0.48 plantas de *A. theophrasti* m^{-1} de hilera resultaría en una pérdida del rendimiento de semilla de algodón de 50%. *A. theophrasti* se mantuvo con una mayor altura y grosor que el algodón a lo largo de toda la temporada de crecimiento. Tanto la altura como el diámetro de tallo del algodón se redujeron con el aumento en la densidad de *A. theophrasti*. Además, la interferencia de *A. theophrasti* retrasó la madurez del algodón, especialmente con densidades de *A. theophrasti* de 1 a 8 plantas m^{-1} de hilera. Además, el número y peso de los frutos del algodón, el número de semillas por fruto, y el porcentaje de fibra también fueron reducidos. La calidad de la fibra no fue influenciada por la densidad de la maleza cuando se analizaron los resultados promediando dos años. Sin embargo, la uniformidad del largo de la fibra y el grosor de la fibra fueron adversamente afectados en 2014. La competencia intra-específica de *A. theophrasti* afectó la biomasa de la maleza en forma dependiente de la densidad variando desde 97 a 204 g $planta^{-1}$ de peso seco. La producción de semilla de *A. theophrasti* por planta o por metro cuadrado fue descrita mediante una respuesta logarítmica. A una densidad de 1 planta m^{-1} de hilera de algodón, *A. theophrasti* produjo aproximadamente 20,000 semillas m^{-2}. El impacto adverso de *A. theophrasti* sobre el crecimiento y desarrollo del algodón identificado en este estudio ha indicado la necesidad de un manejo efectivo de esta especie cuando la densidad de la maleza es mayor de 0.25 a 0.5 plantas m^{-1} de hilera y esto se debe hacer antes de la madurez de la semilla de la maleza.

Velvetleaf, also known as butterprint, Indian mallow, China jute or, in Chinese, *ching-ma*, is an annual broadleaf weed of the Malvaceae family thought to be native to China (Li 1970). It was historically cultivated for medicinal and ornamental purposes as well as for use as fiber and an oil source (Kirby 1963). However, it has escaped from cultivation and become weedy in orchards, vegetable farms, and cropping fields in China (Li 1998). Velvetleaf is now present in many other countries as

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* First, second, fourth, fifth, and sixth authors: Associate Professor, Master Student, Assistant Professor, Assistant Professor, and Associate Professor, State Key Laboratory of Cotton Biology, Institute of Cotton Research, Chinese Academy of Agricultural Sciences, Anyang, China 455000; third author: Senior Weeds Research Scientist, Graham Centre for Agricultural Innovation, Wagga Wagga Agricultural Institute, NSW Department of Primary Industries, Wagga Wagga, NSW 2650, Australia. Corresponding author's E-mail: maxy_caas@126.com

a result of the attempted use of this plant species as a source of domestically grown fiber (Dempsey 1975; Spencer 1984).

Velvetleaf is a competitive annual weed in crop fields, in part, because of its high seed production (Winter 1960), high seed viability (Lueschen and Andersen 1980; Muenscher 1955), and high latency (Nurse and DiTommaso 2005; Spencer 1984), which allows velvetleaf to form a persistent soil seed bank. Velvetleaf is difficult to eradicate once it forms a well-established soil seed bank (Cortés et al. 2010). Weed seed populations can increase rapidly if a few plants survive and produce seeds, and for this reason, it is important to prevent late-season weed seed production to eliminate future problems (Bagavathiannan and Norsworthy 2012; Walsh 2014). Moreover, velvetleaf is highly competitive for light because it is a vigorous sub-shrub-like plant that can reach a height of 3 m (Benvenuti et al. 1994). Competition for light is the main cause of yield losses because of velvetleaf interference in various crops (Akey et al. 1990; Begonia et al. 1991; Smith et al. 1990; Zanin and Sattin 1988).

Herbicides have largely been used to prevent yield loss from weed interference. However, the continued use of herbicides is often offset by the increased frequency of more-tolerant weed species or by the evolution of herbicide resistance (Heap 2014). As of 2014, atrazine-resistant velvetleaf populations have been confirmed in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] fields and nurseries in Serbia, the United States, and New Zealand (Heap 2014; James and Cooper 2012; Pavlović et al. 2007).

Velvetleaf interference as a function of weed density can significantly reduce the yield of most agronomic crops, including corn, soybean, and cotton. Several studies reported that corn yield loss from velvetleaf interference approached a maximum asymptote around the weed density of 10 plants m^{-2}, with further density increases resulting in minor increases in crop damage (Lindquist et al. 1996). McDonald et al. (2004) compiled 19 site–yr of corn–velvetleaf competition data and showed that velvetleaf can cause corn yield loss ranging from a negligible 2% to complete crop failure. Previous research has documented substantial soybean yield loss from velvetleaf competition (Akey et al. 1991; Begonia et al. 1991; Dekker and Meggitt 1983). At an approximate density of 6 plants m^{-2}, velvetleaf competition resulted in a 40% reduction in soybean yield (Ziska 2012). Velvetleaf is also one of the most competitive weeds in cotton fields, where 16 velvetleaf plants in 12 m of crop row reduced seed cotton yields as much as 45% (Chandler 1977). Another study indicated that cotton yield and velvetleaf density were correlated via a decreasing hyperbolic function and the cotton profitability threshold was about 2 velvetleaf plants m^{-2} (Cortés et al. 2010).

The evidence for yield reductions from competition with weeds has been well documented, but vegetative growth of cotton, represented by plant height and stem diameter, is another important aspect of cotton growth (Bouchagier et al. 2008). Previous weed interference studies have indicated that cotton is sensitive to weed competition and its vegetative growth is generally less sensitive than cotton yield and yield components when exposed to weed competition (Christidis and Harrison 1955; Poonguzhalan et al. 2013). However, adverse impacts on the vegetative growth of cotton from weed competition have also been reported. Significant reductions in cotton height have been reported because of the competition of spurred anoda [*Anoda cristata* (L.) Schlecht.], prickly sida (*Sida spinosa* L.), velvetleaf, Venice mallow (*Hibiscus trionum* L.), and devil's-claw [*Proboscidea louisianica* (P. Mill.) Thellung] (Chandler 1977; Mercer et al. 1987). Barnett and Steckel (2013) found that cotton height could be reduced by half because of the competition from giant ragweed (*Ambrosia trifida* L.) at 1.6 plants m^{-1} of row. Similarly, Buchanan and Burns (1971a,b) claimed that, at a density of 6.6 plants m^{-1} of row, sicklepod [*Senna obtusifolia* (L.) H.S. Irwin & Barneby], tall morningglory [*Ipomoea purpurea* (L.) Roth], Canada cocklebur [*Xanthium strumarium* var. *canadense* (P. Mill.) Torr. & Gray], and redroot pigweed (*Amaranthus retroflexus* L.) reduced cotton height by 27, 40, 37, and 33%, and stem diameter by 39, 41, 52, and 43%, respectively, when compared with the weed-free control.

Previous research on weed interference mainly focused on cotton yield and plant height or stem diameter at maturity and has not evaluated the weed effects on cotton maturity or growth. Barnett and Steckel (2013) found that high densities of giant ragweed (0.8 and 1.6 plants m^{-1} of row) delayed cotton maturity, which affected final cotton lint yield. It has been documented that the competition

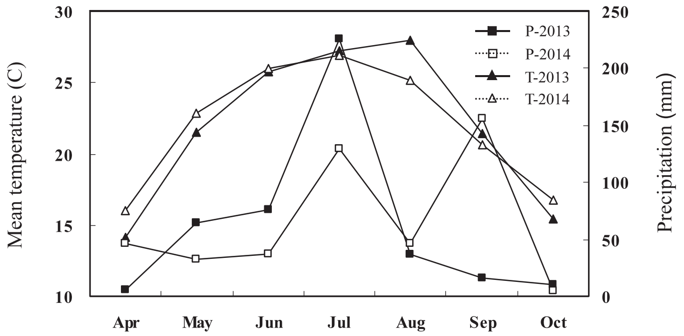

Figure 1. Meteorological data (Anyang Meteorological Bureau) for the experimental site during the experimental periods (August–October 2013 and 2014). Abbreviations: T, temperature; P, precipitation.

from coastal plain yellowtops [*Flaveria bidentis* (L.) Kuntze] delayed the cotton budding stage, and the sympodial branch number and square and boll number per plant were consequently reduced (Peng et al. 2012). So far, information is not available, to our knowledge, on the interference impact of velvetleaf on the growth and development of cotton under field conditions. Hence, studies were carried out to characterize the influence of velvetleaf density on cotton growth, development, yield, and fiber properties and to evaluate velvetleaf growth and seed production at several densities in cotton.

Materials and Methods

Experiment Information. Field studies were conducted at the Institute of Cotton Research (36.13°N, 114.85°E), China, from April to October in 2013 and 2014. The soil type was a Typic Haplustepts, with a pH of 8.0, and an organic matter of 1.5%. Meteorological data at the experimental site during the experimental periods are presented in Figure 1. The site is characterized by wet and hot summers from May to August. which is representative of the Yellow River cotton-producing area of China.

Field Arrangement. The field was irrigated, disked, harrowed, and fertilized with compound fertilizer at 1.500 kg ha^{-1} (N : P_2O_5 : K_2O = 24 : 11 : 5, $\geq$ 40%; Zhengzhou Naweigao Fertilizer Co., Ltd, Henan Province, China) before planting. Plots included four rows, 8 m long and 80-cm wide. 'CCRI 79', a commonly grown cotton cultivar in the region, was sown by hand at a row spacing of 80 cm in each plot at about 200 seeds per 8 m of row on April 27, 2013, and on May 1, 2014. Simultaneously, seeds of velvetleaf, collected the previous summer from the same location, were hand-planted in hills at densities of 0, 1, 2, 4, 8, 16, 32, and 64 plants per 8 m of cotton row or to 0, 0.125, 0.25, 0.5, 1, 2, 4, and 8 plants m^{-1} of row in the center two rows of each plot. Seeds were planted approximately 1 to 2 cm deep and 10 cm away from the cotton row at desired intervals immediately after cotton planting. The outside rows of each plot served as borders between adjacent plots. The velvetleaf plants emerged simultaneously with cotton plants, approximately 10 d after sowing. Cotton seedlings were thinned at the three- to four-leaf stage to 4 seedlings m^{-1} of row (50,000 cotton plants ha^{-1}), and velvetleaf seedlings were thinned at the two- to four-leaf stage to obtain the final prescribed density in each plot. The experimental design was a randomized complete block with four replications; 150 kg ha^{-1} urea (N $\geq$ 46.4%; Anyang Chemical Industry Co., Ltd, Henan Province, China) and 300 kg ha^{-1} compound fertilizer were used in mid-June and mid-July to optimize cotton growth. Insect and disease control practices were applied as required. No herbicides and additional irrigation were used during these experiments. All other weeds were removed by hoeing at weekly intervals throughout the growing season.

Data Collection. Cotton plant height, stem diameter, and square, bloom, and boll number per plant were measured from five randomly selected plants in the center 6 m of the center two rows of each plot. The measurements were carried out once every 2 wk from the cotton seedling stage to the preharvest stage each year, for a total of eight times in 2013 (34, 49, 65, 79, 97, 110, 131, and 141 d after planting [DAP]) and in 2014 (42, 57, 71, 89, 102, 118, 132, and 148 DAP). Height was measured in centimeters from the soil surface to the apical meristem, and stem diameter was determined at the soil line with calipers to the nearest 0.01 mm. Bolls were classified and recorded, including small bolls (< 2 cm in diameter), large bolls ($\geq$ 2 cm in diameter), and cracked bolls. In addition, the plant height and stem diameter of velvetleaf were also simultaneously measured from two to five randomly selected velvetleaf plants in each plot. From late July to late September in both years, the matured seed capsules of velvetleaf were manually collected at weekly intervals and hand threshed. In 2013, seeds were collected from all velvetleaf plants in each plot. The capsules per plot were pooled, hand-threshed, and cleaned seed was weighed. Total seed production per plot was calculated by dividing the total seed weight per plot by the unit seed weight (based on four 1,000-seed samples). In 2014, two to five randomly selected plants per plot were used to estimate the velvetleaf seed production. Velvetleaf plants were marked, and capsules of each plant were removed and pooled separately. Total seed production per plot was calculated based on the number of seeds per plant and the number of velvetleaf plants in each plot. All velvetleaf plants reached matured and were removed from plots in late September of both years (September 20, 2013, and September 19, 2014). Two to five randomly selected velvetleaf plants from each plot were cut at ground level with pruning shears, dried at 70 C for 48 h and weighed to determine the individual weed dry biomass.

At the end of the growing season, cotton in the center two rows in each plot was hand-harvested twice, first at 50% open bolls and again at 100% open bolls. Weights of the total hand-harvested cotton were recorded. Immediately before cotton harvest, one mature boll from the middle branch was harvested from each of 10 randomly selected plants in each plot and weighed to determine boll weight. Then, all bolls were ginned together on a small single-roller gin to determine lint percentage, seed number per boll, and seed index. Lint percentage is an expression of the ratio of lint to seed cotton yield. The seed was acid delinted before weight determination. Four lots of 100-seed random samples were collected from each plot and measured, and the average weight was regarded as the seed index. After the measurement, a 25-g lint sample was subjected to fiber-quality tests, which included fiber length, length uniformity, micronaire, breaking elongation, and fiber strength, at the Supervision, Inspection and Test Center of Cotton Quality, Ministry of Agriculture, Anyang City, China.

Statistical Analyses. All data were analyzed using generalized linear models (GLMs) and by treating velvetleaf density and year as fixed factors to test for significant main effects and interactions. Because there were significant weed density by year interactions, data were analyzed separately by year. ANOVA and Fisher's protected LSD tests were used to determine variation among treatments. Regression analyses were performed to analyze the following relationships:

1. Velvetleaf density (plant m^{-1} of row) and cotton and weed plant height and stem diameter
2. Velvetleaf density (plant m^{-1} of row) and weed dry biomass, including individual plant biomass (g $plant^{-1}$) and total dry biomass (kg ha^{-1})
3. Velvetleaf density (plant m^{-1} of row) and weed seed production, including seed production per plant (seeds $plant^{-1}$) and total seed production (seeds m^{-2}).

These relationships were established from the best fits of the experimental data to appropriate functions, and coefficients of determination (r^2) were reported to indicate the amount of variation in the dependent variables that can be explained by the independent variable. The resulting functions of the quadratic, exponential, or logarithmic type coincided with those previously reported by Cortés et al. (2010).

The Gompertz equation (Equation 1; Askew and Wilcut 2002a) was fit to plant heights and stem diameters of cotton and velvetleaf in each plot over the growing season:

$$Y = a \exp[b \exp(kT)] \qquad [1]$$

where Y is the plant height in centimeters or stem diameter in millimeters, a is the upper asymptote for late-season plant height or stem diameter, b and k are constants, exp is the base of the natural logarithms, and T is the time in days after planting (DAT).

A two-parameter hyperbolic decay regression model (Equation 2; Barnett and Steckel 2013) was used to describe the density-dependent effects of velvetleaf on seed cotton yield:

$$Y = ab/(b + D) \qquad [2]$$

where Y is the seed cotton yield, a is the asymptote or estimate of maximum cotton yield, b is the estimate of the velvetleaf density at which 50% yield loss occurs, and D is the weed density per meter of crop row.

The rectangular hyperbola (Equation 3; Cousens 1985) was used to relate cotton yield loss (Y) to velvetleaf density (D):

$$Y = iD/[1 + (iD)/a]. \qquad [3]$$

Table 1. Parameter estimates for functions describing the effect of velvetleaf density (*D*) or days after planting (*T*) on plant height or stem diameter (*Y*) of cotton and velvetleaf.

			$Y = a + bD + cD^2$				$Y = a \exp[b \exp(kT)]$			
Parameters	Species	Year	*a*	*b*	*c*	r^2	*a*	*b*	*K*	r^2
Plant ht/cm	Cotton	2013	79.6	−5.58	0.26	0.795	125.6	−12.2	−0.038	0.998
		2014	71.9	−4.94	0.27	0.985	79.6	−26.0	−0.068	0.987
	Velvetleaf	2013	122.8	24.23	−1.96	0.970	229.8	−28.6	−0.058	0.998
		2014	121.7	15.41	−1.19	0.919	194.0	−18.1	−0.056	0.992
Stem diam/mm	Cotton	2013	12.1	−2.22	0.19	0.973	18.0	−4.0	−0.022	0.992
		2014	11.7	−1.83	0.15	0.950	12.0	−5.2	−0.042	0.980
	Velvetleaf	2013	21.8	−0.92	0.02	0.826	26.8	−16.7	−0.059	0.991
		2014	20.6	−0.36	−0.04	0.816	22.9	−25.4	−0.076	0.994

where *i* is the initial unit yield loss at low weed densities, and *a* is the asymptote for the percentage of yield loss.

Coefficients of determination (r^2) were calculated for nonlinear regressions and used to determine the goodness of fit to nonlinear models. All probabilities were two-tailed, and the significance level was set at $P = 0.05$. Analysis was performed with the statistical software SPSS (version 13.0, IBM Corporation, Armonk, NY).

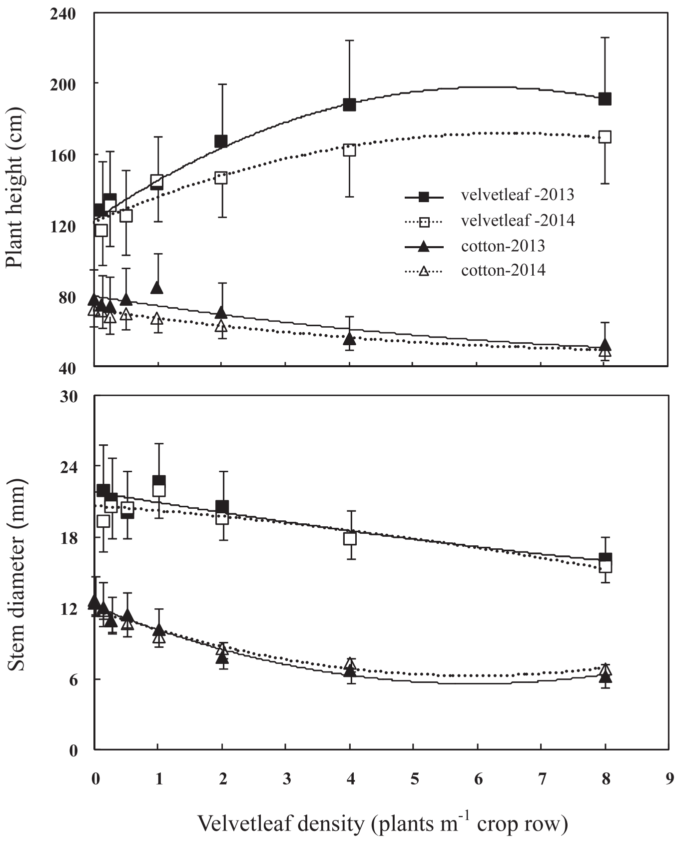

Figure 2. Impact of velvetleaf density on plant height and stem diameter of cotton and velvetleaf. Plant height and stem diameter data were averaged over the growing season, and vertical bars indicate 1 SEM. Estimated parameters for these functions for 2013 and 2014 are given in Table 1.

Results and Discussion

Plant Height and Stem Diameter. Plant height and stem diameter of velvetleaf and cotton changed with the weed density (Table 1; Figure 2). The mean height of velvetleaf increased with increasing weed density from 1 to 8 plants m^{-1} of row. Conversely, cotton height decreased because of competition from velvetleaf, especially at densities > 2 plants m^{-1} of row. Velvetleaf at high densities reduced cotton growth, which is consistent with the competitive effect of velvetleaf on cotton observed by Cortés et al. (2010). Increasing velvetleaf densities had similar effects on the stem diameters of both cotton and velvetleaf. Stem diameter of velvetleaf and cotton decreased with increasing velvetleaf density. The intraspecific competition for space and light resulted in taller, slenderer velvetleaf plants, and the interspecific competition between cotton and velvetleaf led to thinner, shorter cotton, especially at the higher weed densities. According to the regression analyses, each additional velvetleaf plant per meter of row caused a 5 cm decrease in cotton plant height and a concomitant 14 to 22 cm increase in velvetleaf height. Stem diameter reduction over the 2 yr averaged approximately 2 and 0.6 mm for each velvetleaf plant per meter of row for cotton and velvetleaf, respectively.

Plant height and stem diameter of velvetleaf and cotton over the season fit the Gompertz growth model well (Equation 1) when they were averaged

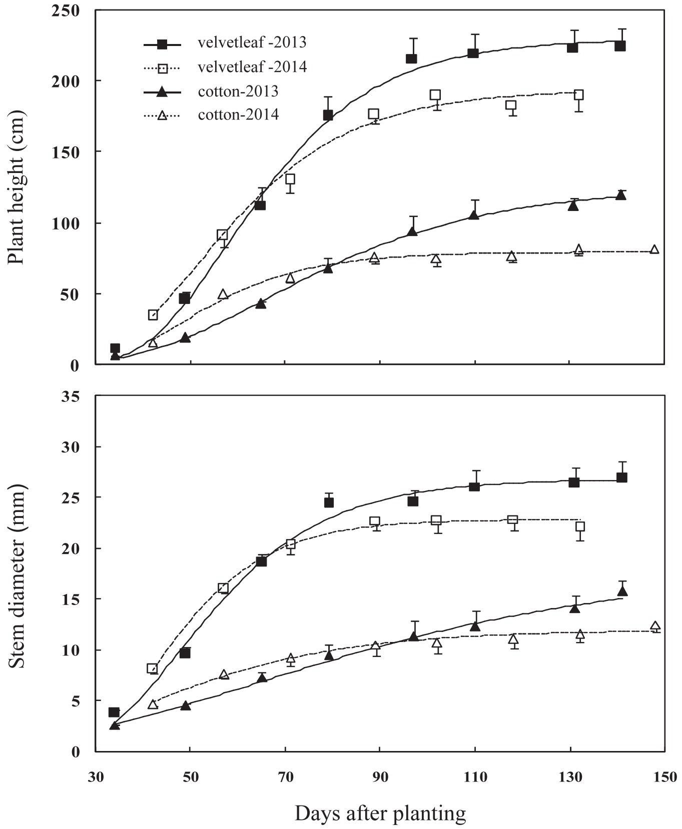

Figure 3. Predicted plant height and stem diameter of cotton and velvetleaf over the growing season in 2013 and 2014. Plant height and stem diameter data were averaged over weed densities, and vertical bars indicate 1 SEM. Estimated parameters for these functions for 2013 and 2014 are given in Table 1.

over velvetleaf densities (Table 1; Figure 3). Velvetleaf was taller and thicker than cotton throughout the season. These findings concurred with Bailey et al. (2003) who reported velvetleaf reduced cotton height at higher weed densities. Because velvetleaf had a distinct competitive advantage in plant height and stem diameter over cotton during the entire growing season when weed plants emerged concurrent with cotton, it was necessary for effective weed management as early as possible to avoid weed interference.

Cotton Reproductive Growth. Reproductive growth of individual cotton plants was characterized by the number of squares, blooms, and bolls per plant, which were not combined because peak bloom did not occur at the same time each year and because the total number of fruiting positions at a given date varied between 2013 and 2014. In 2013, cotton squares and blooms were initially observed at 65 DAP for all treatments (Figure 4). However, the numbers of cotton squares, blooms, and bolls peaked at different times, depending on the given weed densities. Peak cotton squares and blooms counts occurred at 79 DAP when velvetleaf densities were $\leq$ 0.5 plant m^{-1} of row. However, the cotton squares and blooms did not peak until 131 DAP when velvetleaf densities were $\geq$ 1 plant m^{-1} of row. Small bolls peaked at 97 to 110 DAP in the weed-free control treatment and at the weed density of 0.125 plant m^{-1} of row, whereas its peak was delayed to 110 or 131 DAP at velvetleaf densities of 0.25 and 0.5 plant m^{-1} of row, respectively. When the weed densities increased to $>$ 1 plant m^{-1} of row, small bolls did not peak until 131 or 141 DAP. Large bolls peaked at 131 DAP in the weed-free control and at the weed density of 0.125 plant m^{-1} of row, and the peak was delayed to 141 DAP when the weed density was $>$ 1 plant m^{-1} of row. Cracked bolls were observed at 131 DAP in the weed-free control and at the weed density of 0.125 and 1 plant m^{-1} of row, and then, the number of cracked bolls increased as the cotton matured. However, there were no cracked bolls until 141 DAP when velvetleaf density was $\geq$ 2 plants m^{-1} of row (Figure 4).

The impacts of velvetleaf density on peaks of cotton squares, blooms, and bolls were also evident in 2014 (Figure 5). The emergence of cotton squares and blooms concentrated in July in the weed-free control and at velvetleaf densities of 0.125 to 2 plants m^{-1} of row. When velvetleaf densities were 4 and 8 plants m^{-1} of row, cotton squares and blooms did not peak until 132 DAP, with only about 3 cotton squares and blooms $plant^{-1}$. When velvetleaf densities were $\leq$ 2 plants m^{-1} of row, small bolls were first observed at 71 DAP and peaked at 89 DAP. Small boll peak was delayed to 118 DAP at weed densities of 4 and 8 plants m^{-1} of row. Large bolls peaked at 118 or 132 DAP in the weed-free control and at the weed densities of 0.125 and 0.5 plant m^{-1} of row, but there were only a few large bolls without an obvious peak when the weed density was $\geq$ 4 plants m^{-1} of row. Similar to 2013 results, cracked bolls mainly occurred after 130 DAP, and the number of cracked bolls decreased with increasing velvetleaf densities. Moreover, there were no cracked bolls until 148 DAP when velvetleaf density was at 8 plants m^{-1} of row (Figure 5).

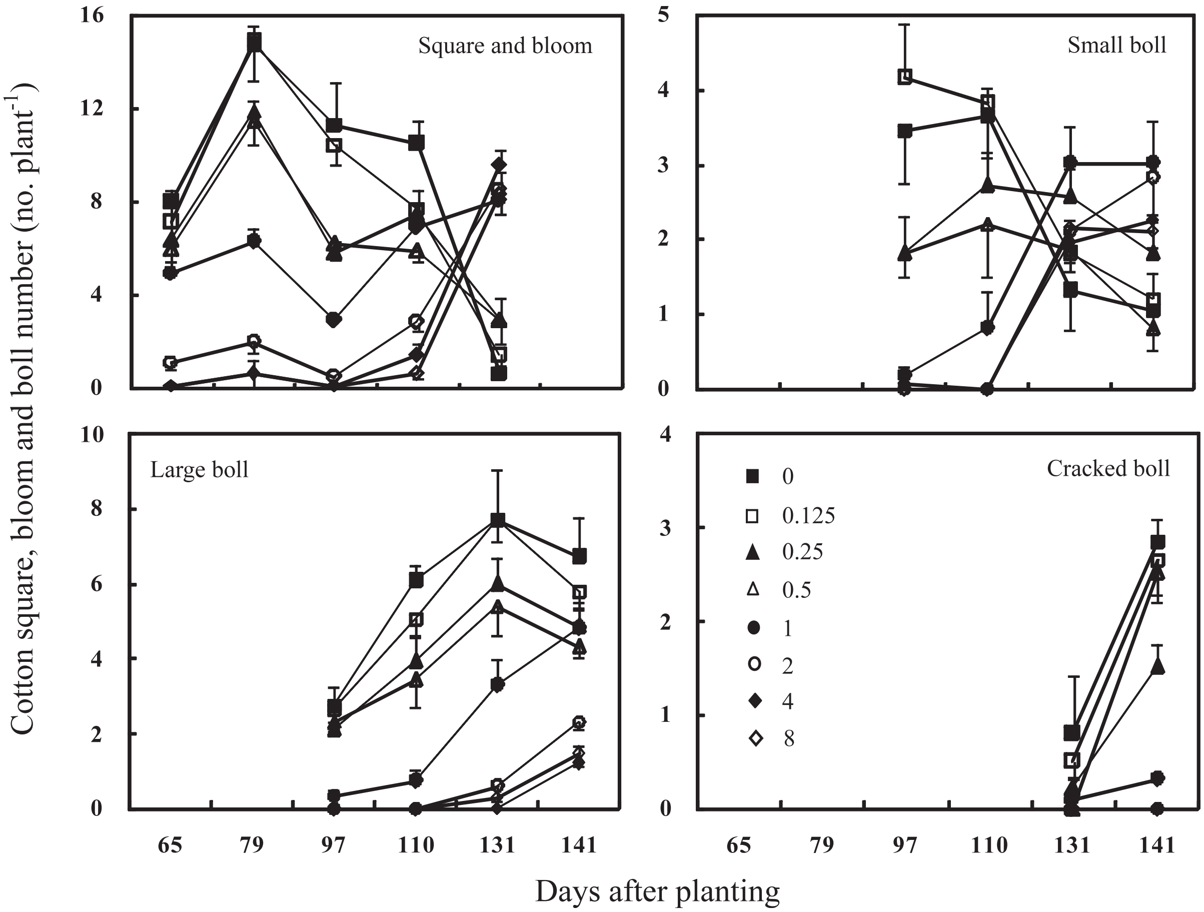

Figure 4. Seasonal variation of the number of cotton squares, blooms and bolls under different velvetleaf densities in 2013. Vertical bars indicate 1 SEM.

These results indicate that velvetleaf interference can delay cotton maturity, especially at densities $\geq$ 1 plant m^{-1} of row. Moreover, weed density had negative impact on square, bloom, and boll numbers when data were averaged across the season in each year (data not presented). Interference of redroot pigweed in cotton studied at the same time and same place (Ma et al. 2015) came to the same conclusions as this research. Similar control strategies are needed to reduce the interference of these two weed species, velvetleaf and redroot pigweed. The weeds were taller and thicker than cotton throughout the season and affected the reproductive growth of cotton when weed plants emerged concurrent with cotton. Therefore, it is necessary that effective weed management begin early in the growing season (Ma et al. 2015).

Seed Cotton Yield. Seed cotton yield was closely correlated with the density of velvetleaf plants. Seed cotton yield in weed-free controls was 1,953 and 4,428 kg ha^{-1} in 2013 and 2014, respectively. As velvetleaf density increased, seed cotton yield decreased. The threshold density at which statistically significant yield reduction appeared was at 0.25 and 0.5 weed plant m^{-1} of row in 2013 and 2014, respectively, which reduced cotton seed yield 22 to 32%. The hyperbolic decay regression model (Equation 2) estimated that a weed density of 0.44 to 0.48 plant m^{-1} of row would result in a 50% reduction in seed cotton yield compared with the maximum yield (Figure 6). Previous studies reported that Palmer amaranth (*Amaranthus palmeri* S. Wats.) at 0.38 to 0.87 plant m^{-1} of row reduced cotton yield 50% (Morgan et al. 2001; Rowland et al. 1999). Snipes et al. (1982) reported that 0.37 to 0.53 Canada cocklebur per meter of row reduced cotton yields by 50%. Similarly, Barnett and Steckel (2013) reported that a density of 0.26 giant ragweed plants m^{-1} of row caused a 50% cotton yield loss.

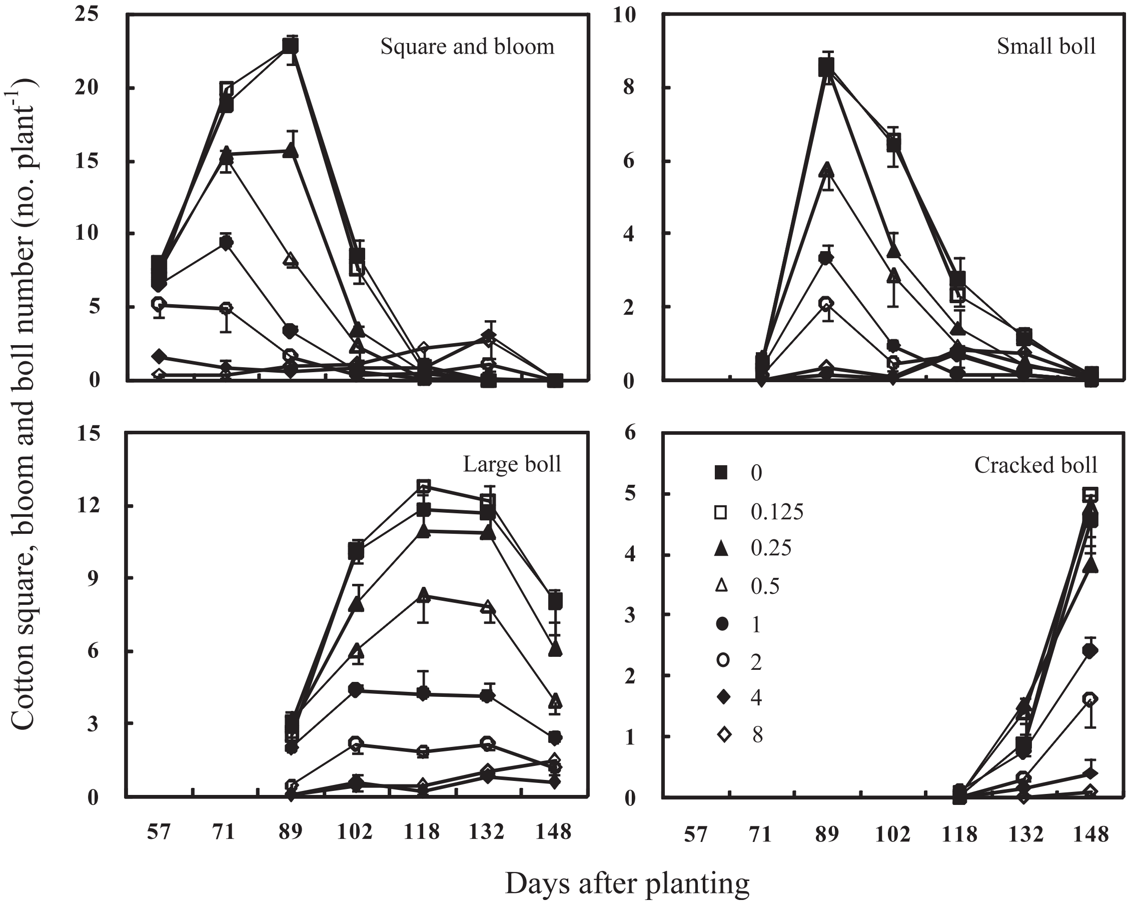

Figure 5. Seasonal variation of the number of cotton squares, blooms, and bolls under different velvetleaf densities in 2014. Vertical bars indicate 1 SEM.

These results suggest that velvetleaf is as competitive with cotton as other weed species.

When seed cotton yield was transformed to the percentage of the weed-free control, it regressed well with a rectangular hyperbolic equation at various weed densities (Equation 3; Figure 6). Because the predicted asymptote (*a*), which represented the maximum yield reduction, was greater than 100% each year, it was manually set to 100% to predict the parameter *i*, the incremental yield loss per unit velvetleaf density. In 2013 and 2014, estimated *i* values were 200% and 174% yield loss, respectively. By comparison, researchers in Spain reported *a* and *i* parameters for early emerged velvetleaf in cotton at 83.9 to 98.6% and 19.0 to 42.2%, respectively (Cortés et al. 2010). Bailey et al. (2003) estimated that *i* values were 30 or 149% in different years. Askew and Wilcut (2002a) found that velvetleaf was more competitive against cotton than it was against many other large broadleaf weeds. For example, the three competitive weed species Canada cocklebur (Snipes et al. 1982), jimsonweed (*Datura stramonium* L.) (Scott et al. 2000), and Palmer amaranth (Rowland et al. 1999) at 1 plant m^{-1} of row, reduced cotton yields by 52, 65, and 66%, respectively, whereas velvetleaf at 1 plant m^{-1} of row reduced cotton yield by 71 to 85% in this study.

Cotton Yield Components. Weed density had a significant effect on boll weight, lint percentage, and seed number per boll in both 2013 and 2014, with the exception of lint percentage in 2013 (Table 2). In 2013, all velvetleaf densities from 0.125 to 0.5 plants m^{-1} of row had similar boll weights (6 g) compared with the weed-free control; however, velvetleaf at densities of 1 to 8 plants m^{-1} of row caused significant reductions (19%) in boll weight compared with the weed-free control. The threshold density at which significant boll weight reduction occurred was 0.25 velvetleaf plant m^{-1} of row when

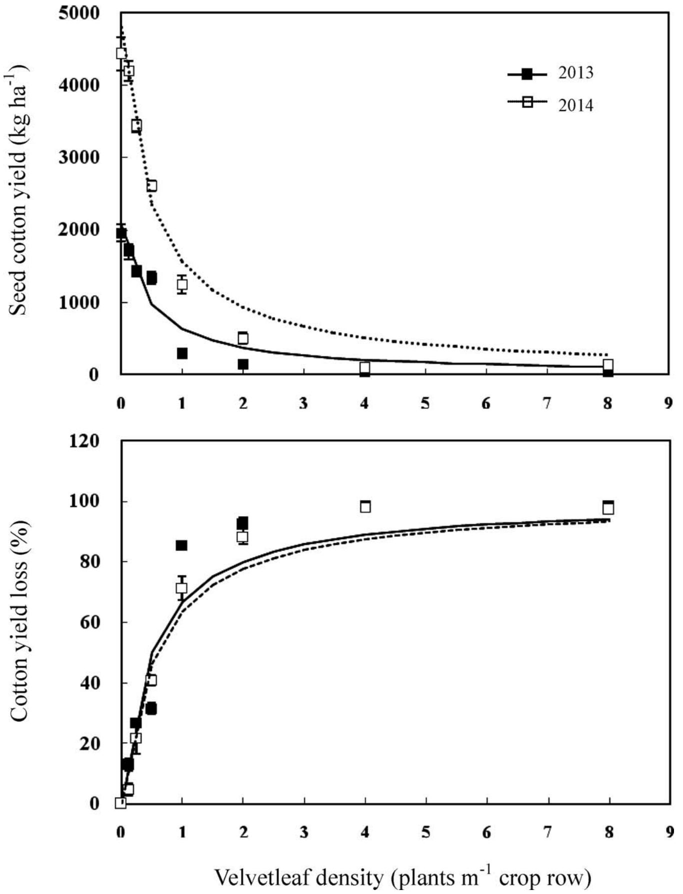

Figure 6. Cotton yield loss associated with increasing velvetleaf density in 2013 and 2014. Equations and r^2 values were $Y = 2{,}079.2 \times 0.44/(0.44 + D)$ and 0.919, respectively, in 2013, and $Y = 4{,}794.3 \times 0.48/(0.48 + D)$ and 0.960, respectively, in 2014, for seed cotton yield. Equations and r^2 values were $Y = 200.4D/(1 + 200.4D/100)$ and 0.915, respectively, in 2013 and $Y = 173.7D/(1 + 173.7D/100)$ and 0.952, respectively, in 2014, for cotton yield loss. Regressions are based on treatment means, and vertical bars indicate 1 SEM.

measured in 2014, and velvetleaf at the density of 0.25 to 8 plants m^{-1} of row caused nearly 8 to 28% reductions in boll weight. Cotton lint percentage was not affected by velvetleaf competition in 2013, but there were significant reductions (6 to 13%) in lint percentage as a result of weed competition at the densities of 1 to 8 velvetleaf plants m^{-1} of row in 2014. Seed numbers per boll were reduced at the high densities of 1 to 8 weed plants m^{-1} of row and the reduction was about 8 to 30%. Seed index was not affected by velvetleaf competition both years.

Boll number and weight are the major cotton yield-determining factors when the number of cotton plants is changeless (Arle and Hamilton 1973; Tingle and Steele 2003). In this study, boll

Table 2. Influence of velvetleaf densities on cotton yield components.[a]

Velvetleaf density	Boll weight		Lint percentage		Seed Nos.		Seed index	
	2013	2014	2013	2014	2013	2014	2013	2014
No. m^{-1} row	g		%		No. boll^{-1}		G	
0	6.3 ± 0.09 a	7.5 ± 0.18 a	36.6 ± 0.49 a	43.3 ± 0.27 a	35.6 ± 0.81 a	38.7 ± 1.10 a	11.1 ± 0.09 abc	11.0 ± 0.11 abc
0.125	6.4 ± 0.17 a	7.4 ± 0.11 ab	36.4 ± 0.58 a	43.2 ± 0.64 a	35.5 ± 1.12 a	37.7 ± 0.29 ab	11.3 ± 0.04 ab	11.4 ± 0.22 ab
0.25	6.3 ± 0.13 a	6.9 ± 0.20 bc	36.9 ± 0.38 a	43.8 ± 0.27 a	34.9 ± 0.34 a	35.9 ± 0.55 ab	11.2 ± 0.19 ab	11.0 ± 0.17 abc
0.5	6.2 ± 0.09 a	6.9 ± 0.18 bc	35.5 ± 0.15 a	43.3 ± 0.54 a	34.8 ± 0.57 a	36.6 ± 0.29 ab	11.4 ± 0.22 a	11.1 ± 0.30 abc
1	5.1 ± 0.09 b	6.4 ± 0.09 d	38.0 ± 0.27 a	40.7 ± 0.68 b	30.4 ± 0.38 b	35.5 ± 0.52 b	10.3 ± 0.11 c	10.8 ± 0.15 c
2	5.1 ± 0.03 b	5.5 ± 0.25 e	37.9 ± 0.22 a	39.2 ± 0.49 bc	29.3 ± 0.65 b	31.9 ± 1.13 c	10.5 ± 0.15 bc	10.7 ± 0.20 c
4	5.1 ± 0.10 b	5.4 ± 0.27 e	36.7 ± 1.80 a	37.6 ± 1.84 c	29.3 ± 0.25 b	29.9 ± 1.47 c	10.6 ± 0.20 abc	10.6 ± 0.23 c
8	5.1 ± 0.00 b	5.4 ± 0.06 e	36.4 ± 0.75 a	39.6 ± 0.20 bc	30.9 ± 1.90 b	27.0 ± 0.46 d	10.4 ± 0.35 c	11.5 ± 0.19 a

[a] Means ± SE within columns followed by the same letter are not significantly different between treatments at the 0.05 probability level as determined by Fisher's protected LSD test.

Table 3. Influence of velvetleaf densities on cotton fiber quality.[a]

Velvetleaf density	Fiber length		Length uniformity		Micronaire	
	2013	2014	2013	2014	2013	2014
No. m^{-1} row	mm		%		unit	
0	27.5 ± 0.06 a	30.4 ± 0.06 a	82.5 ± 0.02 b	85.1 ± 0.36 a	4.7 ± 0.09 a	5.5 ± 0.07 a
0.125	27.7 ± 0.14 a	30.1 ± 0.40 a	83.4 ± 0.40 b	85.4 ± 0.24 a	4.8 ± 0.13 a	5.6 ± 0.05 a
0.25	28.0 ± 0.17 a	29.6 ± 0.17 a	83.4 ± 0.44 b	84.6 ± 0.79 ab	4.9 ± 0.04 a	5.6 ± 0.12 a
0.5	27.5 ± 0.23 a	29.9 ± 0.22 a	84.0 ± 0.31 ab	84.6 ± 0.26 ab	4.7 ± 0.01 a	5.4 ± 0.06 ab
1	28.6 ± 0.46 a	30.1 ± 0.14 a	83.2 ± 0.41 b	83.5 ± 0.51 b	4.7 ± 0.12 a	5.1 ± 0.13 cd
2	28.5 ± 0.40 a	30.4 ± 0.36 a	83.9 ± 0.46 ab	84.2 ± 0.61 ab	4.9 ± 0.15 a	5.0 ± 0.07 d
4	28.3 ± 0.22 a	29.5 ± 0.64 a	83.9 ± 0.60 ab	81.9 ± 0.30 c	5.0 ± 0.32 a	5.2 ± 0.12 bcd
8	28.4 ± 0.21 a	29.6 ± 0.22 a	85.9 ± 0.65 a	81.9 ± 2.60 c	4.8 ± 0.21 a	5.3 ± 0.02 abc

[a] Means ± SE within columns followed by the same letter are not significantly different between treatments at the 0.05 probability level as determined by Fisher's protected LSD test.

[b] Abbreviation: cN tex^{-1}, count-related tenacity.

number per plant and boll weight tended to decrease as the velvetleaf density increased, and then, seed cotton yield in both years was reduced when velvetleaf densities were ≥ 0.25 or 0.5 weed plant m^{-1} of row. Other researchers reported similar results with yield reduction caused by weed competition as a primary result for the reduction in cotton boll number and weight (Castner et al. 1989; Ma et al. 2015).

Cotton Fiber Quality. Velvetleaf densities did not affect fiber length, fiber length uniformity, micronaire, breaking elongation, and fiber strength of the hand-harvested samples when combined over the two experiments (data not presented); however, some parameters were affected when analyzed within individual experiment. Velvetleaf densities did not affect the fiber length, breaking elongation, and fiber strength in both 2013 and 2014 or fiber length uniformity and micronaire in 2013 (Table 3). Compared with the weed-free controls, fiber length uniformity was reduced significantly at 4 and 8 velvetleaf plants m^{-1} of row in 2014. Micronaire was reduced at 1, 2, and 4 velvetleaf plants m^{-1} of row in 2014; however, no further reductions were noted among these three treatments. This result was similar to earlier reports that fiber quality traits are not as sensitive as cotton yield in assessing the effects of weed interference (Barnett and Steckel 2013; Ma et al. 2015; Smith et al. 2000). However, other studies have indicated that certain weed species, including ivyleaf morningglory (*Ipomoea hederacea* Jacq.), hogpotato [*Hoffmannseggia glauca* (Ortega) Eifert], devil's-claw, and johnsongrass [*Sorghum halepense* (L.) Pers.], could reduce fiber quality at high densities (Castner et al. 1989; Mercer et al. 1987; Rogers et al. 1996; Wood et al. 2002).

Weed Biomass. Velvetleaf dry biomass per plant decreased as plant density increased, and the relationship between velvetleaf density and individual dry biomass was exponential, and the year effects were significant (Figure 7). Weed weights combined over the two experiments showed a reduction from 204 g $plant^{-1}$ at the density of 0.125 plant m^{-1} of row to 97 g at the density of 8 plants m^{-1} of row. The density-dependent effects on weed biomass per plant indicate that intraspecific competition occurs in the range of densities evaluated. In other studies with similar weed density ranges, increasing plant density also reduced dry biomass of weeds in cotton, including buffalobur (*Solanum rostratum* Dunal) (Rushing et al. 1985), Canada cocklebur (Snipes et al. 1982), jimsonweed (Scott et al. 2000), and velvetleaf (Bailey et al. 2003).

Regression analysis showed that velvetleaf biomass per hectare tended to increase with increasing weed density. The results fit the quadratic model well, and coefficients of determination (r^2) were 0.995 and 0.992 in 2013 and 2014, respectively (Figure 7). The lowest density of 0.125 velvetleaf plant m^{-1} of row produced 409 and 227 kg ha^{-1} of weed dry matter in 2013 and 2014, respectively, whereas the highest density of 8 velvetleaf plants m^{-1} of row produced weed dry biomass ranging from 8,647 to 11,045 kg ha^{-1}. Each additional velvetleaf plant m^{-1} of row represented an increase

Table 3. Extended.

Breaking elongation		Fiber strength[b]	
2013	2014	2013	2014
%		cN tex^{-1}	
6.7 ± 0.06 a	6.3 ± 0.02 a	27.2 ± 0.31 a	29.4 ± 0.51 a
6.7 ± 0.08 a	6.3 ± 0.03 a	26.6 ± 0.35 a	29.7 ± 0.23 a
6.6 ± 0.05 a	6.3 ± 0.00 a	26.8 ± 0.14 a	28.6 ± 0.30 ab
6.7 ± 0.05 a	6.3 ± 0.02 a	26.8 ± 0.25 a	29.1 ± 0.32 a
6.6 ± 0.08 a	6.3 ± 0.03 a	27.5 ± 0.82 a	28.4 ± 0.49 ab
6.6 ± 0.08 a	6.3 ± 0.03 a	26.9 ± 0.67 a	28.6 ± 0.25 ab
6.7 ± 0.05 a	6.4 ± 0.05 a	26.0 ± 0.70 a	27.3 ± 1.70 b
6.6 ± 0.00 a	6.3 ± 0.00 a	27.1 ± 0.20 a	28.1 ± 0.80 ab

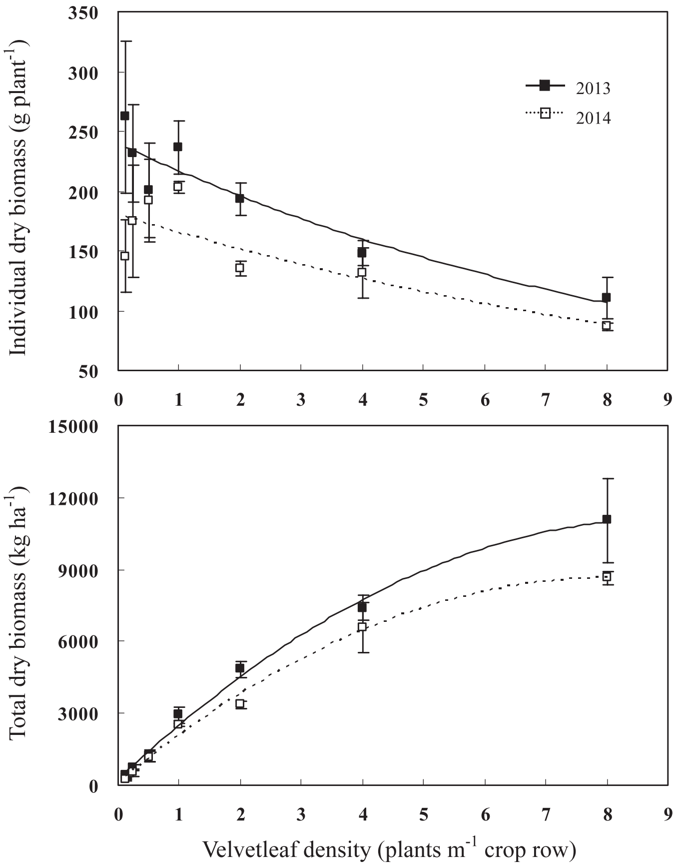

Figure 7. Relationship between velvetleaf density and its dry biomass in 2013 and 2014. Equations and r^2 values were $Y = 240.1 \exp(-0.102D)$ and 0.925, respectively, in 2013 and $Y = 180.6 \exp(-0.089D)$ and 0.779, respectively, in 2014, for individual dry biomass. Equations and r^2 values were $Y = 259.9 + 2{,}402.3D - 132.8D^2$ and 0.995, respectively, in 2013, and $Y = 60.0 + 2{,}127.6D - 131.7D^2$ and 0.992, respectively, in 2014, for velvetleaf dry biomass ha^{-1} of cotton field. Regressions are based on treatment means, and vertical bars indicate 1 SEM.

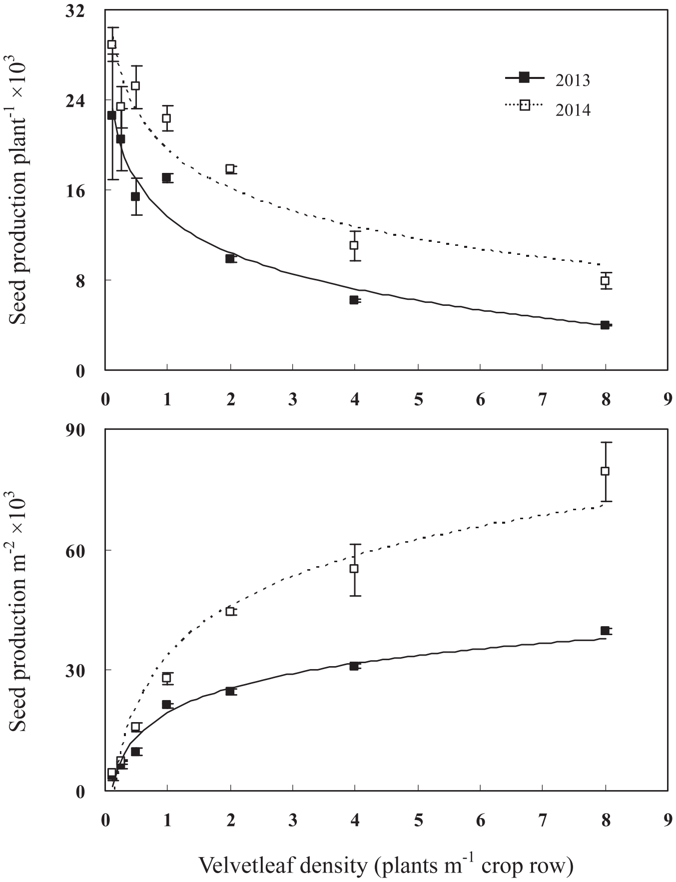

Figure 8. Velvetleaf seed production as a function of plant density in 2013 and 2014. Equations and r^2 values were $Y = 13{,}623.4 - 4{,}623.1 \ln D$ and 0.949, respectively, in 2013, and $Y = 19{,}479.2 - 4{,}912.1 \ln D$ and 0.914, respectively, in 2014, for seed production per plant. Equations and r^2 values were $Y = 19{,}415.4 + 8{,}870.5 \ln D$ and 0.974, respectively, in 2013, and $Y = 33{,}308.3 - 17{,}794.9 \ln D$ and 0.955, respectively, in 2014 for seed production per square meter. Regressions are based on treatment means, and vertical bars indicate 1 SEM.

in dry weed biomass of 2,269 and 1,996 kg ha^{-1} in 2013 and 2014, respectively.

Weed Seed Production. Velvetleaf seed production per plant was density dependent as indicated by a logarithmic response (Figure 8). Velvetleaf seed production per plant decreased as weed density increased and reduced from 22,509 at 0.125 plant m^{-1} of row to 3,954 at 8 plants m^{-1} of row in 2013 and from 28,917 to 7,921 in 2014. Similar to the previous study by Cortés et al. (2010), the number of velvetleaf seed production per square meter increased with increasing weed density and also fit a logarithmic function well, with a determination coefficient of 0.974 and 0.955 in 2013 and 2014, respectively (Figure 8). At a density of 1 plant m^{-1}

of cotton row, velvetleaf produced 21,257 and 27,943 seeds m^{-2} in 2013 and 2014, respectively. Previous studies reported that velvetleaf at 1 plant m^{-1} cotton row could produce 6,000 seeds (Cortés et al. 2010). By comparison, devil's-claw (Mercer et al. 1987), jimsonweed (Scott et al. 2000), ladysthumb (*Polygonum persicaria* L.) (Askew and Wilcut 2002a), Pennsylvania smartweed (*Polygonum pensylvanicum* L.) (Askew and Wilcut 2002b), and pale smartweed (*Polygonum lapathifolium* L.) (Askew and Wilcut 2002c) at 1 plant m^{-1} cotton row produced 4,700, 23,000, 40,000, 22,000, and 44,000 seeds m^{-2}, respectively. Weed seed production is a concern to farmers and others who try to manage weeds to improve weed-management or crop-production programs (Askew and Wilcut 2002a–c). Late-season weed seed production always contributes to the seed bank replenishment, exacerbating problems in subsequent crops and increasing future weed-management costs (Bagavathiannan and Norsworthy 2012). Results from this study demonstrated that seed production for velvetleaf is prodigious. In addition, velvetleaf seeds exhibit high longevity, which is increased by physical dormancy because of an impermeable seed coat (Dorado et al. 2009). Therefore, growers need to adopt weed-management programs to control velvetleaf early in the growing season to avoid producing seeds and to reduce the soil seed bank of weeds.

Conclusions. Results from this study indicated that velvetleaf was a competitive weed in cotton, which affected cotton growth and development and decreased cotton yield even at low densities (0.25 or 0.5 velvetleaf plant m^{-1} of row). The primary resources weeds and crops compete for are light, nutrients, and water. In general, the species that grow rapidly or first capture environmental factors will succeed (Black et al. 1969; Donald 1958; Patterson 1982). Although leaf area indices, a better measure of the potential light interception and competitiveness of crops against weeds (Amini et al. 2014) for cotton and velvetleaf were not measured in this study, velvetleaf was a vigorous sub-shrub-like plant that could reach a height of 3 m, and it always gained a height advantage and spread over the top of the cotton canopy. The shading of velvetleaf might result in more-efficient use of light than cotton exhibits (Bailey et al. 2003). The elements of competition (light, nutrients, and water) are least likely to be separated. Competition for light affected cotton growth, which in turn affected the cotton plants' ability to compete for nutrients and water (Salisbury and Chandler 1993). In contrast, inability to shade cotton and compete for light early in the growing season could result in an overall lack of competitiveness (Askew and Wilcut 2002a–c). Furthermore, weeds that have rapid seedling growth and grow tall quickly compared with the crop with which they are interfering are most competitive (Buchanan and Burns 1970; Tingle and Steele 2003). The same was found in this study. Velvetleaf had a distinct competitive advantage in plant height and stem diameter over cotton during the entire growing season, and its interference with cotton started during the vegetative phase and continued until the reproductive phase. These findings concur with those of Cortés et al. (2010) who reported that the aggressive early season growth and ability to intercept light contributed to the strong competitiveness of velvetleaf with cotton.

Although there was limited influence on cotton yield under low weed densities ($\leq$ 0.125 or 0.25 velvetleaf plant m^{-1} of row), late-season weed plants should be controlled effectively because of the high fecundity and prolonged seed production of velvetleaf. Moreover, velvetleaf seedling emergence occurred from April to early August in the experimental area (our own observations), but weed control measures usually ceased around early July in the cotton-production systems. More data are needed to accurately estimate seed bank dynamics, and additional field research is important to thoroughly understand the phonological development and seed production of velvetleaf relative to the time of cotton emergence. Future work should address the effect of weed removal at various cotton growth stages to determine the critical information for timely management of velvetleaf.

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Literature Cited

Akey AC, Jurik TW, Dekker J (1990) Competition for light between velvetleaf (*Abutilon theophrasti*) and soybean (*Glycine max*). Weed Res 30:403–411

Akey AC, Jurik TW, Dekker J (1991) A replacement series evaluation of competition between velvetleaf (*Abutilon theophrasti*) and soybean (*Glycine max*). Weed Res 31:63–72

Amini R, Alizadeh H, Yousefi A (2014) Interference between red kidneybean (*Phaseolus vulgaris* L.) cultivars and redroot pigweed (*Amaranthus retroflexus* L.). Eur J Agron 60:13–21

Arle HF, Hamilton KC (1973) Effect of annual weeds on furrow irrigated cotton. Weed Sci 22:496–499

Askew SD, Wilcut JW (2002a) Ladysthumb interference and seed production in cotton. Weed Sci 50:326–332

Askew SD, Wilcut JW (2002b) Pennsylvania smartweed interference and achene production in cotton. Weed Sci 50:350–356

Askew SD, Wilcut JW (2002c) Pale smartweed interference and achene production in cotton. Weed Sci 50:357–363

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

Bailey WA, Askew SD, Dorai-Raj S, Wilcut JW (2003) Velvetleaf (*Abutilon theophrasti*) interference and seed production dynamics in cotton. Weed Sci 51:94–101

Barnett KA, Steckel LE (2013) Giant ragweed (*Ambrosia trifida*) competition in cotton. Weed Sci 61:543–548

Begonia GB, Aldrich RJ, Salisbury CD (1991) Soybean yield and yield components as influenced by canopy heights and duration of competition of velvetleaf (*Abutilon theophrasti* Medik.). Weed Res 31:117–124

Benvenuti S, Macchia M, Stefani A (1994) Effects of shade on reproduction and some morphological characteristics of *Abutilon theophrasti* M., *Datura stramonium* L. and *Sorghum halepense* L. Pers. Weed Res 34:283–288

Black CC, Chen TM, Brown RH (1969) Biochemical basis for plant competition. Weed Sci 17:338–344

Bouchagier P, Efthimiadou A, Katsileros A, Bilalis D, Efthimiadis P (2008) Adverse effect of bermudagrass on physiological and growth components of cotton. J Agron 7:49–55

Buchanan GA, Burns ER (1970) Influence of weed competition on cotton. Weed Sci 18:149–154

Buchanan GA, Burns ER (1971a) Weed competition in cotton, I: sicklepod and tall morningglory. Weed Sci 19:576–580

Buchanan GA, Burns ER (1971b) Weed competition in cotton, II: cocklebur and redroot pigweed. Weed Sci 19:580–582

Castner EP, Murray DS, Hackett NM, Verhalen LM (1989) Interference of hogpotato (*Hoffmanseggia glauca*) with cotton (*Gossypium hirsutum*). Weed Sci 37:688–694

Chandler JM (1977) Competition of spurred anoda, velvetleaf, prickly sida, and Venice mallow in cotton. Weed Sci 25:151–158

Christidis BG, Harrison GJ, eds (1955) Cotton Growing Problems. New York: McGraw-Hill. Pp 435–462

Cortés JA, Mendiola MA, Castejón M (2010) Competition of velvetleaf (*Abutilon theophrasti* M.) weed with cotton (*Gossypium hirsutum* L.) economic damage threshold. Span J Agric Res 8:391–399

Cousens R (1985) A simple model relating yield loss to weed density. Ann Appl Biol 107:239–252

Dekker J, Meggitt WF (1983) Interference between velvetleaf (*Abutilon theophrasti* Medic.) and soybean (*Glycine max* (L.) Merr.) I. growth. Weed Res 23:91–101

Dempsey JM, ed (1975) Fiber crops. Chapter 8 *in* China Jute. Gainesville, FL: University of Florida Press. Pp 397–413

Donald CM (1958) The interaction of competition for light and for nutrients. Aust J Agri Res 9:421–435

Dorado J, Fernández-Quintanilla C, Grundy AC (2009) Germination patterns in naturally chilled and non-chilled seeds of fierce thornapple (*Datura ferox*) and velvetleaf (*Abutilon theophrasti*). Weed Sci 57:155–162

Heap I (2014) International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/summary/home.aspx. Accessed December 10, 2014

James TK, Cooper JM (2012) Control of the recently-introduced weed butterprint (*Abutilon theophrasti*) in maize. N Z Plant Prot 65:64–68

Kirby RH, ed (1963) Vegetable Fibres: Botany, Cultivation, and Utilization. New York: Interscience. 46 p

Li HL (1970) The origin of cultivated plants in Southeast Asia. Econ Bot 24:3–19

Li YH, ed (1998) Weeds of China. Beijing, China: China Agricultural Press. 1617 p

Lindquist JL, Mortensen DA, Clay SA, Schmenk R, Kells JJ, Howatt K, Westra P (1996) Stability of corn (*Zea mays*)—velvetleaf (*Abutilon theophrasti*) interference relationships. Weed Sci 44:309–313

Lueschen WE, Andersen RN (1980) Longevity of velvetleaf (*Abutilon theophrasti* M.) seeds. Weed Sci 34:617–622

Ma XY, Wu HW, Jiang WL, Ma YJ, Ma Y (2015) Interference between redroot pigweed (*Amaranthus retroflexus* L.) and cotton (*Gossypium hirsutum* L.): growth analysis. PloS One 10:e0130475.

McDonald AJ, Riha SJ, Mohler CL (2004) Mining the record: historical evidence for climatic influences on maize—*Abutilon theophrasti* competition. Weed Res 44:439–445

Mercer KL, Murray DS, Verhalen LM (1987) Interference of unicorn-plant (*Proboscidea louisianica*) with cotton (*Gossypium hirsutum*). Weed Sci 35:807–812

Morgan GM, Baumann PA, Chandler JM (2001) Competitive impact of Palmer amaranth (*Amaranthus palmeri*) on cotton (*Gossypium hirsutum*) development and yield. Weed Technol 15:408–412

Muenscher WC, ed (1955) Weeds. New York: MacMillan. 336 p

Nurse RE, DiTommaso A (2005) Corn competition alters the germinability of velvetleaf (*Abutilon theophrasti*) seeds. Weed Sci 53:479–488

Patterson DT (1982) Effects of shading and temperature on showy crotalaria (*Crotalaria spectabilis*). Weed Sci 30:692–697

Pavlović D, Vrbničanin S, Božic' D, Simončič A (2007) The study of methods for determination of metabolism based resistance of *Abutilon theophrasti* medic. to atrazine. J Cent Eur Agric 8:435–442

Peng J, Ma Y, Li X, Ma X, Xi J, Ma Y, Li X (2012) Competition of an alien invasive weed *Flaveria bidentis* with cotton. Cotton Sci 24:272–278 [In Chinese]

Poonguzhalan P, Ayyadurai R, Gokila J (2013) Effect of crop–weed competition in cotton (*Gossypium hirsutum* L.)—a review. Agric Rev 34:157–161

Rogers JB, Murray DS, Verhalen LM, Claypool PL (1996) Ivyleaf morningglory (*Ipomoea hederacea*) interference with cotton (*Gossypium hirsutum*). Weed Technol 10:107–114

Rowland MW, Murray DS, Verhalen LM (1999) Full season Palmer amaranth (*Amaranthus palmeri*) interference with cotton (*Gossypium hirsutum*). Weed Sci 47:305–309

Rushing DW, Murray DS, Verhalen LM (1985) Weed interference with cotton (*Gossypium hirsutum*), I: buffalobur (*Solanum rostratum*). Weed Sci 33:810–814

Salisbury CD, Chandler JM (1993) Interaction of cotton (*Gossypium hirsutum*) and velvetleaf (*Abutilon theophrasti*) plants for water is affected by their interaction for light. Weed Sci 41:69–74

Scott GH, Askew SD, Wilcut JW, Brownie C (2000) *Datura stramonium* interference and seed rain in *Gossypium hirsutum*. Weed Sci 48:613–617

Smith DT, Baker RV, Steele GL (2000) Palmer amaranth (*Amaranthus palmeri*) impacts on yield, harvesting, and ginning in dryland cotton (*Gossypium hirsutum*). Weed Technol 14:122–126

Smith BS, Murray DS, Weeks DL (1990) Velvetleaf (*Abutilon theophrasti* M.) interference with cotton (*Gossypium hirsutum*). Weed Technol 4:799–803

Snipes CE, Buchanan GA, Street JE, Mcguire JA (1982) Competition of common cocklebur (*Xanthium pensylvanicum*) with cotton (*Gossypium hirsutum*). Weed Sci 30:553–556

Spencer NR (1984) Velvetleaf, *Abutilon theophrasti* (Malvaceae), history and economic impact in the United States. Econ Bot 38:407–416

Tingle CH, Steele GL (2003) Competition and control of smellmelon (*Cucumis melo* var. *dudaim Naud.*) in cotton. Weed Sci 51:586–591

Walsh M (2014) The importance of harvest weed seed control in weed management. Int Pest Control 56:268–270

Winter DM (1960) The development of the seed of *Abutilon theophrasti*, I: ovule and embryo. Am J Bot 47:8–13

Wood ML, Murray DS, Banks JC, Verhalen LM, Westerman RB, Anderson KB (2002) Johnsongrass (*Sorghum halepense*) density effects on cotton (*Gossypium hirsutum*) harvest and economic value. Weed Technol 16:495–501

Zanin G, Sattin M (1988) Threshold level and seed production of velvetleaf (*Abutilon theophrasti* Medicus) in maize. Weed Res 28:347–352

Ziska L (2012) Observed changes in soyabean growth and seed yield from *Abutilon theophrasti* competition as a function of carbon dioxide concentration. Weed Res 53:140–145

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