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Texasweed (*Caperonia palustris*) Interference in Drill-Seeded Rice

Rakesh K. Godara, Billy J. Williams, Eric P. Webster, James L. Griffin, and James P. Geaghan*

Field research was conducted near Saint Joseph, LA, in 2008 and 2009 to evaluate Texasweed interference in drill-seeded rice. Season-long Texasweed interference at 1 plant m^{-2} was estimated to cause 5% yield loss. Yield loss from 10 and 50 plants m^{-2} was 31 and 61%, respectively. Yield loss was primarily due to a reduction in effective tillers per square meter. Thousand-grain weight of rice was not affected by season-long Texasweed interference. Path analysis indicated yield component compensation, i.e., a reduction in effective tillers per square meter probably caused an increase in grains per panicle. However, that effect was not strong enough to reverse the detrimental effect of reduced effective tillers per square meter on rice yield. The critical period of Texasweed interference to cause more than 5% yield loss was estimated to be between 0 and 6 wk after rice emergence.

Nomenclature: Texasweed, *Caperonia palustris* (L.) St. Hil. CNPPA; rice, *Oryza sativa* L. ORYSA.
Key words: Broadleaf weed competition, time of removal, weed density, critical period.

Se realizó una investigación de campo en Saint Joseph, LA en 2008 y 2009 para evaluar la interferencia de *Caperonia palustris* en arroz de siembra directa. La interferencia de 1 planta m^{-2} de *C. palustris* a lo largo de todo el ciclo del cultivo se estimó que causó 5% de pérdida en el rendimiento. La pérdida en el rendimiento debido a 10 y 50 plantas m^{-2} fue 31 y 61%, respectivamente. Esta pérdida se debió primordialmente a una reducción en los retoños o hijos efectivos por m^{-2}. El peso de mil granos de arroz no fue afectado por la interferencia de *C. palustris* a lo largo del ciclo productivo. Un análisis de trayectoria (path) indicó la presencia de una compensación en el componente de rendimiento (por ejemplo, una reducción en retoños efectivos por m^{-2} probablemente causó un incremento en granos por panícula). Sin embargo, este efecto no fue suficientemente fuerte para revertir el efecto dañino de la reducción en los retoños efectivos por m^{-2} sobre el rendimiento. Se estimó que el período crítico de interferencia de *C. palustris* para evitar 5% de pérdidas en el rendimiento está entre 0 y 6 semanas después de la emergencia del arroz.

Texasweed, also known as *sacatrapo*, is an annual, broadleaf plant belonging to the Euphorbiaceae family (Bryson and DeFelice 2009). It has smooth cotyledons and coarsely pubescent stems and petioles. The leaves are 3 to 15 cm long, alternate, broadly lanceolate, and serrated on the margins. Seeds are dark brown, 2.5 mm in diameter, and minutely pitted. Texasweed can grow up to 3 m tall. Texasweed is often mistaken for mexicanweed [*Caperonia castanifolia* (L.) St. Hil.], which is a perennial plant with a glabrous stem (Godfrey and Wooten 1981).

Texasweed is an introduced species in the United States (USDA-NRCS 2011) and is native to the warmer parts of South America, south of Paraguay (Godfrey and Wooten 1981). It has been described as a nonnative, naturalized species in the southern United States (Gann et al. 2007), where it is listed as an invasive and noxious weed (SWSS 1998). Texasweed has existed in the Unites States as a wetland plant (Godfrey and Wooten 1981) but has not been a major problem in crop areas. However, in the past several years, Texasweed has become common in rice, cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] fields in Texas, Louisiana, Mississippi, and Arkansas (Koger et al. 2004; Poston et al. 2007). Presently, Texasweed is one of the most troublesome weeds in Texas and Louisiana rice production, where it is ranked third and fifth most troublesome weed in the two states, respectively (Gianessi et al. 2002). Other weeds, such as red rice (*Oryza sativa* L.), which grow taller than rice also reduce rice harvest efficiency (Smith 1968). Texasweed seeds are an important source of contamination in rice and result in a lower price because of dockage (personal observation).

Season-long, broadleaf weed interference has been reported to cause significant yield reduction in rice. Smith (1968) reported 19 and 17% yield loss from season-long interference from 5 plants m^{-2} of hemp sesbania [*Sesbania herbacea* (P. Mill.) McVaugh] and northern jointvetch [*Aeschynomene virginica* (L.) B.S.P.], respectively. Season-long interference of spreading dayflower (*Commelina diffusa* Burm. f.) at 22 plants m^{-2} caused 18% rice yield reduction (Smith 1984). Caton et al. (1997) reported 39% rice yield loss from redstem (*Ammannia coccinea* Rottb.) interference at 100 plants m^{-2} in a glasshouse study. Zhang et al. (2004) reported 45% rice yield loss from alligatorweed [*Alternanthera philoxeroides* (Mart.) Griseb.] interference. Currently, there is no information, to our knowledge, on Texasweed interference in rice or any other crops. Smith (1968) reported that hemp sesbania and northern jointvetch interference up to 6 wk after rice emergence caused only 2% yield loss in drill-seeded rice; the yield loss from season-long interference of the two weeds was 19% and 17%, respectively. Smith (1968) also concluded that those weeds reduced rice yield primarily because of shading

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* First, third, and fourth authors: Graduate Student, Professor, and Professor, School of Plant Soil and Environmental Sciences, Louisiana State University and A&M College, Baton Rouge, LA 70803; second author: Weed Specialist, Scott Research Extension Center, Louisiana State University Agricultural Center, 212-B Macon Ridge Road, Winnsboro, LA 71295; fifth author: Professor and Head, Department of Experimental Statistics, Louisiana State University and A&M College, Baton Rouge, LA 70803. Current address of first author: Louisiana State University Agricultural Center, Northeast Research Station, P.O. Box 438, Saint Joseph, LA 71366. Corresponding author's E-mail: rkgodara@gmail.com

effects at the time of rice grain filling and were not competitive if removed before they were tall enough to shade the rice plants. Smith (1984) reported similar findings for spreading dayflower. If the nature of Texasweed–rice interference is similar to the broadleaf weed species reported by Smith (1968, 1984) then POST control will be sufficient to avoid any economic yield loss. However, if yield loss is caused by interference within 6 wks after emergence (WAE), then, PRE or early POST (EPOST) or both control measures will be required. Therefore, it is important to know the critical period of Texasweed control in rice.

The critical period of weed control (CPWC) is defined as the period after crop establishment during which the yield losses due to unmanaged weeds exceed the acceptable yield loss (AYL)(Knezevic et al. 2002). The AYL is the yield loss level at which the cost of the weed management practice is equal to the benefit from employing it. The AYL is generally assumed to be 2 to 10% (Cousens 1988; Knezevic et al. 2002); however, the AYL can vary depending on the benefit–cost ratio of the weed management practice (Knezevic et al. 2002). Critical periods are composed of two components, viz., the critical weed-free period (CWFP) required to obtain at least 100% AYL of the yield obtained under season-long weed-free conditions, and the critical period of weed removal (CPWR), which is the time after which unmanaged weeds cause a yield reduction greater than the AYL (Knezevic et al. 2002).

Experiments were conducted to evaluate Texasweed interference in drill-seeded rice. The objectives were (1) to determine the effect of Texasweed density on rough rice yield and percentage of moisture, (2) to determine the area of influence of Texasweed interference in drill-seeded rice, and (3) to determine the critical period of Texasweed control in drill-seeded rice.

Materials and Methods

General. Field studies were conducted to evaluate Texasweed interference in drill-seeded rice in 2008 and 2009 at the Louisiana State University Agricultural Center's Northeast Research Station, near St. Joseph, LA. Soil was a Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquerts) with pH 6.1 and 2.1% organic matter.

Field preparation during each year consisted of a fall-disking, followed by a spring-disking and two passes in opposite directions with a two-way bed conditioner equipped with rolling baskets and S-tine harrows set to operate 15 cm deep. 'Cocodrie' rice was drill-seeded at 100 kg ha^{-1} on April 29, 2008, and June 02, 2009, at 19-cm row spacing. Plots consisted of eight rows 4.5 m long.

Clomazone (Command 3ME herbicide, FMC Corporation, Agricultural Products Group, 1735 Market Street, Philadelphia, PA 19103) at 560 g ai ha^{-1} was applied the day after planting to control grasses. Clomazone has no activity on Texasweed (Anonymous 2011). The study area was surface-irrigated immediately after application of PRE herbicides. Cyhalofop-butyl (Clincher SF herbicide, Dow AgroScience, Indianapolis, IN 46268) at 313 g ai ha^{-1} and fenoxaprop-ethyl (Ricestar HT herbicide, Bayer CropScience, P.O. Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709) at 122 g ai ha^{-1} were applied for POST grass control. Cyhalofop-butyl and fenoxaprop-ethyl have no activity on Texasweed (Anonymous 2011). Herbicides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa. Hemp sesbania, the only other major broadleaf weed in the experimental area, was removed by hand-weeding as needed.

A 10-cm flood was established 5 to 6 wk after planting, when rice reached the four- to five-leaf stage, and was maintained until 2 wk before harvest. Nitrogen in the form of prilled urea (46–0–0, N–P–K) was broadcast applied at 126 kg ha^{-1} just before flood. An additional 42 kg ha^{-1} of nitrogen was broadcast-applied at panicle initiation stage of rice.

Texasweed Density Study. The density study was conducted using an additive design, wherein rice density was constant, and Texasweed density was variable (Harper 1977). Two experiments were conducted in 2008 and one in 2009. One of the 2008 experiments was conducted using a natural Texasweed population. Experimental plots had natural variation in Texasweed density and provided a range of densities. The average Texasweed density in experimental plots ranged from 5 to 60 plants m^{-2}. Texasweed plants were hand-thinned 7 d after rice emergence to increase the uniformity of the density within each plot. To achieve that, each plot was divided in to 0.5-m^2 sections using a 1.0-m by 0.5-m quadrat. The section with the sparsest Texasweed density was visually identified within each plot, and Texasweed plants were counted in that section. The Texasweed count thus obtained was used as the basis for the number of Texasweed plants to be retained in each section of that plot. Spacing between plants within each section was based on visual judgement. Texasweed emerging after hand-thinning were removed by hand-weeding. After hand-thinning, the average Texasweed density in experimental plots ranged from 0 to 40 plants m^{-2}.

The authors expected that controlling new flushes of Texasweed and other broadleaf in an area of high braodleaf weed indestation weeds would be a tedious job; therefore, a separate experiment was conducted in 2008 in an area with very low braodleaf weed infestion. In that experiment, and in the 2009 experiment, Texasweed densities were obtained by planting Texasweed seeds. The experimental design was a randamized complete block with three replications. Texasweed seeds were planted by hand at 0, 2, 4, 6, 10, 20, 30, and 40 seeds m^{-2}. To achieve uniformity in planting, plots were divided into 0.5-m^2 sections, and seeds were planted one section at a time. The seeds used in the study were collected from the local population at the site of the experiments. Fruit-bearing Texasweed plants from rice paddies at Louisiana State University Agricultural Center Northeast Research Station near Saint Joseph, LA, were cut in fall of 2007 and 2008. The cut plants were kept in 0.93-m by 0.53-m by 0.5-m high-density polyethylene containers (Sterilite 45-gallon tote, model 1948, Sterilite Corporation, P.O. Box 8001, Townsend, MA 01469) to air-dry under shade at room temperature. Naturally dehisced dark-brown seeds from the bottom of the containers were collected and stored in 1-L capacity, high-density polyethylene jars (32 oz. square jar, model 66188, United States Plastic Corporation, 1390 Newbrecht Rd., Lima, OH 45801) at room temperature. Texasweed seeds collected in this manner in fall of 2007 and 2008 were used in the experiments conducted in summer of 2008 and 2009, respectively.

Texasweed plants emerged before or along with rice in the experiments involving natural Texasweed population; however, in experiments involving Texasweed seed planting, there was a lag of about 7 d between rice and Texasweed emergence. Texasweed density was recorded by counting the number of plants in a 1-m^2 area in the center of each plot before flooding. The indended design was a randomized complete block, but Texasweed emergence was not 100%, and density treatments were not similar across replications. However, the three experiments provided 67 data points with varying Texasweed densities.

Rice height, rough rice yield, yield components, and percentage of moisture in rice harvest samples were recorded at the time of rice harvest. Rice was harvested on October 3 and October 15 in 2008 and 2009, respectively. Percentage of moisture in rice harvest samples will be referred to as percentage of moisture. Rice height was obtained by measuring five rice plants per plot from the ground to the tip of the extended panicle. In 2008, rough rice yield and rice sample moisture data were obtained by harvesting whole plots using a small-plot combine. In 2009, the small-plot combine could not be used because of inclement weather at the time of harvest, so rice yield data were obtained by threshing whole-plant samples hand-harvested from a 1-m^2 area in the middle of each plot. Percentage of moisture data at harvest were not collected in 2009 because the combine harvester was not used. Data on rice yield components were obtained from whole-plant samples hand-harvested from randomly selected, 2-m row length from the two center rows in each plot. Filled grains from 10 panicles, randomly selected from the harvested samples, were counted using a seed counter (Seed counter model 850-3, International Marketing and Design Corporation, 13802 Lookout Road, Suite 200, San Antonio, TX 78233) and weighed. Grains per panicle were calculated by dividing grain count by 10 and thousand-grain weight was calculated by dividing the weight by number of grains and multiplying by 1,000.

Rough rice yield was adjusted to 12% moisture, and data were converted to percentage of yield loss (percentage of the weed-free plots). The average of the weed-free plots was used to convert the data to percentage of yield loss. A graphical examination of the data showed a nonlinear relationship of Texasweed density with percentage of yield loss. Regression analysis was performed to model the percentage of yield loss as a function of Texasweed density. The rectangular hyperbolic model (Cousens 1985) was used to describe the relationship:

$$Y = aX/[(1 + aX)/b], \qquad [1]$$

where Y is percentage of yield loss, X is Texasweed density, a is the percentage of yield per unit of X when X approaches zero, and b is an asymptote corresponding to the maximum yield loss when X approaches infinity.

The NLMIXED procedure of SAS (SAS 2003 software, Version 9.1.3, SAS Institute, 100 Campus Drive, Cary, NC 27513-2414) was used to fit the nonlinear models in Equation 1. Replication within a year was considered a random effect. At first, a full-model with a different set of parameters for each of the three experiments conducted in 2008 and 2009 was fit. Then, a reduced model with same parameters for all the three experiments was fit. A null-model likelihood ratio test was used to compare the two models. The null-model likelihood ratio test showed no difference between years and experiments within the year 2008. Therefore, based on the criteria of better fit and parsimony, the model with the same set of parameters for combined data of both years (2008 and 2009) was selected as the final model. Normality of the residuals was confirmed using the UNIVARIATE procedure of SAS (SAS Institute). Graphical examination of the residuals showed homogeneous distribution about zero.

The effect of Texasweed density on the percentage of moisture at harvest was described by the traditional von Bertalanffy model (Sparre and Vanema 1998):

$$Y = Y_{\max}\{1 - \exp[-b(X - X_0)]\}, \qquad [2]$$

where Y is the percentage of moisture, X is Texasweed density, $Y_{\max}$ is the percentage of moisture as X approaches infinity, X_0 is the density point where Y is zero, and b is a rate coefficient. The statistical procedure of selecting the final model was similar to that used for yield-loss data.

A path coefficient analysis was carried out to study the direct and indirect effects of Texasweed density on yield components and rough rice yield. A path coefficient diagram is an a priori model of the cause-and-effect relationship between confounded variables (Li 1975). Donald and Khan (1996) stated, "Unlike multiple regression or correlation analyses, path coefficient analysis does not assume independence among predictor variables. In fact, change in one predictor variable is assumed to cause changes in other predictor variables for a given data set, i.e., predictor variables are "confounded" and change in an interdependent, compensatory way. Path analysis cannot be used to demonstrate the causality, but it can be used to study the implications of assuming a particular model of causation between confounded variables". In the path analysis used for this study, it was assumed that Texasweed density reduces rough rice yield through its effect on yield components. Thus, the effect of Texasweed density on rough rice yield was not assumed to be direct but mediated through its effect on effective tillers per unit area, grains per panicle, and thousand-grain weight. The three yield components were assumed to have a compensatory relationship with each other. This means that each of the three yield components changes in response to change in others. Path analysis was done using the TCALIS procedure of SAS (SAS 2008 software, Version 9.2, SAS Institute). Pooled data from the three density experiments conducted in 2008 and 2009 was used for path analysis.

Area of Influence Study. The area of influence study was conducted using 8 and 10 rice plots in 2008 and 2009, respectively. The experimental design was a repeated measure in distance. The four repeated measures were the increasing

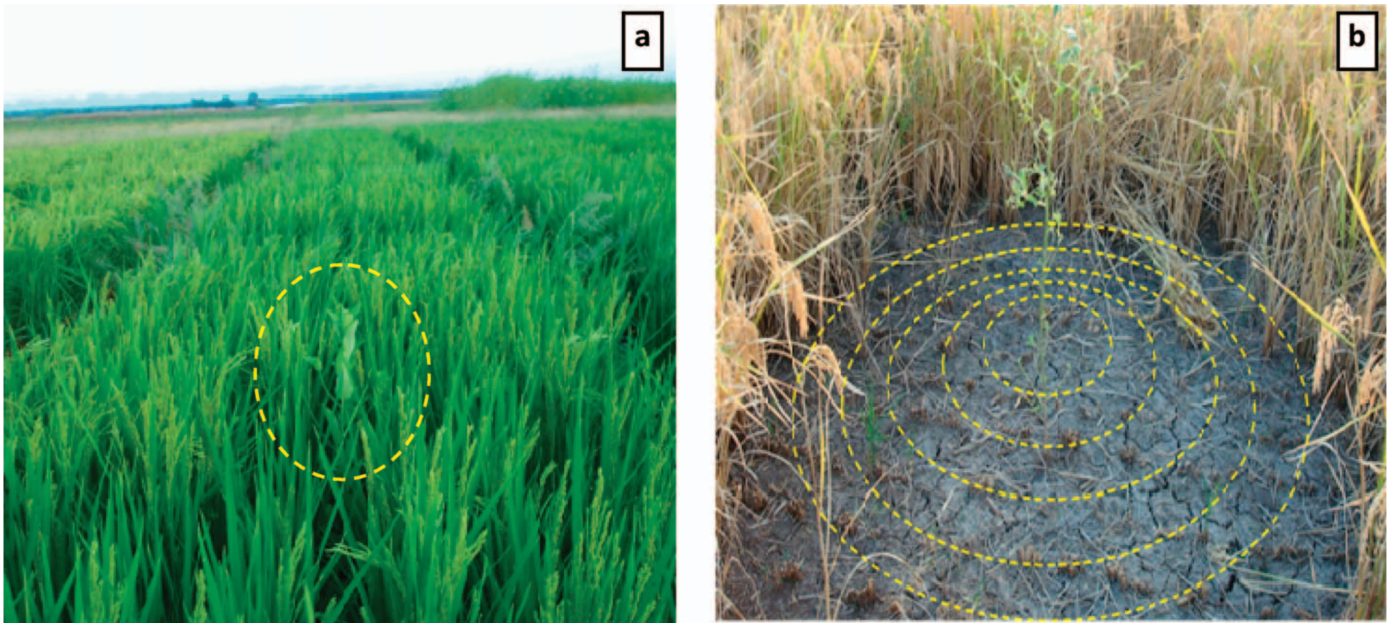

Figure 1. Area of influence study (a) central Texasweed plant in a plot; and (b) harvest scheme, 20-cm concentric bands. A color version of this figure is available in the online journal.

distances of 20, 40, 60, and 80 cm from the single Texasweed plant in the center of each plot. The plots were considered subjects, and distance from the central Texasweed plant was the repeated measure.

Five Texasweed seeds, obtained as described in the Texasweed density study, were planted in the center of each rice plot just after rice seeding, respectively. The Texasweed plants were thinned to 1 plant plot^{-1} 3 d after emergence. The experimental plots (Figure 1a) were kept free of weeds, except for the central Texasweed plant in each plot, using PRE and POST herbicides as described earlier and hand-weeding. The central Texasweed plants in the experimental plots were shielded from herbicides by covering them with plastic buckets at the time of herbicide application. The area immediately adjacent to the Texasweed plant was kept weed-free by hand-weeding.

Rice was harvested from four 20-cm-wide, concentric, circular bands around the central Texasweed plant in each experimental plot (Figure 1b). Because rice was drill-seeded in rows spaced 19 cm apart, the choice of 20-cm-wide harvest bands allowed only one rice row on each side of the central Texasweed plant to be included in each harvest band.

Effective tillers per square meter, rice height, rice yield, harvest index, grains per panicle, and thousand-grain weight were recorded for each concentric band within each plot using the harvested rice from the respective circular band . Effective tillers per square meter were calculated by dividing total number of effective tillers in the harvested rice by the area harvested. Rice height was measured, and the total number of grains and filled grains in each harvested rice were counted as described in the Texasweed density study, and the percentage of filled grains was calculated. Filled grains were used to calculate rough rice yield, grains per panicle, and thousand-grain weight. Rough rice yield was calculated by dividing the total weight of filled grains by the respective area harvested for each concentric band within each plot and was adjusted to 12% moisture. Other parameters were calculated using the procedure described for Texasweed density study, but instead of 10 panicles, the whole rice sample harvested from each concentric band within each plot was used.

To determine the effect of distance from the central Texasweed plant on rice growth, yield, and yield components, data were subjected to repeated-measures analysis using MIXED procedure of SAS (SAS 2003 software). Year and plot within a year were considered random effects. Distance from the central Texasweed plant was considered a repeated measure, with plot within year as a subject. Normality of the residuals was confirmed using the UNIVARIATE procedure of SAS (SAS 2003). Graphical examination of the residuals showed homogeneous distribution about zero. Means were separated using Tukey's test, and letter groupings were generated using the PDMIX800 macro in SAS (Saxton 1998). Linear and quadratic contrasts were then constructed to study the response as a function of the distance from central Texasweed plant.

Critical Period Study. Experiments were conducted in 2008 and 2009 using a natural population of Texasweed. A randomized complete-block design with three replications was used in both years. The average Texasweed density in the experimental plots was approximately 40 and 15 plants m^{-2} in 2008 and 2009, respectively. Treatments were weed-competition periods of 0 (season-long weed-free), 1, 2, 3, 4, 6, 8, and 12 wk after rice emergence (WAE) and weed-free periods of 0 (season-long weedy), 1, 2, 3, 4, 6, 8, and 12 WAE. Rice reached maturity at 16 WAE; therefore, season-long, weed-free plots were considered weed-free up to 16 WAE. Similarly, season-long, weedy plots were considered weedy up to 16 WAE.

In weed-competition period treatments, Texasweed were allowed to emerge at planting and compete for 1, 2, 3, 4, 6, 8, and 12 WAE; after the intended period, the plots were kept weed-free for remainder of the season. Emerged Texasweed were removed by hand-weeding. Bispyribac-sodium (Regiment herbicide, Valent Corporation, P.O. Box 8025, Walnut Creek, CA 94596) at 29 g ai ha^{-1} plus imazosulfuron (League herbicide, Valent) at 224 g ai ha^{-1} were applied to control any escapes and prevent new emergence. Bispyribac-sodium and imazosulfuron combination was used because it provided greater than 90% Texasweed control in our earlier experiments (Godara 2010).

In weed-free treatments, plots remained weed-free for the intended period, after which, Texasweed was allowed to emerge and compete with rice for the remainder of the season. Plots were kept free of Texasweed by hand-weeding and applying carfentrazone-ethyl (Aim EC herbicide, FMC Corporation) at 18 g ai ha^{-1}. Carfentrazone-ethyl controls Texasweed shorter than 10 cm (Anonymous 2008) and provided 100% control of cotyledon stage Texasweed in the experimental plots. Carfentrazone-ethyl has limited to no residual activity at the rates used (Anonymous 2008); therefore, these applications did not affect Texasweed emergence after intended weed-free period.

Rough rice yield data in 2008 were obtained by harvesting whole plots using a small-plot combine. In 2009, a small-plot combine could not be used because of inclement weather at the time of harvest, and yield data were obtained by threshing whole-plant samples hand-harvested from a 1-m^2 area in the middle of each plot. Rough rice yield was adjusted to 12% moisture. Yield data were converted to relative yield (percentage of weed-free). The average of the observations for the weed-free control was used to convert the data to percentage of weed-free control.

A visual examination of the scatter plots of the response variables against weed-free period or weed-competition period showed a nonlinear trend. Therefore, several nonlinear growth curves, as suggested in the literature (Cousens 1988; Hall et al. 1992; Knezevic et al. 2002), were selected as potential models for weed-competition period and weed-free period data. The visual examination of the scatter plots of the response variables against weed-free period or weed-competition period also showed a possible year effect. Therefore, the above-selected nonlinear models were first fit with year as a fixed effect and then, again, with year as a random effect. The NLMIXED procedure of SAS (SAS 2003 software) was used to perform nonlinear regression. Null-model likelihood ratio tests for nested models and Akaike's information criteria values for unrelated models were used to compare different models, and the criteria of better fit and parsimony was used to select a final model.

A four-parameter logistic model (Equation 3) with year as a fixed effect (separate sets of parameters for each year) provided the best fit for both weed-free and weed-competition period data:

$$Y = Y_{\max} + \|(Y_{\max} - Y_0)/\langle\{1 + \exp[-(X - X_0)]\}/b\rangle\|, \quad [3]$$

where Y is the relative yield (percentage of the weed-free control), and X is WAE, $Y_{\max}$ is the upper asymptote, Y_0 is the lower asymptote, X_0 is the time after emergence where the inflection occurs, and b is the slope at the inflection point.

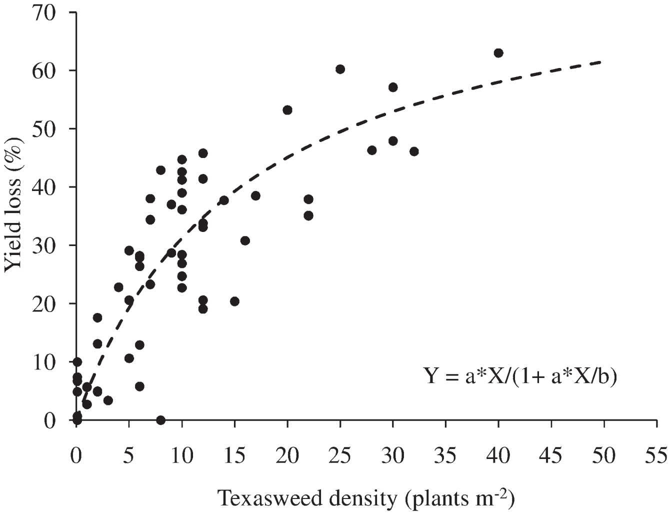

Figure 2. Effect of Texasweed density on rough rice yield. Equation 1, where Y and X are the yield loss and Texasweed density, respectively. Parameter and standard errors (in parentheses) were a = 5.07 (0.64) and b = 81.20 (10.62).

Normality of the residuals was confirmed using the UNIVARIATE procedure of SAS (SAS 2003 software). Graphical examination of the residuals showed homogeneous distribution about zero.

The AYL level used to predict the critical period of weed interference was arbitrarily set at 5%. The CWFP was calculated from the model fitted to weed-free period treatment data; the CWFP was up to the WAE when the estimated relative yield was (100 − AYL), i.e., 95%. The CPWR was calculated from the model fitted to weed-competition period treatment data; CPWR started at WAE when the estimated relative yield was (100 − AYL), i.e. 95%. CPWC was calculated as the duration where CWFP and CPWR overlapped.

Results and Discussion

Texasweed Density Study. Texasweed density did not affect rice height (data not shown). The response of rice yield to Texasweed density was significant (Figure 2). Based on the a value, predicted rice yield loss from season-long Texasweed interference at 1 plant m^{-2} was 5%. Texasweed infestation at 10 and 50 plants m^{-2} caused 31 and 61% yield loss, respectively. Season-long interference of hemp sesbania and Northern jointvetch at about 10 plants m^{-2} caused 40 and 19% yield loss in drill-seeded rice (Smith 1968).

The results of the path coefficient analysis carried out to study the cause-and-effect relationship between rough rice yield and yield components are presented in Figure 3 and Table 1. Double-headed arrows in the path diagram (Figure 3) illustrate the assumption that change in two variables compensates for one another (Donald and Khan 1996). Single-headed arrows illustrate that one variable is assumed to affect another without being influenced by it (Donald and Khan 1996). In the path analysis, Texasweed

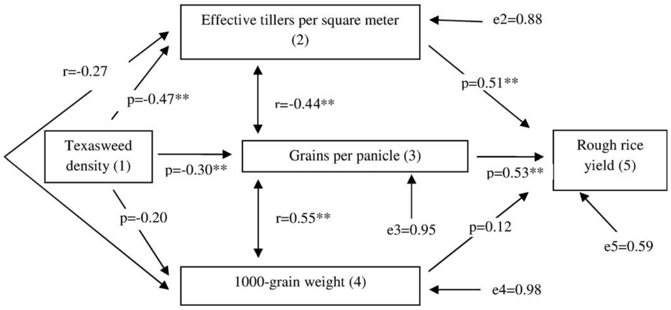

Figure 3. Diagrammatic representation of direct and indirect effect of yield components on rough rice yield in interference experiments conducted using planted densities. Single-headed arrows represent direct influences measured by path coefficients (*p*), double-headed arrows indicate correlation coefficients (*r*), and *e* represents residual error. Positive or negative values of the coefficient *p* imply an increase or decrease in affected variable, respectively, because of an increase in affecting variable. Coefficients marked with asterisks are significantly different from zero at * $P \leq 0.05$; ** $P \leq 0.01$.

Table 1. Path of association between the response variable, rough rice yield, and the direct and indirect predictor variables, effective tillers per square meter, grains per panicle, and thousand-grain weight, and Texasweed density combined over 2008 and 2009.

Path of association	Calculations[a]	Value
Effective tillers per square meter → rough rice yield		
Direct effect	p25	0.51
Indirect effect via grains per panicle	r23 × p35	−0.23
Indirect effect via thousand-grain weight	r24 × p45	−0.03
Total correlation	r25	0.25
Grains per panicle → rough rice yield		
Direct effect	p35	0.53
Indirect effect via culms per square meter	r23 × p25	−0.22
Indirect effect via thousand-grain weight	r34 × p45	0.07
Total correlation	r35	0.38
Thousand-grain weight → rough rice yield		
Direct effect	p45	0.12
Indirect effect via culms per square meter	r24 × p25	−0.14
Indirect effect via grains per panicle	r34 × p35	0.29
Total correlation	r45	0.27
Texasweed density → rough rice yield		
Indirect effect via culms per square meter	p12 × p25	−0.24
Indirect effect via grains per panicle	p13 × p35	−0.16
Indirect effect via thousand-grain weight	p14 × p45	−0.02

[a] Abbreviations: p, path coefficient; r, correlation coefficient obtained from Figure 3.

density was assumed to reduce rough rice yield by affecting yield components. The results (Figure 3) show that an increase in Texasweed density was associated with a reduction in the number of effective tillers per square meter ($P = -0.47$) and thus reduced rice yield (Table 1). Texasweed density did not affect thousand-grain weight, which is indicated by the nonsignificant path coefficient (Figure 3). Thousand-grain weight also had no direct effect on rough rice yield (Figure 3; Table 1). Texasweed interference also reduced grains per panicle ($P = -30.0$), which subsequently resulted in yield reduction (Table 1). Although both the number of effective tillers per square meter and grains per panicle were adversely affected by the increasing Texasweed density, the significant negative correlation ($r = -0.44$) between effective tillers per square meter and grains per panicle indicated yield-component compensation (Figure 3). The reduction in number of effective tillers per square meter was compensated, to some degree, by an increase in number of grains per panicle. However, that effect was not strong enough to reverse the detrimental effect of reduced effective tillers per unit area on rough rice yield. The results indicate that Texasweed reduces rough rice yield by affecting both effective tillers per unit area and grains per panicle. These results are in contrast to the findings of Smith (1968) on hemp sesbania and northern jointvetch and Smith (1984) on spreading dayflower interference in rice, where reduction in rice yield was attributed to decreased grain filling because of shading.

Based on the data from experiments conducted in 2008, Texasweed density had a significant effect on the moisture content of the rice grain sample at harvest. Increasing Texasweed density increased moisture content of the rice harvest sample (Figure 4). The higher moisture content of the rice harvest samples was probably due to a contamination with Texasweed capsules, which were still green at the time of harvest. Rice sample from plots having high Texasweed density also seemed to have higher contamination of Texasweed seeds; however, that was not quantified.

Area of Influence Study. Rice height and thousand-grain weight were not affected by the distance from the central Texasweed plant (data not presented). The linear and quadratic contrasts for those responses were also not significant. For other parameters, Tukey's test did not show any differences between 40, 60, and 80 cm distances, but contrast analysis showed significant linear and quadratic trends (Table 2). The significant linear and quadratic contrasts indicated an increase in rough rice yield, effective tillers per square meter, harvest index, grains per panicle, and

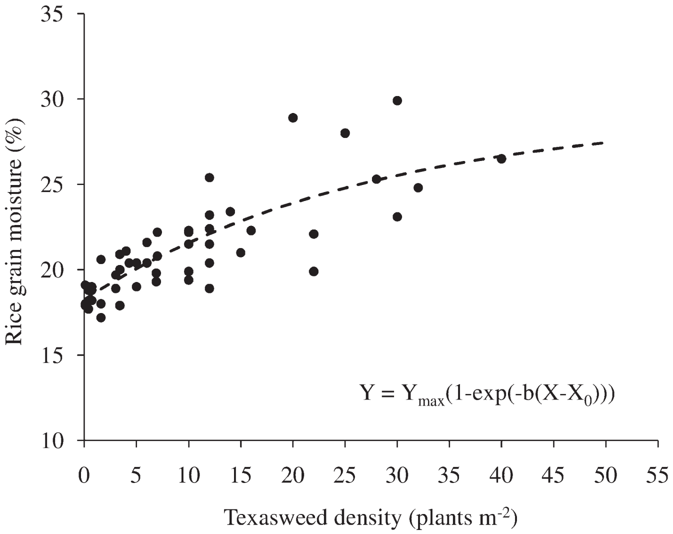

Figure 4. Effect of Texasweed densities on percentage of moisture in the rice harvest sample in 2008. Equation 2, where *Y* and *X* are the moisture percentages and Texasweed density, respectively. Parameter and standard errors (in parentheses) were $Y_{max} = 29.29$ (3.32), $b = 0.036$ (0.017), and $X_0 = 27.12$ (8.72).

Table 2. Effect of the distance from central Texasweed plant on rough rice yield and yield components, averaged over 2008 and 2009.[a]

Distance	Rough rice yield	Effective tillers square meter	Harvest index	Grains per panicle	Filled grains
cm	kg ha^{-1}		%		%
20	2,608 b	263 b	35.7 b	72 b	45.4 b
40	4,432 a	316 a	41.8 ab	80 ab	54.4 a
60	4,719 a	305 a	43.6 a	85 a	54.0 a
80	5,010 a	321 a	43.8 a	85 a	53.5 ab
	P value				
Contrasts					
Linear	0.0002	0.0007	0.0095	0.0158	0.0100
Quadratic	0.0423	0.0504	0.1225	0.1763	0.0117

[a] Means within each column followed by a common letter are not significantly different at P = 0.05 using Tukey's test.

percentage filled with increasing distance from the Texasweed plant in a plot.

Critical Period Study. Season-long weed interference caused 65 and 24% yield loss in 2008 and 2009, respectively (Figures 5 and 6). Texasweed population in the experimental area was relatively low, 15 plants m^{-2} in 2009 compared with 40 plants m^{-2} in 2008. This difference in the average Texasweed density in the experimental area probably explains the observed difference in rice yield loss between the two years.

CWFP was estimated to be between 5 and 6 WAE in both years (Figures 5 and 6). Weed-free conditions maintained until 6 WAE provided yields similar to the season-long, weed-free treatment. This may be attributed to Texasweed not emerging after flood establishment, which was at around 6 WAE. Weed-free periods of 2 and 4 WAE also produced higher yields than did the season-long weedy plots. CPWR was estimated to be 0 and 2 WAE in 2008 and 2009, respectively (Figures 5 and 6). CPWC was thus 0 to 6 WAE in 2008 and 2 to 5 WAE in 2009. The difference in CPWR between the 2 yr may be due to the difference in Texasweed density as discussed earlier. Martin et al. (2001) also emphasized the importance of weed density in determining the critical period of interference.

Texasweed interference for 4 WAE accounted for more than 50% of the yield loss caused by season-long interference (Figures 5 and 6). That is in contrast to the finding of Smith (1968, 1984) for hemp sesbania, northern jointvetch, and spreading dayflower interference in rice. Smith (1968) reported that interference from 5 plants m^{-2} of hemp sesbania and northern jointvetch up to 6 wk after rice emergence caused only 2% yield loss in drill-seeded rice. Whereas, the yield loss from season-long interference of the two weeds was 19 and 17%, respectively. Smith (1968) also concluded that those weeds reduced rice yield primarily because of shading effects at the time of rice grain filling and were not competitive if removed before they were tall enough to shade the rice plants. Smith (1984) reported similar findings for spreading dayflower. Season-long interference at

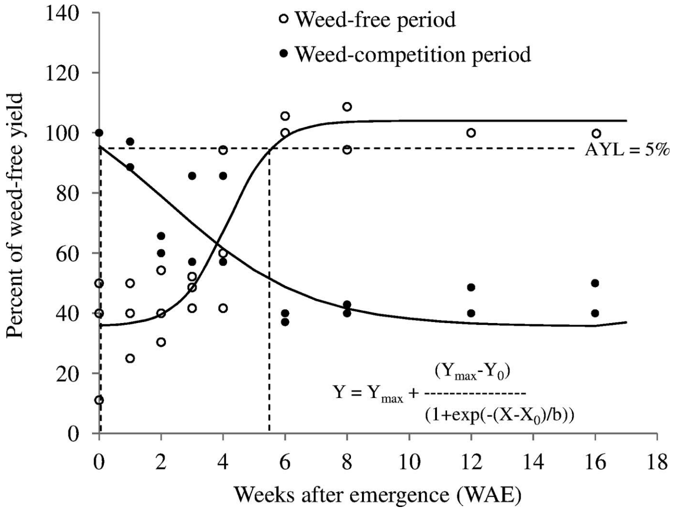

Figure 5. The effects of Texasweed interference and weed-free periods on relative rice yield in 2008. Equation 3, where Y and X are the relative rice yield and weeks after rice emergence (WAE), respectively. Parameter estimates and standard errors were $Y_{max} = 118.15$ (14.36), $Y_0 = 35.56$ (4.70), $b = 2.27$ (0.80), and $X_0 = 2.22$ (1.14) for weed interference period; $Y_{max} = 103.96$ (2.92), $Y_0 = 35.53$ (5.50), $b = -0.7693$ (0.32), and $X_0 = 4.12$ (0.31) for the weed-free period.

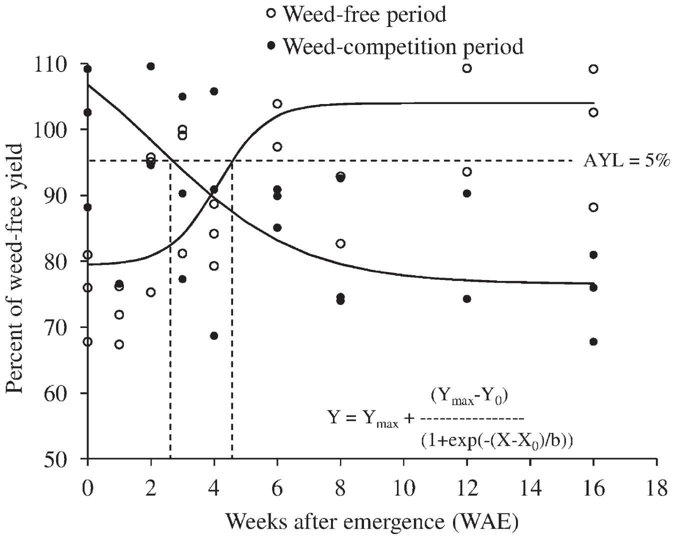

Figure 6. The effects of Texasweed interference and weed-free periods on relative rice yield in 2009. Equation 3, where Y and X are the relative rice yield and weeks after rice emergence (WAE), respectively. Parameter estimates and standard errors were $Y_{max} = 118.15$ (14.36), $Y_0 = 76.52$ (4.42), $b = 2.27$ (0.80), and $X_0 = 2.22$ (1.14) for weed interference period; $Y_{max} = 103.96$ (2.92), $Y_0 = 79.34$ (4.00), $b = -0.7693$ (0.32), and $X_0 = 4.12$ (0.31) for weed-free period.

22 plants m^{-2} caused 18% rice yield loss, whereas a weed interference period of 20 to 80 d after emergence did not cause any yield reduction. The 18% yield reduction observed in season-long, weedy plots was attributed to the adverse effects of shading from spreading dayflower on the rice grain-filling process. Weed species in Smith (1968, 1984) did not emerge with the crop in the same field but were grown in a greenhouse and transplanted 6 to 11 d after rice emergence. In addition, those weed species were reported to grow taller than rice and form a thick canopy above the rice. In the present study, Texasweed plants grew taller than rice, but the individual plant did not form a thick and wide canopy in rice plots. Average height for rice and Texasweed at the boot stage of the rice was 82 and 110 cm, respectively. The average canopy diameter of a Texasweed plant was 22 (± 5) cm.

Previous work by Smith (1968, 1984) showed that broadleaf weeds reduced rice yield primarily by shading rice plants and reducing grain filling. However, the present studies demonstrate that Texasweed interference reduced rice yield much earlier in the season. Both the Texasweed density and area of influence studies showed that Texasweed interference reduced rice yield by affecting the number of effective tillers per unit area. Effective tillers per unit area are a function of tillering, which begins when rice is at the four- to five-leaf stage. These results indicate that substantial yield losses can occur if Texasweed control is delayed beyond 2 WAE. In addition, rice should be kept free of Texasweed until 5 to 6 WAE or until permanent flood establishment.

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