Optimum Plant Population of Bt and Non-Bt Corn in Wisconsin

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ABSTRACT

Bt (*Bacillus thuringiensis*) corn (*Zea mays* L.) hybrids resist European corn borer [*Ostrinia nubilalis* (Hübner)] damage and lodge less, creating interest among growers, agronomists, and seed companies in their yield response to increasing plant population. Corn hybrids with Bt and non-Bt traits were evaluated from 2002 to 2004 across 10 locations in Wisconsin in 76-cm rows at target populations from 61 750 to 123 500 plants ha^{-1} to (i) determine the agronomic and economic optimum plant population for corn and (ii) identify agronomic and economic optimum plant populations for Bt and non-Bt hybrids. The quadratic model for both grain yield and grower return response to plant population was significant. The maximum yield plant population (MYPP) for Bt and non-Bt corn was 104 500 and 98 800 plants ha^{-1}, respectively. The overall MYPP for corn was 102 400 plants ha^{-1}, which is 28 300 plants ha^{-1} more than the current Wisconsin recommendation of 74 100 plants ha^{-1}. Planting corn to the MYPP increased grain yield by 4.2% over the current population recommendation. However, the economically optimum plant population (EOPP) for both Bt and non-Bt corn was 83 800 plants ha^{-1}. It was concluded that Bt corn hybrids require higher plant populations for maximizing yield potential; however the higher harvest costs related to those greater yields and the higher seed costs associated with attaining those populations resulted in no difference in the EOPP between Bt and non-Bt corn. Plant population recommendations for corn should be near 83 800 plants ha^{-1}, the point where the EOPP was achieved. Since this recommendation is affected by rising seed and management costs and variable market prices, a periodic evaluation of plant population response for newly released hybrids should be done.

SINCE 1996, several seed companies have commercialized new transgenic maize hybrids resistant to European Corn Borer (ECB) (Seydou et al., 2000). These new hybrids, commonly known as Bt corn, have been genetically engineered to incorporate genes of Bt (Koziel et al., 1993; Armstrong et al., 1995), a toxin effective against larvae from both first and second ECB generations. Resistance to second generation ECB will reduce stalk lodging, which may result in higher MYPP in Bt corn.

Lodging is a major constraint to maximizing grain yields in modern maize production (Sibale et al., 1992). High incidence of lodging is one of the hazards of increasing plant populations to get maximum yields. The most serious effect of denser stands is the higher incidence of stalk breakage (Stringfield and Thatcher, 1947). Crosbie (1982) showed that a large proportion of the grain yield improvement could be attributed to reduced stem lodging and ear droppage, and that the reduction in nonharvestable grain yield was most significant at higher plant populations. Lodging can increase several-fold with high populations and may result in very high harvest losses that more than negate any yield increase that may have occurred with the higher plant population (Olson and Sander, 1988). The potential for increased lodging at high plant populations is a deterrent for recommending harvest populations for grain corn much above 74 100 plants ha^{-1} (Cox, 1997).

Lauer and Wedberg (1999) compared initial Bt corn hybrid introductions to their isolines, (the non-Bt equivalents of the Bt hybrids used) and to standard adapted hybrids in the northern U.S. Corn Belt. They concluded that yield of initial Bt hybrids was either equivalent to or better than standard adapted hybrids, except in environments with low incidence of ECB. Under low or no incidence of ECB initial Bt hybrids yielded less than standard adapted hybrids. Yields of isoline hybrids were 10% less than Bt hybrids and standard adapted hybrids, regardless of whether the ECB treatment was the infestation level, natural level, or ECB free. Stalk lodging was also greater in the high yielding standard hybrids compared to the Bt hybrids (7.1 vs. 2.5%, respectively).

Graeber et al. (1999) compared Bt hybrids to non-Bt hybrids and concluded that the Bt hybrids reduced or eliminated first and second generation damage caused by ECB, yielded 4 to 6.6% greater than non-Bt hybrids, had decreased stalk lodging and greater test weight. The Bt and non-Bt hybrids were not different for tasseling date, silking date, leaf appearance date, individual leaf area, and plant height. Compared with non-Bt plants, Bt plants exhibited 9.7% greater total plant weight in 1997 and 9.4% greater grain yield in 1998 (Seydou et al., 2000).

According to Singer et al. (2003), the MYPP for Bt corn should be higher than non-Bt corn subjected to ECB damage because of the reduced potential for stalk lodging. Regression analysis of grain yield response to plant population for Bt and near-isoline non-Bt hybrids did not reveal a consistent hybrid response, although some evidence suggested Bt hybrids were more efficient than near-isolines at producing yield as plant population increased. The inability to identify different MYPPs for Bt and near-isolines was due to minimal stalk lodging and plant population treatments that did not maximize yield in most instances.

In a study conducted in New York during the 1970s, Knapp and Reid (1981) reported highest grain yield was attained at 54 340 plants ha^{-1}. Almost two decades later, Cox (1997) reported that MYPPs of individual hybrids ranged from 79 040 to greater than 88 920 plants ha^{-1} under favorable conditions and from about 69 160 to greater than 88 920 plants ha^{-1} under dry conditions. Frequency of drought is a concern that might deter a

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Published in Agron. J. 98:914–921 (2006).
Corn
doi:10.2134/agronj2005.0144

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Abbreviations: Bt, *Bacillus thuringenisis*; ECB, European corn borer; EOPP, economically optimum plant population; MN RM, Minnesota relative maturity [rating]; MYPP, maximum yield plant population.

producer from increasing plant population. Cox (1997) stated that high plant populations do not decrease grain yields in dry years. In fact, plant population less than 74 100 plants ha^{-1} resulted in more yield loss than observed for plant populations greater than 74 100 plants ha^{-1}, even under dry conditions.

In a population study conducted by Nafziger (1994), that had limited yields caused by drought, the MYPP was near 61 750 plants ha^{-1}, indicating that the risk of maintaining high populations even under dry conditions is not as high as it might have been with older hybrids. Newer hybrids appear to have improved ability to resist barrenness and other types of injury associated with high plant populations. According to Olson and Sander (1988), high plant populations are more water-use efficient than low plant populations. While water use is increased as plant population is increased, the increase is small and not proportional to stand increase.

Consequently, there appears to be minimum risk associated with planting high populations in a dry year other than additional seed costs. Carmer and Jackobs (1965) stated that reductions in yield are less rapid for populations in excess of the MYPP than for those below the MYPP. Such research demonstrates that it is a bigger risk not planting to the environment's maximum potential.

Cox (1997) suggested that periodic evaluations of plant population responses should be conducted on newly released hybrids in specific growing regions to accurately adjust plant population recommendations. Performance of new Bt hybrids have never been reported in a high stress, high population environment. The objectives of this study were (i) to determine the MYPP and EOPP for corn in Wisconsin and (ii) identify MYPP and EOPP for Bt and non-Bt hybrids.

MATERIALS AND METHODS

Experiments were conducted from 2002 to 2004 at 10 locations in Wisconsin. Trial locations were chosen that represented the diverse soils and climates of the state of Wisconsin. The locations were grouped into three relative maturity production zones. Soil characteristics at each location are listed in Table 1. All locations were managed according to recommended commercial production practices for maximizing grain yield. Cultural practices specific to each location are listed in Table 2. Weeds were controlled by appropriate herbicide treatments. To control corn rootworm (*Diabrotica* spp.), tefluthrin was applied in-furrow at a rate of 0.15 kg active ingredient (a.i.) ha^{-1} at planting to all locations that had corn as the preceding crop.

The experimental design at each location was a complete factorial arrangement of treatments in a randomized complete block with three replications. Factors were hybrid and plant population. Corn hybrids ranged from full-season to shorter-season maturity for their respective zones and were classified using the Minnesota relative maturity rating (Table 3). During 2002, target plant populations of 61 750, 74 100, 86 450, 98 800, 111 150, and 123 500 plants ha^{-1} were used and during 2003 and 2004 target plant populations of 64 220, 79 040, 93 860, 108 680, and 123 500 plants ha^{-1} were used. The target plant populations used represented increments around the recommended plant population of 74 100 plants ha^{-1} and provided a range of plant populations for the covariate analysis.

Plots consisted of four rows (Arlington had eight rows) 6.7 m long and 0.76 m apart. Plots were over-planted and hand-thinned at growth stage V5–6 to achieve the desired target population (Ritchie et al., 1993). Plots were planted with a Kinze corn planter mounted with fluted cone units (Kinze Manufacturing, Williamsburg, IA).

Data collected before grain harvest included: preharvest plant population, ear population, dropped ears, and lodged plants. Plants were considered stalk lodged if corn stalks were broken below the ear or root lodged if the plants were leaning at greater than a 45° angle. Percent lodging was calculated based on the total number of plants lodged $plot^{-1}$ divided by the total number of plants $plot^{-1}$.

The two middle rows of each plot were harvested for grain yield with a self-propelled Kincaid Plot Combine (Kincaid Equipment Manufacturing, Haven, KS). The combine was equipped with a HarvestMaster GrainGage HM-1000 (Juniper Systems, Logan, UT) to measure plot grain yield, test weight, and moisture content. Plot yields were adjusted to a standard moisture content of 155 g kg^{-1}.

In the economic analysis, grower return was determined using a partial budget that focused only on those costs and revenues that changed when plant population changed (Swinton and Lowenberg-DeBoer, 1998). There was no attempt to quantify costs associated with harvesting lodged corn. Grower return was the product of commodity price with yield subtracting production costs (Table 4). Costs were obtained from the "Estimated Costs of Crop Production in Iowa—2004 (Duffy, 2004) and Landmark Co-op (Cottage Grove, WI). Corn price was determined using a marketing strategy that had 50% of the crop sold in November and 25% forward contracted (less basis) to March and July, respectively. The November Average Cash price was derived from Wisconsin Ag

Table 1. Soil type for 10 Wisconsin locations in 2002, 2003, and 2004.

Location	Soil series name	Description and taxonomic name
		Southern zone
Arlington	Plano silt loam	fine-silty, mixed, superactive, mesic Typic Argiudolls
Janesville	Plano silt loam	fine-silty, mixed, superactive, mesic Typic Argiudolls
Lancaster	Fayette silt loam	fine-silty, mixed, superactive, mesic Typic Hapludalfs
		South Central zone
Fond du Lac	Virgil silt loam	fine-silty, mixed, superactive, mesic Udollic Endoaqualfs
Galesville	Downs silt loam	fine-silty, mixed, superactive, mesic Mollic Hapludalfs
Hancock	Plainfield sand	mixed, mesic Typic Udipsamments
		North Central zone
Chippewa Falls	Sattre silt loam	fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Mollic Hapludalfs
Marshfield	Loyal silt loam	fine-loamy, mixed, superactive, frigid Oxyaquic Glossudalfs
Seymour	Hortonville clay loam	fine-loamy, mixed, active, mesic Haplic Glossudalfs
Valders	Kewaunee clay loam	fine, mixed, mesic Typic Hapludalfs

Table 2. Cultural practices for 10 Wisconsin locations in 2002, 2003, and 2004.

				Soil test value				
Location	**Year**	**Plant date**	**Harvest date**	**pH**	**Organic matter**	**P**	**K**	**Previous crop**
					%	—— ppm ——		
				Southern zone				
Arlington	2002	30 Apr.	21 Oct.	6.2	3.3	79	247	Soybean
	2003	3 May	17 Oct.	6.5	5.4	112	281	Soybean
	2004	29 Apr.	20 Oct.	7.0	3.9	69	258	Soybean
Janesville	2002	26 Apr.	11 Oct.	6.9	3.1	66	229	Soybean
	2003	25 Apr.	21 Oct.	6.6	3.9	98	229	Soybean
	2004	27 Apr.	12 Oct.	6.8	3.2	51	171	Soybean
Lancaster	2002	26 Apr.	14 Oct.	7.3	2.1	57	157	Soybean
	2003	28 Apr.	7 Oct.	6.9	2.3	53	80	Soybean
	2004	27 Apr.	14 Oct.	7.4	2.1	60	147	Soybean
				South Central zone				
Fond du Lac	2002	10 May	17 Oct.	7.1	4.2	42	100	Soybean
	2003	3 May	22 Oct.	6.7	2.9	47	57	Soybean
Galesville	2002	3 May	9 Oct.	6.6	3.2	43	161	Soybean
	2003	28 Apr.	20 Oct.	6.5	3.1	47	85	Soybean
	2004	28 Apr.	25 Oct.	6.1	3.8	22	150	Soybean
Hancock	2002	29 Apr.	10 Oct.	6.4	0.7	120	47	Soybean
	2003	24 Apr.	15 Oct.	6.2	0.8	112	30	Soybean
	2004	24 Apr.	13 Oct.	6.8	0.7	98	96	Soybean
				North Central zone				
Chippewa Falls	2002	3 May	16 Oct.	6.4	2.1	30	111	Soybean
	2003	29 Apr.	24 Oct.	6.5	2.4	26	61	Soybean
	2004	28 Apr.	25 Oct.	6.4	2.1	25	109	Soybean
Marshfield	2002	15 May	31 Oct.	6.4	3.1	62	172	Soybean
	2003	1 May	8 Oct.	6.5	3.4	66	109	Alfalfa
	2004	29 Apr.	3 Nov.	6.5	2.9	38	103	Soybean
Seymour	2003	2 May	24 Oct.	7.3	2.8	25	97	Soybean
	2004	2 May	24 Oct.	7.5	2.6	41	179	Corn
Valders	2002	15 May	17 Oct.	6.4	3.1	62	172	Corn
	2003	2 May	24 Oct.	6.8	3.6	102	110	Corn
	2004	4 May	27 Oct.	6.9	4.1	91	186	Corn

Statistics, and the March and July future prices were derived from the Chicago Board of Trade Futures price on the first business day in December.

Table 3. Corn hybrids tested at three Wisconsin production zones during 2002, 2003, and 2004.

Year	Hybrid	Trait	MN RM†
	Southern zone		
2002	Pioneer 37R71	Bt	99 d
	Dairyland 1410	non-Bt	110 d
2003	Pioneer 37R71	Bt	99 d
	Renk RK622	non-Bt	100 d
	Pioneer 34M95	Bt	109 d
	Pioneer 34M94	non-Bt	109 d
2004	Pioneer 34M95	Bt	109 d
	Pioneer 34M94	non-Bt	109 d
	Jung HDS104	non-Bt	106 d
	South Central zone		
2002	Pioneer 37R71	Bt	99 d
	Dekalb DKC4442	Bt	95 d
2003	Pioneer 37R71	Bt	99 d
	Renk RK622	non-Bt	100 d
	Dekalb DK5018	Bt	100 d
	Dekalb DK5143	non-Bt	100 d
2004	Dekalb DK5018	Bt	100 d
	Dekalb DK5143	non-Bt	100 d
	North Central zone		
2002	Pioneer 37R71	Bt	99 d
	Cargill 4521Bt	Bt	105 d
2003	Pioneer 37R71	Bt	99 d
	Renk RK622	non-Bt	100 d
	NK Brand N3030Bt	Bt	93 d
	NK Brand N3030	non-Bt	95 d
2004	NK Brand N3030Bt	Bt	93 d
	NK Brand N3030	non-Bt	95 d

† Minnesota relative maturity rating.

Data were analyzed by covariate analysis using the PROC MIXED procedure (Littell et al., 1996) of SAS (SAS Institute, 2001). The covariate was plant population at harvest. Thus, the data from each individual plot was used and not the treatment means. Data were pooled over years by location, zone, and overall. For determining the expected mean squares and appropriate *F* tests in the analysis of covariance, random effects for the location analysis were year, rep(location × year), zone × year, and hybrid(trait); for the zone analysis random effects were year, location(year), rep(location × year), and hybrid (trait); and year, location(zone × year), rep × location(zone × year), and hybrid(trait) for the overall analysis. Least square means of the fixed effects were computed, and the PDIFF option of the LSMEANS statement was used to display the differences among least square means for comparison. This option uses Fisher's protected least significant difference, and comparison was conducted at $P \leq 0.05$. The coefficient of determination (R^2) was derived using the predicted values calculated by PROC MIXED ($R^2 = 1 - [(y_{\mathrm{ij}} - y_{(\mathrm{Pred})})^2/(y_{\mathrm{ij}} - y_{(\mathrm{grand\ mean})})^2]$).

The final model that was used to determine each of the regression equations was attained using backward stepwise selection. This procedure starts with the full model and sequentially deletes factors and their interactions. The factor producing the smallest *F* value is deleted at each stage and the model is complete when the factors remaining in the model produce a value of $P \leq 0.05$.

For each location-trait, zone-trait, and overall-trait data pool, the maximum yield, maximum grower return, and their respective plant populations were calculated. Maximum yield plant population and EOPP were calculated by taking the first derivative of either the yield or economic function and solving for *X* (plant population). The plant population at 95% of maximum yield was also calculated to account for any upward bias

Table 4. Economic values for determining grower return for 2002–2004.

	2002	2003	2004	Avg.
Market price (\$ Mg^{-1})	88.20	88.20	82.29	86.23
Retail seed prices (\$ per 80 000 seed bag)				
Bt hybrids	121.45	126.44	137.13	128.34
Non-Bt hybrids	99.90	99.74	108.60	102.75
Harvest costs				
Handling (\$ Mg^{-1})	0.63			
Hauling (\$ Mg^{-1})	1.26			
Trucking (\$ Mg^{-1} per 100 km)	7.88			
Drying (\$ Mg^{-1} for each 10 g kg^{-1} > 155 g kg^{-1})	1.18			
Storage (\$ Mg^{-1} for 30 d)	1.34			

created by our quadratic model. If the calculated optimum plant population was outside of the plant population range for each data pool combination, then the optimum plant population was the same as the population of the actual maximum yield or grower return. If the calculated plant population at 95% maximum *Y* was outside of the plant population treatments for each data pool combination, then the plant population at 95% of maximum *Y* equaled the lowest actual plant population tested at that location (Lauer et al., 1999).

Maximum net returns to seed costs for the economic model were obtained by equating the first derivatives of the grower return response equation to zero, solving for *X* (EOPP), substituting *X* into the response equation and solving for maximum return. The ±\$2.50 ha^{-1} error bars were calculated by taking the maximum net returns to seed costs subtracting \$2.50 and solving for *X* using the quadratic equation. Seed cost/market price ratio is calculated using seed costs as \$1000 $seeds^{-1}$ and market price as \$ Mg^{-1}.

RESULTS AND DISCUSSION

Growing conditions varied considerably among locations and years. In 2002, warm, dry conditions during April were followed by cool, wet conditions during early May to early June and followed by hot, dry conditions in early July. Hot and dry weather during pollination lowered yields in Fond du Lac, Janesville, Seymour, and Valders. Timely rains in Chippewa Falls, Galesville, and Lancaster resulted in favorable pollination and grain yields. In Seymour, cool, wet conditions during April and May severely affected corn emergence, development, and subsequent stand establishment causing this location to be dropped from the analysis for 2002.

In 2003, spring conditions were cooler and dryer than average, followed by hot, dry conditions in mid-July. Favorable plant emergence resulted in adequate stand establishment at most locations. However, emerged stands at Marshfield and Valders were poor due to a cold, wet spring at Marshfield and heavy crusting at Valders, but plant population treatments were able to be applied within target levels at both locations. Chippewa Falls and Lancaster had reduced grain yields caused by dry, hot weather from mid-July through August. Although variable, grain yields were above average at Seymour and Valders.

In 2004, spring conditions were good through early May followed by cooler and wetter than average conditions. Record rainfall occurred during May and early June at Chippewa Falls, Fond du Lac, Marshfield, Seymour, and Valders. Cool conditions slowed early season development, however good growing conditions during the summer allowed crop development to catch up during September. Grain yields were above average at Lancaster. At Fond du Lac, wet field conditions after planting severely affected corn emergence, development, and subsequent stand establishment causing this location to be dropped from the analysis for 2004.

Grain Yield

The significance of *F* values attained from the analyses of covariance for grain yield, grain moisture, lodging, and grower return are shown in Table 5. The covariate variable (harvest plant population) was significant for grain yield for all three data pools (Table 5). Increasing plant population significantly increased grain yield (Table 6 and Fig. 1). A significant plant population × trait interaction for grain yield was observed for all three data pools (Table 5). As harvest plant population increased from 64 220 to 123 500 plants ha^{-1}, Bt corn yielded 5.9 to 8.0% more than non-Bt corn, respectively (Table 6 and Fig. 1). This yield increase for Bt hybrids was consistent with Bode and Calvin (1990), Graeber et al. (1999), Lauer and Wedberg (1999), and Dillehay et al. (2004).

Table 5. Significance of *F* values from analysis of covariance of grain yield, grain moisture, lodging, and grower return, 2002 to 2004. Data were pooled over years by location, zone, and overall.

Source of variation	Grain yield	Grain moisture	Lodging	Grower return
Location				
Trait (T)	NS†	NS	NS	NS
Location (L)	*	***	**	**
T × L	NS	*	*	NS
Harvest plant population (P)	***	NS	NS	***
P × T	**	NS	NS	NS
P × L	***	***	***	***
P × T × L	**	*	***	*
P^2	***	NS	***	***
P^2 × T	NS	NS	NS	NS
P^2 × L	***	***	NS	**
P^2 × T × L	NS	*	NS	NS
Zone				
T	NS	NS	NS	NS
Zone (Z)	**	*	NS	***
T × Z	NS	**	**	NS
P	***	***	NS	***
P × T	*	NS	NS	NS
P × Z	NS	***	***	NS
P × T × Z	NS	NS	*	NS
P^2	***	NS	**	***
P^2 × T	NS	NS	NS	NS
P^2 × Z	**	NS	NS	*
P^2 × T × Z	NS	NS	NS	NS
Overall				
T	NS	NS	NS	NS
P	***	***	*	***
P × T	*	NS	*	NS
P^2	***	NS	***	***
P^2 × T	NS	NS	NS	NS

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† NS, no significant differences at $P \leq 0.05$.

Table 6. Regression equations and predicted corn yields for selected plant populations, 2002 to 2004.

Data pool	Trait	LSD†	Polynomial regression‡ $Y = A + B(P) + C(P^2)$			R^2§	Predicted yield: Final population (plants ha^{-1}) 64 220	79 040	93 860	108 680	123 500	Maximum yield	Population at 95% of maximum yield	Maximum yield plant population
Location			A	B	C		Mg ha^{-1}						plants ha^{-1}	
Arlington	Bt	c-g	3.89	1.75	−0.087	0.52	11.6	12.3	12.7	12.7	12.3	12.7	73 700	100 800
Arlington	non-Bt	d-i	5.85	1.46	−0.087	0.56	11.6	11.9	11.9	11.4	10.6	12.0	57 600	83 800
Chippewa Falls	Bt	hj	7.98	0.51	−0.028	0.78	10.1	10.3	10.4	10.3	10.1	10.4	59 700	92 800
Chippewa Falls	non-Bt	k	8.02	0.32	−0.028	0.96	8.9	8.8	8.6	8.2	7.8	8.9	54 800	57 800
Fond du Lac	Bt	c-h	8.94	0.63	−0.029	0.63	11.8	12.2	12.4	12.4	12.4	12.5	64 200	111 000
Fond du Lac	non-Bt	e-j	8.49	0.59	−0.029	0.79	11.1	11.4	11.5	11.5	11.4	11.6	58 700	103 700
Galesville	Bt	bcd	4.54	1.79	−0.084	0.87	12.5	13.4	13.9	14.0	13.8	14.0	77 200	106 100
Galesville	non-Bt	e-i	4.80	1.61	−0.084	0.77	11.7	12.3	12.5	12.4	11.9	12.5	68 600	95 900
Hancock	Bt	a	6.66	1.69	−0.073	0.98	14.5	15.4	16.0	16.3	16.3	16.3	81 400	114 700
Hancock	non-Bt	ab	6.38	1.61	−0.073	0.98	13.7	14.5	15.1	15.2	15.1	15.2	77 600	109 800
Janesville	Bt	bce	6.53	1.33	−0.063	0.65	12.4	13.1	13.4	13.5	13.3	13.5	72 200	104 900
Janesville	non-Bt	bce	5.26	1.45	−0.063	0.65	12.0	12.8	13.3	13.6	13.5	13.6	81 900	114 600
Lancaster	Bt	b-f	0.48	2.75	−0.145	0.82	12.2	13.1	13.5	13.2	12.3	13.5	73 100	94 600
Lancaster	non-Bt	c-h	1.56	2.55	−0.145	0.86	11.9	12.6	12.7	12.1	10.9	12.7	66 800	87 700
Marshfield	Bt	gh	6.96	0.69	−0.030	0.94	10.2	10.5	10.8	10.9	10.9	10.9	71 700	114 100
Marshfield	non-Bt	jk	6.82	0.58	−0.030	0.98	9.3	9.5	9.6	9.5	9.3	9.6	55 400	95 100
Seymour	Bt	c-g	3.85	1.55	−0.070	0.95	10.9	11.7	12.2	12.4	12.3	12.5	81 200	111 000
Seymour	non-Bt	e-i	3.02	1.56	−0.070	0.94	10.1	11.0	11.5	11.7	11.6	11.7	82 600	111 600
Valders	Bt	e-i	4.15	1.59	−0.083	0.60	10.9	11.5	11.7	11.6	11.1	11.7	69 100	95 700
Valders	non-Bt	fgh	2.41	1.72	−0.083	0.73	10.0	10.8	11.2	11.3	10.9	11.3	77 300	103 400
Zone														
NC	Bt	b	4.41	1.33	−0.067	0.85	10.2	10.8	11.1	11.0	10.7	11.1	71 400	100 300
NC	non-Bt	b	4.16	1.27	−0.067	0.94	9.6	10.0	10.2	10.1	9.7	10.2	67 700	95 400
SC	Bt	a	7.11	1.33	−0.060	0.94	13.2	13.9	14.3	14.5	14.4	14.5	75 900	110 600
SC	non-Bt	a	6.85	1.27	−0.060	0.92	12.5	13.1	13.5	13.5	13.3	13.5	71 700	105 200
S	Bt	a	6.55	1.33	−0.066	0.71	12.4	13.0	13.2	13.2	12.9	13.3	69 100	100 800
S	non-Bt	a	6.29	1.27	−0.066	0.68	11.7	12.2	12.4	12.3	11.9	12.4	65 300	95 900
Overall														
	Bt	a	6.11	1.27	−0.061	0.86	11.8	12.4	12.7	12.7	12.5	12.8	72 100	104 500
	non-Bt	a	5.90	1.20	−0.061	0.89	11.1	11.6	11.8	11.8	11.5	11.8	67 600	98 800

† LSD, Least Significant Difference as calculated by Proc Mixed. Averaged across plant population treatments, grain yield means from areas and traits followed by the same letter are not significantly different ($P \leq 0.05$).

‡ Y, corn grain yield in Mg ha^{-1}; P = final plant population in plants ha^{-1}/10 000.

§ R^2, coefficient of determination.

The analysis also showed the quadratic coefficient of plant population to be significant (Tables 5 and 6). In previous plant population studies, Nafziger (1994) and Porter et al. (1997) found that the quadratic model provided the best fit. Using a quadratic model of the harvest plant population to fit the data, we observed high coefficients of determination (R^2) in all data pools (Table 6). The quadratic coefficients of plant population were sig-

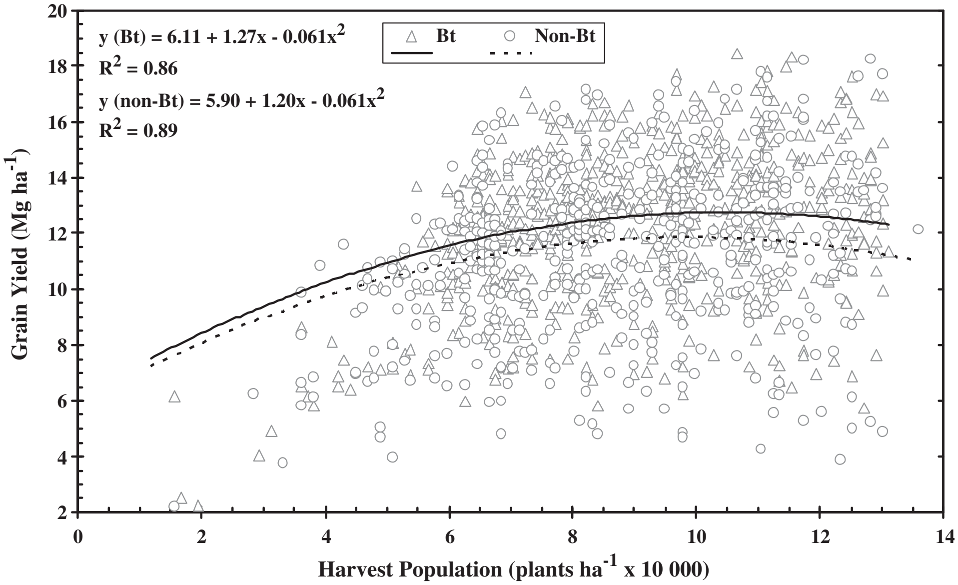

Fig. 1. The relationship between plant population and grain yield for Bt and non-Bt hybrids in Wisconsin during 2002 to 2004. Points represent individual plots.

nificant and negative across all pooling groups (Tables 5 and 6), indicating that the plant population reached a point that was too high to represent the maximum attainable corn yield. The overall MYPP for Bt and non-Bt corn was 104 500 and 98 800 plants ha^{-1}, respectively (Table 6 and Fig. 1). The overall MYPP was 102 400 plants ha^{-1}. This is 28 300 plants ha^{-1} more than the current recommendation. However, if growers use the current recommendation of 74 100 plants ha^{-1}, grain yield would be 95.6% (Bt) and 96.9% (non-Bt) of the grain yield at MYPP (Table 6).

Overall, when plant populations were increased from 74 100 plants ha^{-1} to 102 400 plants ha^{-1}, yields increased by 4.2%. Newer hybrids have improved stress tolerance associated with plant populations above what is currently recommended (Duvick and Cassman, 1999). However, not all environments were favorable to these high plant populations. For example, non-Bt hybrids at Chippewa Falls produced their highest yields at the lowest tested plant population (Table 6).

Grain Moisture

Overall, there was no difference in grain moisture at harvest between Bt and non-Bt corn. These results contradicted previous research (Dillehay et al., 2004; Bruns and Abbas, 2006) regarding grain moisture for Bt hybrids and their respective isolines. In those studies, an increase in grain moisture for Bt hybrids was observed. However, our study compared a different set of Bt and non-Bt hybrids (Bt, non-Bt equivalents, and standard adapted hybrids) than the previous literature. From a production standpoint, this moisture difference is minor and would not likely affect the price received for the grain on the market (Bruns and Abbas, 2006).

Harvest population affected grain moisture content (Table 5). Overall, grain moisture decreased 1.7% when harvest plant population increased from 64 220 to 123 500 plants ha^{-1}. This observation was consistent with Widdicombe and Thelen (2002) where grain moisture decreased 5.2 and 3.5% with increasing plant populations for early and mid-season hybrids, respectively. Other than at high plant populations, a difference in grain moisture was seen sporadically and attributed to a variety of factors including weather, soil, location, and hybrid. Widdicombe and Thelen (2002) also observed differences in grain moisture among hybrids, which were the result of differences in relative maturity and the time they were allowed to field-dry before harvest. The relative maturities of the hybrids used in this study, although adapted to their zones, were not the same in all locations.

Lodging

Harvest plant population affected lodging. An increase in harvest plant population from 64 220 to 123 500 plants ha^{-1} increased lodging from 5.0 to 15.8%. Pedersen and Lauer (2002) and Bruns and Abbas (2005) found similar results regarding higher plant population effects on lodging percentage. In addition, a significant plant population × trait (overall pool) interaction was observed (Table 5). As plant population increased, from 64 220 to 123 500 plants ha^{-1}, non-Bt corn experienced 22% more lodging than Bt corn. The quadratic coefficient of plant population showed significance in all data pools (Table 5). As plant population increased, the rate of increase for lodging became greater. At low and moderate populations, lodging severity varied considerably depending on location and year. Some of this lodging variability was attributed to stalk rot that was more severe at some locations than others.

Grower Return

Harvest plant population had a significant effect on grower return for all data pools (Table 5). The covariate analysis indicated that the linear and quadratic coefficients of plant population were significant (Table 5 and 7). Grower return increased with increasing plant population to a point of maximum return and then declined (Table 7). Despite Bt corn yielding 6.6% more than non-Bt corn, the yield benefit was offset by the higher costs of seed, handling, hauling, trucking, and storage resulting in no economic benefit to Bt corn. For both Bt and non-Bt hybrids, grower return was optimized at a plant population of 83 800 plants ha^{-1} (Table 7). This population is 9700 plants ha^{-1} greater than the currently recommended plant population of 74 100 plants ha^{-1}.

These results were attained using actual seed costs and market prices effective at the time. Corn growers base their plant population decisions on yield response,

Table 7. Regression equations and predicted grower return for selected plant populations, 2002 to 2004.

						Predicted return						
		Polynomial regression‡				Final population (plants ha^{-1})						
Data pool	LSD†	$Y = A + B(P) + C(P^2)$			R^2§	64 220	79 040	93 860	108 680	123 500	Maximum grower return	Economic optimum plant population
Zone		A	B	C		$ ha^{-1}						plants ha^{-1}
NC	b	186	73.2	−4.49	0.90	471	484	478	451	405	485	81 500
SC	a	404	73.2	−4.14	0.92	703	724	726	710	676	727	88 400
S	a	383	73.2	−4.40	0.75	672	687	683	659	616	688	83 200
Overall												
	–	328	69.4	−4.14	0.88	706	719	714	692	653	619	83 800

† LSD, Least Significant Difference as calculated by Proc Mixed. Averaged across plant population treatments, grower return means from areas followed by the same letter are not significantly different ($P \leq 0.05$).

‡ Y, grower return in $ ha^{-1}; P = final plant population in plants ha^{-1}/10 000.

§ R^2, coefficient of determination.

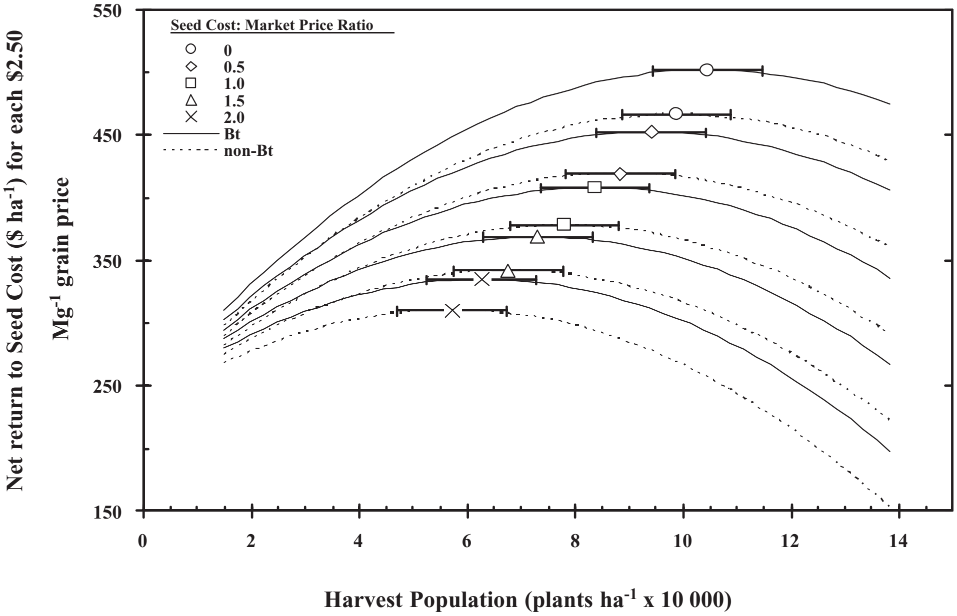

Fig. 2. Economic optimum plant population for Bt and non-Bt hybrids for selected seed cost: market price ratios. Seed costs = $ 1000 seeds^{-1}; Market Price = $ Mg^{-1}; Error bars = ± $2.50 ha^{-1}.

seed cost, expected market price, and the risk of lodging. Using the yield of Bt and non-Bt hybrids from this experiment, an economic model was developed to predict grower returns of Bt and non-Bt corn hybrids over a range of target populations using different seed costs ($1000 seeds^{-1}): corn market price ($ Mg^{-1}) ratios (Fig. 2). The plant population recommendations for maximizing return were similar for Bt and non-Bt hybrids. Bt hybrids showed a greater return (7%) over non-Bt hybrids in all scenarios due to a greater yield potential. The highest gains for increasing plant population came when seed costs were low and market prices were high.

This model is used only to demonstrate how planting decisions in the spring are affected by seed costs and market prices. Because market prices at planting time in the spring can only be estimated, corn growers should base seed purchases on desired seed traits and then adjust planting populations accordingly to maximize yield and profit.

CONCLUSION

Regardless of corn hybrid trait, this study identified MYPP to be approximately 102 400 plants ha^{-1}. Further, it was determined that MYPP for Bt hybrids should be 104 500 plants ha^{-1} and 98 800 plants ha^{-1} for non-Bt hybrids. If plant populations were increased from 74 100 plants ha^{-1} to 102 400 plants ha^{-1}, yields would increase by 4.2%. However, corn management systems must be justified on the basis of economic returns, rather than on crop yield alone (VanGessel et al., 1995). Overall, Bt corn hybrids yielded 6.6% greater and had 22% less lodging than non-Bt hybrids. However, the yield and lodging benefits for Bt hybrids were offset by the higher seed and harvest costs associated with Bt corn, adding no economic benefit. This study determined the EOPP to be 83 800 plants ha^{-1} (regardless of hybrid trait) or 9700 plants ha^{-1} more than the current recommendation in Wisconsin.

Farmers and seed companies should continue to periodically evaluate the plant population response of newly released hybrids in specific growing regions to accurately adjust plant population recommendations. In doing so, it is important to keep in mind that economics plays a key role in these recommendations.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contribution of research specialists Kent Kohn and Pat Flannery for their technical assistance; Jung Won Mun and Paul Jenkins for their assistance in data analysis; and to the associate editor and reviewers for the helpful comments. Funding for this research and publication was provided from the USDA Cooperative State Research, Education and Extension Service (CSREES) project WIS0 142-4897.

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