Light Interception and Yield Potential of Short-Season Maize (*Zea mays* L.) Hybrids in the Midsouth

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ABSTRACT

The midsouthern USA typically has a mid- to late-summer drought that limits the productivity of nonirrigated maize (*Zea mays* L.) production. We hypothesized that by increasing seeded population and narrowing row spacing, short-season maize hybrids in the Midsouth would have similar yield but require less irrigation compared with hybrids currently grown. Irrigated experiments were conducted at Fayetteville, AR, in 2001, 2002, and 2003 and at Keiser, AR, in 2002 and 2003. Factors evaluated included maize maturity (75- to 110-d maize hybrids) and maize seeded population (5 to 20 seed m^{-2}) sown in 50-cm rows. Between emergence and black layer, short-season maize hybrids required 30 to 50% less irrigation than did their full-season counterparts. Yield of short-season maize at high plant populations ($\approx$19 plants m^{-2}) was equal to that of full-season hybrids, which reached maximum yield at lower plant populations ($\approx$8 plants m^{-2}). Maize biomass at maturity had a linear relationship with cumulative intercepted photosynthetically active radiation (CIPAR) from emergence to maturity, but maize yield had an asymptotic relationship with CIPAR with little increase in yield for CIPAR above 555 MJ m^{-2}. This research indicates that increasing plant population for short-season maize hybrids increased CIPAR, which compensated for a short growing season to achieve similar potential yield to full-season hybrids in the Midsouth with substantially less irrigation.

M ID-SEASON DROUGHT is a recurrent problem in the Midsouth, and a great deal of effort has been directed toward developing plants that can physiologically withstand drought stress or management systems that avoid drought stress altogether (Edmeades et al., 1999; Howell et al., 1998; Larson and Clegg, 1999; Norwood, 2001). While physiological tolerance of drought stress is a worthwhile endeavor, it typically involves extensive investigation of physiological processes, identification of genetic diversity for target traits, and long-term breeding efforts (Edmeades et al., 1999; Sinclair et al., 2004). Avoidance of drought stress, in contrast, can be achieved by matching crop phenology with prevailing rainfall patterns and is a relatively simple concept. Furthermore, benefits can immediately be reaped by agricultural producers without the need for introgression of physiological traits for drought tolerance.

Maize (*Zea mays* L.) production in the Midsouth typically entails sowing a hybrid that requires 112 to 120 d from emergence to physiological maturity. Sowing density for these hybrids is approximately 7 seed m^{-2} in 0.76-m

or wider rows, and sowing dates are typically in late March or early April (Cartwright et al., 2003). Some producers choose to produce a 108- to 110-d hybrid, however, to aid in distribution of labor requirements. This combination of sowing date and maize maturity generally results in the reproductive phase of maize development coinciding with a midseason drought typically experienced in the Midsouth (Cartwright et al., 2003; Purcell et al., 2003). This results in the need for supplemental irrigation to ensure adequate grain yield.

Previous research in moisture-limited environments other than the Midsouth has indicated that maize crop maturity can be an effective tool to reduce irrigation requirements and avoid drought (Howell et al., 1998; Larson and Clegg, 1999). Therefore, short-season maize hybrids (<90 d from emergence to maturity) would seemingly have potential for avoiding drought in the Midsouth. However, since short-season maize hybrids are primarily grown in the northern USA and southern Canada, there is little research on the adaptability of these hybrids in a more southern environment.

One concern for production of short-season maize hybrids in the Midsouth is that there would be less time for leaf area production and for interception of photosynthetically active radiation (PAR). Any reduction in leaf area or season-long light interception would likely result in decreased yield potential (Tollenaar and Bruulsema, 1988). Therefore, row spacing less than 0.8 m (Andrade et al., 2002; Porter et al., 1997) and plant populations higher than current recommendations (Cox, 1997; Pedersen and Lauer, 2002) are required for short-season hybrids to ensure rapid canopy closure and full light interception (Westgate et al., 1997). The response to narrow row spacing and high plant population, however, has been shown to be hybrid specific in some environments (Westgate et al., 1997). The differential response to increased plant population among environments creates a need for additional research to elucidate a mechanistic, rather than empirical, approach to determining optimal plant population of maize.

We hypothesized that narrowing row spacing and increasing plant population of short-season maize hybrids would compensate for the short growing season, increase season-long light interception, and result in similar yield potential as full-season hybrids. Furthermore, better coordination of crop phenology and prevalent rainfall patterns through use of short-season hybrids was hypothesized to reduce irrigation demand for maize production. The objectives of this research were to (i) determine if yield of short-season maize in the Midsouth was similar

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Abbreviations: CIPAR, cumulative intercepted photosynthetically active radiation; HI, harvest index; PAR, photosynthetically active radiation; RUE, radiation use efficiency.

to full-season hybrids currently being produced in the area, (ii) evaluate the potential of short-season maize hybrids for drought avoidance in the Midsouth, and (iii) develop a mechanistic understanding of the response of maize to seeded population over a wide range of maize maturities and different environmental conditions.

MATERIALS AND METHODS

Location Information and Site Preparation

Field studies were conducted in 2001, 2002, and 2003 at Fayetteville, AR (36°5′ N, 94°10′ W), on a Captina silt loam (fine-silty, siliceous, active, mesic Typic Fagiudults). Plot size was four 0.5-m rows that were 7.5 m long. The plot area was prepared by disking to a 10-cm depth 2 to 3 d before sowing and by applying 112, 110, and 120 kg ha^{-1} of N, P$_2$O$_5$, and K$_2$O, respectively. Additionally, 1.2 kg ha^{-1} of the herbicide Axiom (Bayer CropScience, Research Triangle Park, NC) and 0.18 L ha^{-1} of the insecticide Warrior T (Syngenta Crop Protection Inc., Greensboro, NC) were applied and incorporated.

In 2002 and 2003, experiments were conducted at the Northeast Research and Extension Center at Keiser, AR (35°40′ N, 90°5′ W), on a Convent silt-loam (coarse-silty, mixed, super-active, nonacid, thermic Fluvaquentic Endoaquepts). Plots at this location consisted of four beds that were approximately 15 cm high and spaced 0.95 m apart. Two maize rows 0.4 m apart were centered on top of each bed. Plot length was 10 m, and raised beds were formed the fall before seeding. Plot area was prepared for sowing by applying preplant fertilizer consisting of 112 and 90 kg ha^{-1} of N and P$_2$O$_5$, respectively, and incorporating the same preplant pesticides as used at the Fayetteville location.

Experimental Design

At Fayetteville, experimental design was a split-plot arrangement of a randomized complete block design with four replications (blocks) in 2001 and 2002 and five replications in 2003. The same treatment structure was used at Keiser in 2002 and 2003. Main plots were maize hybrid, and subplots were seeded population (5, 9, 12, 16, and 20 seeds m^{-2}). The hybrids sown in 2001 were Pioneer hybrids 39W54 (73 d) and 39F06 (86 d) and the Syngenta hybrid NK6460 (110 d); the hybrids sown in 2002 were Pioneer hybrids 39W54, 39R34 (77 d), 39T68 (77 d), 39D81 (84 d), and 39F06 and the Garst hybrid G8984 (83 d); and the hybrids sown in 2003 were Pioneer hybrids 39W54, 39R34, 39T68, 39M27 (77 d), 39F06, and 32W86 (114 d).

Procedural Operations and Dates

A four-row John Deere 7100 (Deere & Co., Moline, IL) planter with a cone attachment for each row was used for sowing at Fayetteville. An eight-row John Deere 7100 planter with a cone attachment for each row was used for sowing at Keiser. Maize plant population was determined within 1 wk of emergence by counting the number of plants per 3 m of row at four separate locations within the center two rows (two beds at the Keiser location) of each plot.

All sidedress N applications were made using ammonium nitrate granules. In 2001, plots at Fayetteville were seeded 13 April, and a sidedress application of 130 kg ha^{-1} N was made on 23 May. In 2002, plots were seeded on 4 April at Fayetteville and 11 April at Keiser. Sidedress fertilizer applications were made by broadcast-spreading 130 and 170 kg ha^{-1} N on 14 May and 7 May at Fayetteville and Keiser, respec-

tively. In 2003, plots were seeded 11 April at Fayetteville and 16 April at Keiser. Sidedress fertilizer applications were made by broadcast-spreading 130 and 170 kg ha^{-1} N on 4 June and 13 May at Fayetteville and Keiser, respectively.

To remove any edge effects, 0.6 m of plot area was removed from the end of plots immediately before harvest. Harvest index (HI) samples from 1 m of row at Fayetteville and from 1 m of two rows (one bed) at Keiser were taken for each plot at maturity by clipping plants at the soil surface and bundling. Harvest index samples were dried at approximately 50°C for a period of 5 to 7 d, weighed, and shelled. Harvest index was calculated by determining the ratio of seed mass to the total aboveground plant mass. Total biomass production was calculated as the quotient of grain yield and HI. Average seed mass was calculated by weighing 100 seeds from each HI sample.

Maize was harvested by hand-removing ears from the two center rows at Fayetteville and the four center rows (two center beds) at Keiser. Ears were then fed into a small-plot combine, and grain weight was recorded and corrected to 155 g kg^{-1} moisture content.

Irrigation

Irrigation at Fayetteville was applied by overhead sprinklers when the estimated soil water deficit reached 30 mm. The amount of irrigation varied from 13 to 30 mm per application, depending on wind conditions. Irrigation amounts at Fayetteville were measured using rain gauges placed randomly throughout the experiment at the soil surface. Furrow irrigation was used at Keiser when the estimated soil water deficit reached 44 mm. Irrigation applications were made in 73-mm increments and were assumed to be 60% efficient (i.e., 40% water loss due to runoff). Irrigation data for both locations represent total irrigation applied and do not take into account loss due to runoff. Irrigation was terminated at black layer (Ritchie et al., 1993) at both locations.

Soil water deficit was estimated using the University of Arkansas' Irrigation Scheduling Program, which is available for download (http://www.aragriculture.org/computer/schedule/default.asp; verified 1 Oct. 2004). This program subtracts daily estimates of crop evapotranspiration from daily inputs of either irrigation or rainfall (Cahoon et al., 1990). Irrigation is recommended once the cumulative soil water deficit reaches a critical value that is determined by soil characteristics and rooting depth. Although plant population may have affected evapotranspiration and soil water deficit very early in the season (Howell et al., 1998), irrigation decisions were made based on estimated water deficit for the experiment as a whole. This may have overestimated the amount of irrigation required for lower plant populations. The inability to irrigate on a plot-by-plot basis, however, necessitated estimation of irrigation needs based on the experiment as a whole.

Statistical Analyses

Thermal time for a given day was calculated as the mean daily temperature using a base temperature of 10°C and a maximum temperature of 30°C (Coelho and Dale, 1980). Cumulative thermal time after emergence was determined by summing daily thermal time values. Phenological data were recorded at the Fayetteville location, and dates of phenological events at the Keiser location were estimated each year based on days required to obtain the same amount of thermal time as was required to reach the same phenological events at the Fayetteville location.

We used a digital imagery technique (Purcell, 2000) to estimate fractional light interception approximately every 7 d until

maize reached a height of approximately 1.5 m. At this point, overhead, digital photography was not feasible with available equipment. A final measurement of fractional light interception was made near solar noon approximately 1 wk after tasseling using a 1-m quantum sensor (model LI-191SA, LI-COR, Lincoln NE) by placing the light meter into each plot diagonally between the center two rows.

The digital imagery technique that we used to estimate fractional light intercepted (Purcell, 2000) was originally developed for soybean [*Glycine max* (L.) Merr.]. For soybean, results from this technique agreed well with fractional light interception measurements made with a 1-m quantum sensor, and measurements were relatively insensitive to light intensity, population density, and time of day when photographs were made. The theoretical arguments behind the use of the digital-imagery technique would apply to other crops, including grass species such as maize. Indeed, this technique has been used successfully in wheat (*Triticum aestivum* L.; Caviglia et al., 2003) to estimate fractional light interception.

Leaf expansion and canopy development in maize are temperature dependent (Ritchie and NeSmith, 1991); therefore, fractional light interception measurements were evaluated as a function of thermal time (°Cd). Daily predicted fractional light interception as a function of plant population and thermal time after emergence was obtained for each hybrid at Fayetteville in 2001, 2002, and 2003 and at Keiser in 2002 by response surface analysis using the PROC RSREG function of SAS v. 8.2 (SAS Inst., Cary, NC). Cross products and squared terms were nonsignificant ($P < 0.05$) in predicting fractional light interception at Keiser in 2003; therefore, a multiple linear regression analysis was used instead of response surface analysis. Predicted fractional light interception was calculated for each day for each plot using coefficients obtained from regression analysis, thermal time, and actual plant populations. Since fractional light interception greater than 1 cannot be achieved, a maximum value of 1 was established for daily predicted fractional light interception. Cumulative intercepted photosynthetically active radiation (CIPAR) was determined by calculating the product of daily fractional light interception and daily incident radiation and summing intercepted radiation from maize emergence to physiological maturity (black layer) (Ritchie et al., 1993). Daily PAR was calculated as 50% of the total solar radiation (Monteith, 1977; Sinclair and Muchow, 1999). Total solar radiation was estimated using the procedure of Hargreaves and Samani (1982) as modified by Annandale et al. (2002). Ball et al. (2004) found that this method of estimating solar radiation agreed well with observed values over a wide geographical region without a need for site-specific calibration.

Grain yields for the hybrid Pioneer 39W54 at the Keiser location in 2002 were less than 500 g m^{-2} compared with yields of 600 to 1000 g m^{-2} for hybrids of similar maturity. Therefore, data for this hybrid at Keiser in 2002 were removed from analysis. The hybrid Pioneer 32W86 had extensive lodging at Keiser, AR, in 2003, and data for this hybrid at this location were removed from all analyses as well. Lodging was not evident for other hybrids, regardless of population density, year, or location.

For short-season hybrids, aboveground biomass at harvest (Y, g m^{-2}) was modeled as an exponential function of maize plant population (x, plants m^{-2}) whereby:

$$Y = \alpha(1 - e^{-\beta_1 x}) \qquad [1]$$

where α represents the asymptotic predicted value of Y and β_1 is an indicator of the responsiveness of Y to increasing units of the independent variable (plant population in this case). A model similar to Eq. [1] was used to assess the response of

aboveground biomass at maturity and grain yield (Y variables) to CIPAR (x, MJ m^{-2}), except that this model includes a y intercept (β_0) whereby:

$$Y = \beta_0 + \alpha(1 - e^{-\beta_1 x}) \qquad [2]$$

Regression analyses for maize biomass, yield, average seed mass, and seed number as a function of plant population and for maize biomass and yield as a function of CIPAR were performed using SigmaPlot v. 7.101 (SPSS Inc., Chicago, IL). Outliers for each regression were determined using studentized deleted residuals. Any observation having a studentized deleted residual greater than 2 was removed from analysis. This resulted in roughly seven to eight (approximately 10%) data points being removed from each analysis.

Response of HI to plant population was analyzed by considering maize hybrid as a covariate, with hybrid classified as a nominal variable, and plant population as a continuous variable in the same model. This analysis generated an intercept and slope describing the relationship of the dependent and independent variables and is generally preferred to multiple-comparison procedures when a stepwise series of treatments are applied (Cerrato and Blackmer, 1990; Chew, 1976).

RESULTS

Phenology and Irrigation

Differences in crop maturity among hybrids were primarily due to differences in duration of vegetative development (emergence to silking), which differed from 12 to 21 d among hybrids in different environments (Table 1). In contrast, the difference among hybrids in the duration of reproductive development (silking to black layer) ranged from 4 to 15 d among hybrids in different environments. Phenological development for hybrids of similar maturity in some cases also differed in the duration of vegetative or reproductive development. For example, in Fayetteville in 2002, 39W54 and 39R34 both reached physiological maturity 79 d after emergence (855°Cd), but they differed by 9 d in the duration of their vegetative and reproductive development. The reason(s) for the differences in phenology of hybrids of similar maturity is not known but may be related to hybrid's interaction with temperature and photoperiod.

Irrigation requirements were considerably less for the shortest-season hybrids and increased as time from emergence to black layer increased, but this varied by location. For example, there was 71% difference in irrigation demand between the shortest- and longest-maturity hybrids at Fayetteville in 2002 but only 46% difference at Keiser that same year. Conversely, there was a 40% difference in irrigation demands between the shortest- and longest-maturity hybrids at Fayetteville in 2003 and a 93% difference at Keiser.

Biomass and Yield

Equation [1] explained the relationship between aboveground biomass at harvest of short-season maize and maize plant population very well (Fig. 1A). The variation about the fitted line indicates that there was some genetic variation in response to increased plant population. According to the fitted equation, 90 and 95% of

Table 1. Average crop phenology, harvest date, and irrigation applied from crop emergence to black layer for maize hybrids at Fayetteville in 2001, 2002, and 2003 and Keiser in 2002 and 2003.

Year	Location	Hybrid	Days to silking	Days from silking to black layer	Thermal time to silking	Thermal time to black layer	Harvest date	Irrigation
					°Cd			cm
2001	Fayetteville	39W54	49	31	476	946	27 July 2001	9
		39F06	54	32	541	1001	2 Aug. 2001	11
		N6460	61	39	624	1240	14 Aug. 2001	13
2002	Fayetteville	39W54	48	31	405	855	12 Aug. 2002	7
		39R34	57	22	527	855	12 Aug. 2002	7
		39T68	58	23	541	886	12 Aug. 2002	9
		39D81	65	25	643	1019	12 Aug. 2002	11
		39F06	57	37	527	1084	12 Aug. 2002	12
		G8984	69	27	703	1117	12 Aug. 2002	12
	Keiser	39R34	49†	22	–	–	21 Aug. 2002	15
		39T68	50	23	–	–	21 Aug. 2002	15
		39D81	57	24	–	–	21 Aug. 2002	22
		39F06	49	36	–	–	21 Aug. 2002	22
		G8984	61	26	–	–	21 Aug. 2002	22
2003	Fayetteville	39M27	54	27	457	830	30 July 2003	9
		39R34	57	27	495	874	30 July 2003	9
		39T68	57	27	495	874	30 July 2003	9
		39W54	57	27	495	874	30 July 2003	9
		39F06	62	26	557	935	14 Aug. 2003	10
		32W86	72	37	703	1242	25 Sept. 2003	15
	Keiser	39M27	44	28	–	–	24 July 2003	15
		39T68	47	28	–	–	24 July 2003	22
		39W54	47	28	–	–	24 July 2003	22
		39R34	53	28	–	–	24 July 2003	22
		39F06	53	26	–	–	24 July 2003	22

† Days after emergence for silking and black layer at Keiser were estimated each year based on days required to obtain the same amount of thermal time as was required to reach the same phenological events at the Fayetteville location.

maximum predicted biomass would be achieved at 15 and 20 plants m^{-2}, respectively.

For the full-season hybrids, both linear and nonlinear regressions were nonsignificant ($P < 0.05$) for the relationship between maize aboveground biomass at harvest and plant population (Fig. 1B). This indicates that the lowest-seeded population of 5 plants m^{-2} used in this experiment was sufficient to achieve maximum biomass compared with the 20 plants m^{-2} that were required to achieve roughly the same biomass in short-season maize. Average aboveground biomass at harvest for full-season hybrids (>1117°Cd from emergence to black layer) was 2393 g m^{-2}, which was comparable to 95% of the predicted asymptotic biomass (2409 g m^{-2}) of short-season hybrids used in this experiment.

Equation [1] also described maize yield (g m^{-2}) as a function of plant population (plants m^{-2}) well (Fig. 2A and 2B). Short-season (1135 g m^{-2}) and full-season (1112 g m^{-2}) maize hybrids had statistically similar (i.e., within one standard error) asymptotic yield potential in this study. Similar to biomass, though, the plant population required to achieve maximum yield differed greatly between short- and full-season hybrids. For example, short-season maize produced 1000 g m^{-2} at 13 plants m^{-2}, whereas full-season maize achieved the same production level at 6 plants m^{-2}. To achieve yields of 1100 g m^{-2} required approximately 22 plants m^{-2} for short-season hybrids and 8 plants m^{-2} for full season hybrids.

Covariate analysis of the response of HI to plant population indicated that for all environments there were significant differences among hybrids in HI, but with the exception of Fayetteville in 2001, there was no significant interaction between hybrid and plant population (Table 2). This indicates that, in general, HI did not respond to plant population. Values for HI at Fayetteville tended to be somewhat lower (0.33 to 0.47) than for Keiser (0.41 to 0.54) (Table 3). At Fayetteville, HI values did not appear to be associated with hybrid maturity, but at Keiser, there was a general trend for HI values to decrease as hybrid maturity increased.

For Fayetteville in 2001, the full-season hybrid, N6460, did have a significant decrease in HI as plant population increased (Table 3). Previous studies have reported a reduction of HI as plant population increased (Westgate et al., 1997), which was attributed to an increased number of barren plants at higher plant populations. Plots in this experiment were inspected before harvest each year, and although ear size decreased as plant population increased, there were no barren plants, which is consistent with overall stability of HI observed in this study compared with previous work. The fact that HI was reduced by increased plant population in the longest-season hybrid (N6460) used in this experiment, however, explains why maximum yield was obtained at approximately 5% lower maize plant population than required to obtain maximum biomass production.

Average seed mass decreased as maize plant population increased (Fig. 3A). The average seed mass of Pioneer 32W86, although greater within the range of plant populations evaluated in this study, declined at roughly twice the rate of other hybrids. Since this hybrid was only included in one year of the study, it is difficult to determine if greater average seed mass was the result of genetic potential or environmental conditions. The close fit of average seed mass data for other hybrids indicates that Pioneer 32W86 may have greater genetic potential in terms of seed mass. All hybrids responded to increased plant population by increasing seed number
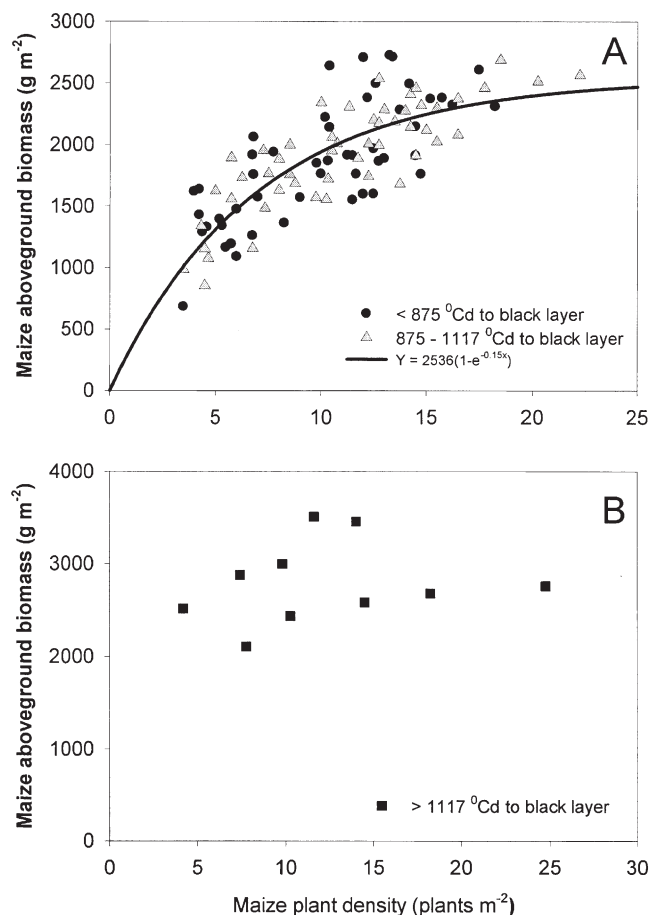
Fig. 1. Mean aboveground biomass at harvest as a function of maize plant population for (A) short-season and (B) full-season hybrids at Fayetteville, AR, in 2001, 2002, and 2003 and Keiser, AR, in 2002 and 2003. Data points are the mean value for each environment by hybrid by seeded population combination. Both linear and nonlinear regression were nonsignificant for full-season hybrids.
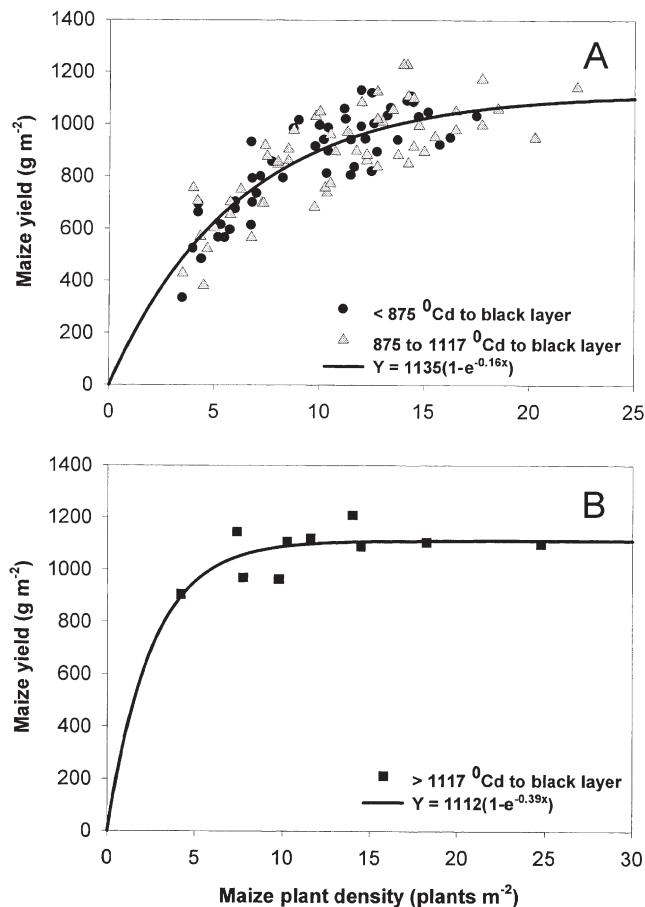

Fig. 2. Mean yield as a function of maize plant population for (A) short-season and (B) full-season hybrids at Fayetteville, AR, in 2001, 2002, and 2003 and Keiser, AR, in 2002 and 2003. Data points are the mean value for each environment by hybrid by seeded population combination.

per square meter (Fig. 3B). The greater response of maize seed quantity relative to that of average seed mass explains the positive relationship of maize yield and maize plant population. Furthermore, the stability of maize seed quantity at high-seeded population helps explain why no yield reduction was seen at the highest-seeded population used in this study.

Light Interception

Initial regression analysis of end-of-season aboveground biomass at harvest (hereafter referred as biomass) as a function of CIPAR from emergence to physiological maturity (black layer formation) revealed that only first-order polynomial terms were significant ($P < 0.05$) in predicting biomass as a function of CIPAR (Fig. 4A). According to the predicted line, aboveground biomass at harvest increased 3.3 g MJ^{-1} of CIPAR intercepted.

The data in Fig. 4A and 4B are similar to measures of radiation use efficiency (RUE, g biomass m^{-2}; Andrade et al., 1992, 1993; Westgate et al., 1997) in which mass of sequential aboveground plant samples are typically regressed against cumulative intercepted radiation (Sin-

clair and Muchow, 1999). The analysis presented in Fig. 4A and 4B, however, does not account for either PAR interception between black layer formation and harvest or for changes in plant mass that may have occurred after physiological maturity. Therefore, the analysis presented in Fig. 4A and 4B should not be considered as a measure of RUE.

In contrast to biomass, second-order polynomial terms were highly significant ($P < 0.01$, $R^2 = 0.65$) in predicting maize yield as a function of CIPAR (data not shown). This model, however, predicted a decline in maize yield for CIPAR greater than 600 MJ m^{-2}. As mentioned earlier, there were no barren plants observed in this experiment, and lodging was not evident for hybrids used in this analysis; therefore, there was no reason to assume that maize yield would decline at high CIPAR. Furthermore, similar experiments measuring soybean biomass (Purcell et al., 2002) and soybean yield (Edwards et al., unpublished, 2005) have indicated that, while crop yield may not increase, it does not decrease at high values of CIPAR. Therefore, yield was expressed as an exponential-function of CIPAR using Eq. [2] (Fig. 4B). The nonlinear regression fit the data well (Fig. 4B), but unlike the quadratic model, predicted maize yield did not decrease at high CIPAR. The predicted asymptotic maximum

Table 2. Analysis of variance (ANOVA) table and Type III hypothesis tests for covariate analysis of maize harvest index as a function of maize hybrid and plant population (PP) at Fayetteville, AR, in 2001, 2002, and 2003, and Keiser, AR, in 2002 and 2003.

Year	Location	Source	df	Sum of squares	Mean square	F value	Prob. F	CV	R^2
2001	Fayetteville	model	6	11.06	1.844	2099	***	6.9	0.39
		error	54	0.05	0.001				
		total	60	11.11					
		Type III hypothesis tests							
		hybrid	3	11.05	3.685	4195	***		
		hybrid × PP	3	0.01	0.003	4	**		
2002	Fayetteville	model	12	20.46	1.705	805	***	10.1	0.40
		error	87	0.18	0.002				
		total	99	20.64					
		Type III hypothesis tests							
		hybrid	6	2.32	0.387	183	***		
		hybrid × PP	6	0.01	0.002	1	NS†		
	Keiser	model	10	21.88	2.188	527	***	13.6	0.18
		error	87	0.36	0.004				
		total	97	22.34					
		Type III Hypothesis Tests							
		hybrid	5	3.21	0.642	155	***		
		hybrid × PP	5	0.01	0.001	1	NS		
2003	Fayetteville	model	12	22.28	1.857	431	***	16.8	0.26
		error	133	0.57	0.004				
		total	145	22.86					
		Type III hypothesis tests							
		hybrid	6	2.84	0.473	110	***		
		hybrid × PP	6	0.04	0.006	1	NS		
	Keiser	model	10	25.70	2.570	240	***	20.2	0.33
		error	86	0.93	0.011				
		total	96	26.63					
		Type III hypothesis tests							
		hybrid	5	3.47	0.694	65	***		
		hybrid × PP	5	0.11	0.021	2	NS		

** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† NS = nonsignificant at the 0.05 level.

Table 3. Coefficients and standard errors for covariate analysis using the model $Y = \beta_0 + \beta_1 x$ describing harvest index of maize hybrids of different maturity as a function of plant population at Fayetteville, AR, in 2001, 2002, and 2003, and Keiser AR in 2002 and 2003.

Year	Location	Hybrid	°Cd to black layer	β_0	SE	β_1	SE
2001	Fayetteville	39W54	946	0.41	±0.20***	−†	±−
		39F06	1001	0.43	±0.02***	−	±−
		N6460	1240	0.48	±0.02***	−0.003	±0.001**
2002	Fayetteville	39W54	855	0.46	±0.03***	−	±−
		39R34	855	0.48	±0.03***	−	±−
		39T68	886	0.33	±0.05***	−	±−
		39D81	1019	0.47	±0.03***	−	±−
		39F06	1084	0.37	±0.03***	−	±−
		G8984	1117	0.47	±0.03***	−	±−
	Keiser	39R34	855	0.53	±0.04***	−	±−
		39T68	886	0.50	±0.04***	−	±−
		39D81	1019	0.45	±0.05***	−	±−
		39F06	1084	0.47	±0.04***	−	±−
		G8984	1117	0.46	±0.04***	−	±−
2003	Fayetteville	39M27	830	0.46	±0.04***	−	±−
		39R34	874	0.39	±0.04***	−	±−
		39T68	874	0.34	±0.04***	−	±−
		39W54	874	0.37	±0.04***	−	±−
		39F06	935	0.30	±0.04***	−	±−
		32W86	1242	0.42	±0.04***	−	±−
	Keiser	39M27	830	0.54	±0.09***	−	±−
		39R34	874	0.47	±0.06***	−	±−
		39T68	874	0.49	±0.06***	−	±−
		39W54	874	0.44	±0.07***	−	±−
		39F06	935	0.41	±0.06***	−	±−

** Significant at the 0.01 level.
*** Significant at the 0.001 level.
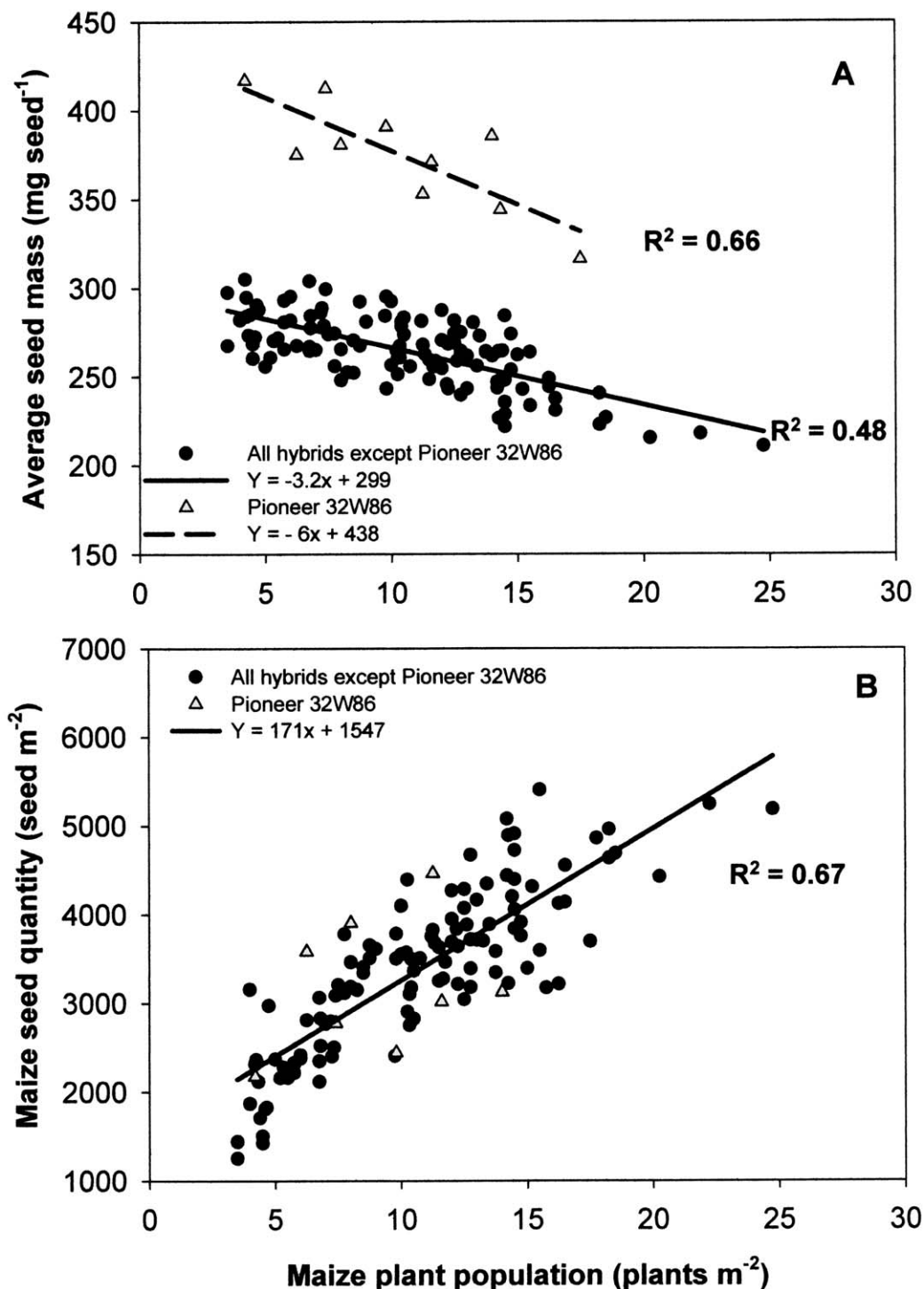† nonsignificant at the 0.05 level.

Fig. 3. (A) Average seed mass and (B) maize seed quantity as a function of plant population at Fayetteville, AR, in 2001, 2002, and 2003 and Keiser, AR, in 2002 and 2003. Data points are the mean value for each environment by hybrid by seeded population combination.

yield for maize was 1288 g m^{-2}, which was greater than the highest realized yield of approximately 1200 g m^{-2}.

Cumulative intercepted photosynthetically active radiation was regressed as a function of plant population and thermal time (°Cd) from emergence to black layer. Initial regression analysis indicated that squared terms and cross-products were nonsignificant, but the intercept and linear terms were highly significant ($P < 0.01$, $R^2 = 0.77$). The resulting equation was

$$CIPAR = -253 + 0.639 \ (°Cd) + 11 \ (\text{maize plants m}^{-2}) \quad [3]$$

Using the relationship in Eq. [3], isolines were plotted for the relationship between CIPAR and maize plant population for maize hybrids requiring 850, 950, 1050, and 1150 °Cd from emergence to black layer (Fig. 5). These isolines represent the amount of predicted CIPAR obtained by hybrids of different maturity as plant popu-
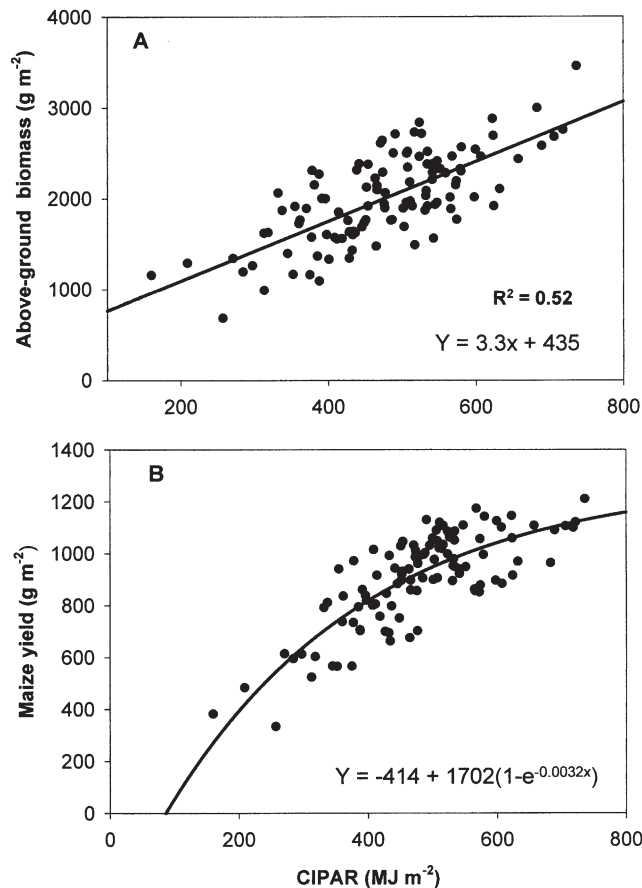
Fig. 4. (A) Maize aboveground biomass at harvest and (B) yield as a function of cumulative intercepted photosynthetically active radiation (CIPAR) at Fayetteville, AR, in 2001, 2002, and 2003 and Keiser, AR, in 2002 and 2003. Data points are the mean value for each environment by hybrid by seeded population combination.

lation increased. Horizontal lines in Fig. 5 represent the amount of CIPAR necessary to produce yields of 900 and 1000 g m^{-2}, using the exponential relationship between yield and CIPAR (Fig. 4B). In general, Fig. 5 indicates that there was a progressive decrease in the plant population required to achieve a given yield level as the thermal time required for maturity increased. For example, maize yield of 1000 g m^{-2} could be obtained by intercepting 555 MJ m^{-2} CIPAR using hybrids requiring 1150, 1050, or 950°Cd from emergence to black layer formation at plant populations of 8, 15, or 20 plants m^{-2}, respectively.

The horizontal line in Fig. 5 at 555 MJ m^{-2} predicts that yields will be ≥1000 g m^{-2}. Although yields ≥ 1000 g m^{-2} were predicted when CIPAR exceeds 555 MJ m^{-2} (Fig. 4B), yields at this point are approaching the asymptote and are of little practical (or statistical) significance. Therefore, the points at which the population-density response lines cross the horizontal yield line at 1000 g m^{-2} represent the approximate minimum plant population required to produce yields ≥ 1000 g m^{-2}, which ranged from 6 plants m^{-2} (for 1150°Cd hybrids) to 18 plants m^{-2} (for 950°Cd hybrids). Plant populations in excess of the minimum population would expectantly give similar yields.

DISCUSSION

As hypothesized, short-season maize hybrids were successful in reducing the irrigation requirement for maize production in the Midsouth. The difference in irrigation requirement between the shortest- and longest-maturity hybrids was on average around 45% or roughly 5 cm most years. Phenological data in Table 1 indicate that even though effects of the typical midseason drought in the Midsouth may be reduced by using short-season maize hybrids, irrigation would likely be required to obtain yields similar to those of this experiment.

Several previous investigators have observed the linear relationship between maize biomass and cumulative intercepted radiation (Andrade et al., 1992, 1993; Tollenaar and Bruulsema, 1988), which is defined as RUE. The asymptotic relationship between maize yield and CIPAR is different from these measures of RUE and has not been documented. Our data indicate that Duncan's (1986) hypothesis about the relationship between soybean yield and seeded population also holds true for maize. That is, there is a maize plant population at which CIPAR increases, yet there is no increase in yield. Optimal agronomic yield of 1000 to 1100 gm^{-2} (Fig. 2A) in this experiment was predicted to occur at CIPAR of 555 to 700 MJ m^{-2}. The Midsouth, however, typically receives greater than 2000 MJ m^{-2} during a frost-free growing system (Purcell et al., 2003). Thus, there are approximately 1300 MJ m^{-2} of CIPAR available for crop production that is not needed to achieve these yields. This assumes that grain yield and not biomass yield is the desired commodity, but this assumption may not true for all cases (Wilhelm et al., 2004).

The 1300 additional MJ m^{-2} of PAR available to the Midsouth production area is more than enough to produce an additional short-season maize or soybean crop. Such a production system would definitely have inefficiencies, such as PAR not intercepted before canopy closure, crop senescence, and grain dry down. Even if a 40% of this 1300 MJ m^{-2} of PAR is assumed for such inefficiencies, sufficient time and PAR are available for production of two warm-season crops in the Midsouth. This research, however, only demonstrates that the necessary resources are present to support a production system with two warm-season crops in the Midsouth. Further research is needed to determine if such a production system is both agronomically and economically feasible.

In this paper, we have developed a framework for understanding the response of maize yield to maize plant population that encompasses and explains variation across a broad range of maturities and different crop-year environments. Additional research is needed, however, to determine if the asymptotic relationship between yield and CIPAR (Fig. 4B) holds true for other geographic areas and for maize hybrids requiring greater than 1117°Cd from emergence to black layer. Our explanation of yield response to seeded population relies on the relationship established between CIPAR and thermal time to physiological maturity (Fig. 4B and 5). The
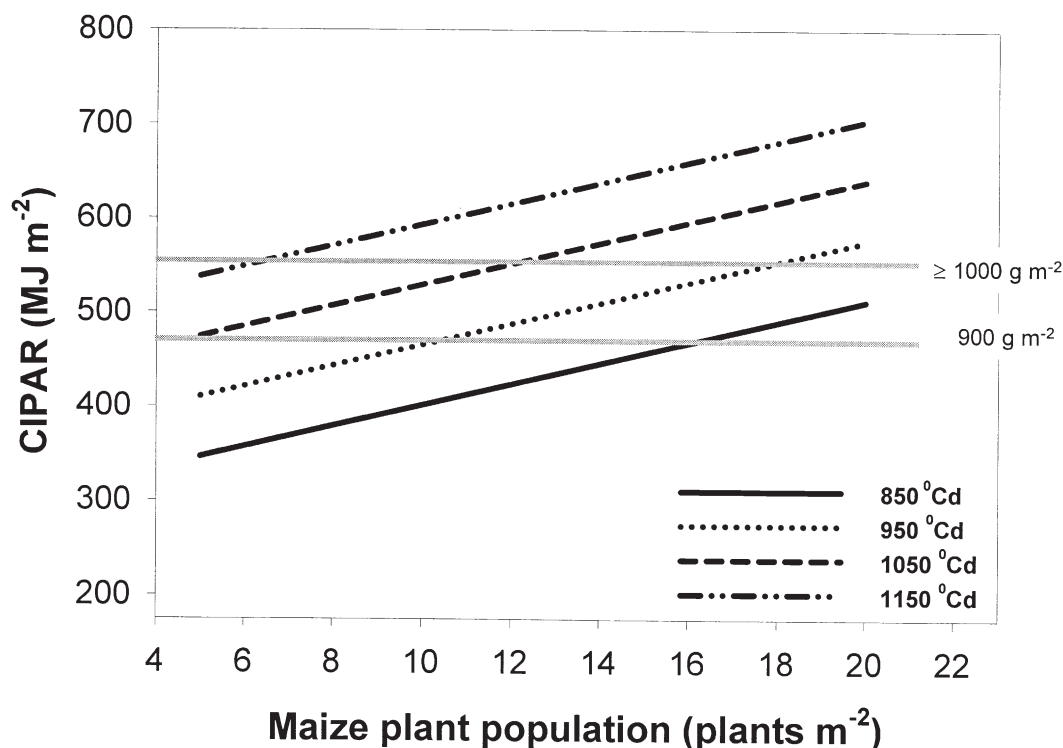
Fig. 5. Relationship between maize plant population and cumulative intercepted photosynthetically active radiation (CIPAR) for maize requiring 850, 950, 1050, or 1150°Cd from emergence to black layer as described by the equation CIPAR = −253 + 0.64 (°Cd) + 11 (maize plants m⁻²). Horizontal lines represent CIPAR necessary to obtain 900, 1000, and 1100 g m⁻² of maize yield, respectively.

relationship shown in Fig. 5 may only apply to those environments in which there is a similar relationship between thermal time and PAR. Additional research in areas that differ in temperature and radiation and, therefore, the amount of incident PAR per unit thermal time is warranted. This would lead to better prediction of how plant maturity, plant population, and environment interact to determine CIPAR and the development of an even broader-based, mechanistic model for optimizing maize seeded population.

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