Published online May, 2008

Soybean

Soybean Seed Yield Response to Planting Date and Seeding Rate in the Upper Midwest

Jason L. De Bruin* and Palle Pedersen

ABSTRACT

Planting date and seeding rate are agronomic decisions that producers can use to maximize soybean [*Glycine max* (L) Merr.] seed yield and economic return. Current information on the response to planting date and seeding rate may underestimate the yield penalty for delayed planting in northern climates and overestimate the seeding rate required to optimize yield. The objective was to determine the effect of planting date and seeding rate on soybean seed yield at environments with different yield potentials in Iowa. Field experiments were conducted in six locations between 2003 and 2006 for a total of 13 environments. Four seeding rates were planted at four dates between late April and the middle of June. No yield difference existed between the late April and early May planting dates and the yield decline rate between each date was consistent among the six locations. Harvest plant populations were not influenced by planting date indicating that plant establishment does not pose a limitation to late April planting. Harvest plant populations required to reach 95% of the maximum yield were as great as 290,800 or as low as 194,000 plants ha^{-1}, for locations seeded in 38-cm row spacing and 157,300 to 211,800 plants ha^{-1} for locations seeded in 76-cm row spacing. Planting in late April or early May increased economic return ha^{-1} but there was no difference between seeding rates of 185,300 and 556,000 seeds ha^{-1}, accounting for additional seed costs. In the cool spring climate of the upper Midwest soybean producers can increase yield by planting soybean 1 to 2 wk earlier than current planting dates. These data also suggest that the optimal seeding rate for most locations is less than current seeding rates.

Planting soybean 1 May compared with 15 May has increased yield by 0.2 Mg ha^{-1} in Minnesota (Lueschen et al., 1992) and 0.3 Mg ha^{-1} in Wisconsin (Grau et al., 1994), but has shown no benefit in either northern or southern Iowa locations between 1994 and 1996 (Whigham, 1998a). Yield benefit from earlier planting increased rapidly as planting was delayed to late May or early June compared with early May planting in states of the upper Midwest (Anderson and Vasilas, 1985; Elmore, 1990; Lueschen et al., 1992; Oplinger and Philbrook, 1992; Pedersen and Lauer, 2004; Whigham et al., 2000; Wilcox and Frankenberger, 1987). Other reports document where no yield response occurs to delayed planting (Elmore, 1990; Oplinger and Philbrook, 1992; Lueschen et al., 1992), and in one study, there was a negative response at one location in 1 yr (Lueschen et al., 1992). Magnitude of the response to early planting can be year (Pedersen and Lauer, 2003), location (Lueschen et al., 1992), and cultivar specific (Elmore, 1990; Grau et al., 1994).

Soybean compensates for space in the canopy by adding branches, resulting in no yield response from increased seeding rates (Carpenter and Board, 1997). Final plant stands as low as 70,000 plant ha^{-1} in equidistant spacing (Egli, 1988) or as high as 388,000 plants ha^{-1} (Oplinger and Philbrook, 1992) have produced optimum yields. Other studies indicate that final plant populations of 250,000 to 350,000 plants ha^{-1} are sufficient to maximize yield (Beuerlein, 1988; Elmore, 1991; 1998; Weber et al., 1966; Wiggans, 1939).

Major soybean yield components are the number of seeds produced m^{-2} and individual seed mass (Board et al., 1999; Egli, 1998). Past research has documented compensatory effects between these two yield components (Board et al., 1999; Sadras, 2007). Little information exists to document yield component changes that occur with changes in time of planting and seeding rate. Elmore (1990) reported that pod number plant^{-1} decreased as planting was delayed and was in agreement with Anderson and Vasilas (1985). Seed mass response varied between the studies as seed mass declined (Elmore, 1990) and increased (Anderson and Vasilas, 1985) from delayed planting. Yield component changes from different seeding rates for indeterminate cultivars indicated that both seed mass (Egli, 1988; Weber et al., 1966) and seeds m^{-2} decreased as seeding rate was reduced (Egli, 1988). Response of primary soybean yield components to planting dates and seeding rates for the Upper Midwest would be useful for identifying primary yield limitations at late planting dates.

Soybean planting typically begins when corn (*Zea mays* L.) planting is complete but can be further delayed based on the recommendation that planting should begin after soil temperature reaches 10°C (Hoeft et al., 2000). Soil temperature data for the past 5 yr indicates that in the north, central, and southern zones of Iowa, the soil temperature at 10-cm soil depth was >10°C and was adequate for planting by the last week of April (Table 1). Probability of a killing frost event (<–1.6°C) (Meyer and Badaruddin, 2001) in Iowa during spring is less than 25% after 25 April for areas south of 42° latitude (south and central)

Iowa State University, 2104 Agronomy Hall, Ames, IA 50011. Received 1 Apr. 2007. *Corresponding author (jsndbrn@iastate.edu).

Published in Agron. J. 100:696–703 (2008).
doi:10.2134/agronj2007.0115

Table 1. Long-term (30-yr) probability of a killing frost (<–1.6 °C) and 5-yr average soil temperature at 10-cm soil depth for the north, central, and southern zones in Iowa.

Date	North†		Central		South	
	%	°C	%	°C	%	°C
1 April	98	5.5	92	7.2	88	8.6
15 April	70	14.1	45	14.6	44	15.0
25 April	46	11.1	19	10.6	16	11.3
1 May	30	10.7	8	11.1	10	12.2
15 May	2	12.9	0	13.6	0	14.8

Source: Iowa Environmental Mesonet (http://mesonet.agron.iastate.edu/index.phtml), Iowa State University Department of Agronomy

† The state was divided into North (areas north of 42°N), Central (areas between 42°N and 41.5°N), and South (areas south of 41.5°N).

and after 1 May for the area north of that latitude (Table 1). Time to emergence for planting dates in late April has been estimated at 7 to 14 d (Andales et al., 2000) and by that time the potential of late spring frost would be reduced to zero. Based on the 5-yr average (1999–2003), <10% of the soybean acres are planted by 2 May, with 80% planted by 30 May (National Agriculture Statistics Service, 2007) even though soil temperatures are >10°C before 2 May.

Growers have avoided planting in late April due to the perceived risks of cold, wet soil, and exposure to seedling diseases, which in certain years can reduce plant stands, seedling health (Hamman et al., 2002), and yield (Wrather et al., 2003). Planting into cool wet soil delays emergence (Andales et al., 2000), may increase imbibitional injury (Bramlage et al., 1979; Helms et al., 1996), and exposure to late spring frost (Meyer and Badaruddin, 2001). Migration of overwintering bean leaf beetles [*Cerotoma trifurcate* (Förster)] to first-emerged soybean fields in spring (Lam and Pedigo, 2000; 2001) causes leaf defoliation and transmission of bean pod mottle virus (Krell et al., 2004), potentially limiting the benefit to early planting.

Current recommendations in Iowa advise producers to begin planting by the last week of April but indicate that equivalent yields can still be attained by planting in the middle of May (Whigham, 1998a; Whigham et al., 2000). Seeding rates used in Iowa differ depending on row spacing. Target plant populations at harvest have been 272,000 and 321,000 plants ha^{-1} (Whigham, 1998b). Common seeding rates used in the state to ensure this harvest population are 494,200; 444,800; and 370,000 seeds ha^{-1} for 19-, 38-, and 76-cm row spacing, respectively. Interactions between planting date and seeding rates have led to the recommendation to increase seeding rates at late planting dates (Beuerlein, 1988; Whigham et al., 2000). Increased seeding rates can be part of a weed management strategy (Nice et al., 2001), but seed costs have increased rapidly within the last decade and low-cost postemergent weed control programs are available.

Specific knowledge of planting date responses at different locations is necessary to determine whether early planting should be a general recommendation. Interactions between cultivar, poor early season growing conditions that limit seedling emergence and growth, and soilborne pathogens may reduce any benefit to planting earlier in the season (Grau et al., 1994). It is therefore hypothesized that the yield response from planting date varies by location, depending on abiotic and biotic stress and yield potential, and that seeding rate is not planting date specific if weeds are controlled. The objective of this study was to determine the effects of planting date and seeding rate on soybean yield, primary yield components, and harvest plant population at locations with different yield potentials.

MATERIALS AND METHODS

Studies were conducted at Ames, Crawfordsville, and Nashua between 2003 and 2005 and at De Witt, Nevada, and Whiting, IA between 2004 and 2006. Specific location positions, soil characteristics, and fertility measurements are listed in Table 2. Experimental design was a randomized complete block in a split-plot arrangement with four blocks. Main plots were four planting dates and subplots were seeding rates of 185,300; 308,900; 432,400; and 556,000 viable seeds ha^{-1}. Target planting dates were the fourth week of April, second week of May, fourth week of May, and the second week of June. Actual planting dates are listed in Table 3 and did not always match target dates due to field conditions that limited timely planting. Fields were chiseled (Ames, Crawfordsville, Nashua) or plowed (De Witt, Nevada, Whiting) in the fall and cultivated in the spring. Cultivars were NK S24-K4 (Syngenta Seed,

Table 2. Field characteristics for six Iowa research locations where studies were conducted with different planting dates and plant populations from 2003 to 2006.

	De Witt	Nevada	Whiting	Ames	Crawfordsville	Nashua
Location	41°49′12′′ N, 90°32′24′′ W	42°1′12′′ N, 93°27′0′′ W	42°7′48′′ N, 96°9′0′′ W	42°2′23.9994′′ N, 96°39′0′′ W	41°14′24′′ N, 91°33′36′′ W	42°57′0′′ N, 92°32′24′′ W
Soil series	Tama silt loam	Webster clay loam	Salix silty clay loam	Webster clay loam	Mahaska silt loam	Kenyon loam
Soil family	fine-silty, mixed, mesic Typic Argiudolls	fine-loamy, mixed, mesic Typic Hapludolls	fine-silty, mixed, mesic Typic Hapludolls	fine-loamy, mixed, mesic Typic Hapludolls	fine, montmorillonitic, mesic Aquic Argiudolls	fine-loamy, mixed, mesic Typic Hapludolls
Soil fertility range						
pH	5.9–7.6	6.2–7.8	6.0–6.3	6.3–6.6	5.9–6.3	7.0–7.1
P, mg kg^{-1}	35–49	6–48	24–72	57–71	20–47	23–27
K, mg kg^{-1}	185–234	197–218	367–443	293–294	89–160	135–161
Organic matter, g kg^{-1}	21–43	35–54	29–37	40–48	44–51	35–38

Table 3. Year of study and planting date for Ames, Crawfordsville, De Witt, Nashua, Nevada, and Whiting between 2003 and 2006.

Location	Year	Late April	Early May	Late May	Early June
Ames	2004	1 May	16 May	3 June	15 June
Ames	2005	30 April	17 May	27 May	15 June
Crawfordsville	2003	8 May	22 May	5 June	17 June
Crawfordsville	2004	28 April	15 May	5 June	15 June
De Witt	2004	3 May	16 May	27 May	7 June
De Witt	2006	24 April	7 May	22 May	2 June
Nashua	2003	23 April	13 May	23 May	5 June
Nashua	2004	23 April	6 May	20 May	4 June
Nevada	2005	9 May	21 May	27 May	5 June
Nevada	2006	26 April	6 May	19 May	3 June
Whiting	2004	27 April	15 May	21 May	3 June
Whiting	2005	27 April	17 May	26 May	6 June
Whiting	2006	27 April	6 May	18 May	1 June

Minneapolis, MN) at Ames and Nashua, DKB 36–51RR (Monsanto Company, St. Louis, MO) at Crawfordsville, and AG 2801 (Monsanto Company, St. Louis, MO) at De Witt, Nevada, and Whiting. All cultivars were glyphosate [*N*-(phosphonomethyl) glycine] resistant. Seeds were inoculated with *Bradyrhizobium japonicum* (EMD Crop BioScience, Brookfield, WI). Plot size was 4.6 by 15.2 m at Nashua and 2.7 by 6.1 m at Ames, Crawfordsville, De Witt, Nevada, and Whiting. Row spacing was 76-cm and planted with a 7000 John Deere planter (John Deere Corp. Moline, IL) at Crawfordsville and Nashua. An Almaco grain drill (Almaco, Nevada, IA) with 38-cm row spacing was used at Ames, De Witt, Nevada, and Whiting.

Plots at Whiting were irrigated each year during the season. Studies were conducted on a producer's field and plots were irrigated along with the rest of the field at the producer's discretion. Irrigation amounts are listed in Table 4. Total rainfall (rain + irrigation) and air temperature was recorded by a field-based weather stations at each of the locations.

Weeds were managed by two applications of glyphosate applied twice during the season at a rate of 1120 g a.i. ha^{-1} at all locations. The insecticide Chlorpyrifos [0,0-diethyl-0-(3,5,6-trichloro-2-pyridinyl) phosphorothioate] (Dow AgroSciences, Indianapolis, IN) was applied at a rate of 840 g a.i. ha^{-1} at Nevada in 2006 and cyfluthrin [cyano (4-fluoro-3-phenoxyphenyl) methyl-3-(2,2-dichloroethenyl)-2,2-dimethyl-sylcopropanecarboxylate] (Bayer CropScience, Research Triangle Park, NC) was applied at 490 g a.i. ha^{-1} at Whiting in 2005 to control bean leaf beetles.

Yield was determined by harvesting the center four and two rows of the 38- and 76-cm row spacing, respectively, with an Almaco plot combine and adjusted to moisture content of 130 g kg^{-1}. Other data acquired at harvest were final plant population and seed mass based on a sample weight of 300 seeds. Seeds m^{-2} was calculated based on seed mass and yield (Board and Modali, 2005).

Economic return for the four seeding rates was evaluated by using a partial budget analysis that included only the factors that changed between treatments. Gross revenue from the sale of the soybean seed was determined and the economic return was adjusted for the additional seed costs for higher seeding rates. Soybean sale price was determined based on the method of Stanger and Lauer (2006). Fifty percent of the crop was sold in November and 25% of the crop was forward marketed to both March and July. Between 2001 and 2005 the average 5-yr cash price was \$0.203 kg^{-1} (National Agriculture Statistics Service, 2007). Future prices for March (\$0.239 kg^{-1}) and July (\$0.246 kg^{-1}) were based on the Chicago Board of Trade on 5 Dec. 2006 and were adjusted for basis. Final sale price was \$0.213 kg^{-1}. Seed cost was set at \$1.2 kg^{-1}, hauling and handling charges

Table 4. Monthly air temperature and rainfall at six locations in Iowa between 2003 and 2006.

		May		June		July		August	
Location	Year	Air temperature	Rainfall	Air temperature	Rainfall	Air temperature	Rainfall	Air temperature	Rainfall
		°C	mm	°C	mm	°C	mm	°C	mm
Ames	2004	18.2 (0.8)	208 (94)	21.1 (–1.4)	91 (–55)	23.1 (–1.2)	50 (–37)	20.6 (–2.4)	132 (40)
	2005	16.6 (–0.8)	111 (–3)	24.2 (1.7)	124 (–22)	25.2 (0.8)	104 (17)	23.3 (0.2)	172 (80)
Crawfordsville	2003	16.2 (–2.3)	165 (67)	21.2 (–2.3)	109 (–1)	24.1 (–1.5)	45 (–62)	24.7 (0.2)	22 (–73)
	2004	18.7 (1.3)	183 (25)	23.1 (0.7)	40 (–55)	23.0 (–1.9)	113 (23)	20.5 (–3.4)	109 (22)
De Witt	2004	17.1 (0.3)	112 (8)	20.8 (–0.8)	89 (–21)	21.3 (–2.6)	48 (–40)	18.6 (–4.0)	99 (–16)
	2006	16.1 (–0.7)	165 (65)	22.8 (1.1)	69 (–36)	24.6 (0.7)	107 (17)	22.6 (–0.1)	132 (15)
Nashua	2003	15.6 (–0.6)	99 (–11)	20.9 (–0.4)	155 (30)	23.2 (–0.3)	76 (–43)	23.6 (1.5)	12 (–112)
	2004	16.9 (0.7)	285 (178)	20.4 (–0.9)	74 (–54)	22.1 (–1.4)	155 (37)	19.9 (–2.2)	74 (–49)
Nevada	2005	15.8 (–0.6)	85 (–27)	23.1 (1.8)	136 (12)	24.0 (0.6)	78 (34)	21.7 (–0.3)	147 (31)
	2006	17.3 (0.9)	53 (–58)	24.1 (2.7)	22 (–97)	24.5 (1.1)	85 (–31)	22.1 (0.1)	158 (40)
Whiting†	2004	16.8 (0.0)	170 (58)	20.4 (–1.4)	74 (–32)	22.5 (–1.8)	114 (19)	19.9 (–3.1)	64 (–19)
	2005	16.6 (–0.2)	102 (–6)	23.5 (1.6)	101 (6)	24.6 (0.4)	72 (23)	22.1 (–1.0)	96 (15)
	2006	16.8 (0.1)	60 (–47)	24.1 (2.1)	51 (–51)	25.0 (0.8)	68 (–27)	22.3 (–0.7)	212 (127)

† Irrigation at Whiting in 2004 was 13 mm on both 7 Sept. and 15 Sept.; in 2005 was 24 mm on 18 July and 34 mm on 7 Aug.; and in 2006 was 13 mm on 20 May, 26 mm on 16 June, 25 mm on 10 July, 13 mm on 17 Aug., and 13 mm on 19 Aug. Irrigation is accounted for in rainfall total.

were \$0.00054 kg^{-1} (Duffy and Smith, 2006) and seeds kg^{-1} was set at 6600 seeds kg^{-1}. Equipment and drying costs were assumed to remain the same or have little influence on the economic return.

Data were analyzed using Proc Mixed in SAS (SAS Institute, 2003). Years and blocks were treated as random effects and all other effects were considered fixed. Box plots and residuals were used to evaluate variance assumptions. Variance was determined to be homogenous for seed yield, seeds m^{-2}, seed mass, and harvest plant populations. A combined analysis was conducted for all variables. Seed yield reductions due to delayed planting were assessed by mean separation among planting dates using least significant difference. Rate of seed yield decline between planting dates was determined for each block based on the difference between late April-early May, early May-late May, and late May-early June planting dates. Differences between planting dates were divided by the number of days between planting and converted to seed yield decline wk^{-1}. Comparison of rates among locations for each planting delay was determined by least significant difference. Differences among rates for the three planting delays, within a location, were determined by testing between the three delays using a 2 degree-of-freedom contrast. Linear models were fit between seeding rate and harvest plant population for each of the six locations using Proc Reg in SAS to determine plant establishment rates. Slope and intercept from each model was used to predict the required seeding rate necessary to achieve desired harvest population for maximum and 95% of the maximum yield. Fitted curves, between the harvest plant population and yield were selected based on model significance and coefficient of determination (R^2) values using Proc NLIN in SAS. Theses curves were used to predict the plant stand that gave yields 95% of the maximum.

RESULTS AND DISCUSSION

Rainfall varied considerably among years and locations (Table 4). Below normal rainfall occurred at Crawfordsville in 2003, De Witt and Nashua in 2004, and Nevada and Whiting in 2006. At Nevada in 2006 rainfall totals were 58, 97, and 31 mm below average in May, June, and July, respectively. Rainfall was below normal at Whiting in June, July, and August each year of the study even though plots were irrigated at various times in the season. Air temperature in May and August tended to be slightly cooler than normal at all locations for all years. At Nevada and Whiting in 2006 June air temperature was 2.7 and 2.1°C above normal, respectively but was normal at other locations.

Locations in this study represent the wide range of growing conditions that exist in Iowa. Average soybean yield for the state between 2002 and 2006 was 3118 kg ha^{-1} (National Agriculture Statistics Service, 2007). Locations close to this average were considered average-yield potential environments and locations above this average were considered high-yield potential environments. Whiting and De Witt were considered high-yield environments as both have well-drained soils and high fertility levels (Table 2). Other locations were average-yield potential environments. Nevada and Ames are located in the Des Moines lobe (Steinwand and Fenton, 1995), an area with high pH, low P availability, and poorly-drained soils. Phosphorus levels were well below test levels in the Nevada, 2005 location (Table 2). Nashua, a northern environment is on highly erodible land with a thin A-horizon, making it rainfall dependent. Crawfordsville is a southern environment with well-drained soil. However, during this study it received below normal rainfall (Table 4).

Harvest Plant Population

An interaction between location and seeding rate indicated that plant establishment was not equal at all locations (Table 5). This interaction was separated using the slice statement in SAS but results were inconclusive. Populations were different from one another at all locations but for each seeding rate there was no difference among locations. Based on the two-way means the interaction occurred at the 556,000 seeds ha^{-1} seeding rate. Plant establishment was lower at Whiting and at Crawfordsville compared with establishment at Nashua (Table 6). Harvest plant populations averaged 273,600 plants ha^{-1} for late April planting and were not increased by delayed planting. No interactions existed with planting date. Oplinger and Philbrook (1992) reported that plant establishment increased at later planting dates as a result of increased soil temperature. Our study indicated that soil temperature and soil moisture do not pose a limitation to plant establishment at late April planting, regardless of location, or seeding rate, and is more consistent with data reported by Lueschen et al. (1992).

Table 5. Seed yield, seeds m^{-2}, seed mass, harvest plant population, and economic return analysis of variance for planting date and seeding rate at Ames, Crawfordsville, De Witt, Nashua, Nevada, and Whiting conducted between 2003 and 2006.

Source	df	Seed yield	Seeds m^{-2}	Seed mass	Harvest plant population	Economic return
		$P > F$				
Location (L)	5	0.0108	0.0891	0.1563	0.8964	0.0108
Planting date (D)	3	0.0001	0.0001	0.3723	0.1145	0.0001
L × D	15	0.1132	0.1911	0.2748	0.2294	0.1132
Seeding rate (S)	3	0.0315	0.1531	0.0001	0.0001	0.8403
L × S	15	0.6868	0.3872	0.0987	0.0514	0.6868
D × S	9	0.3025	0.2262	0.8040	0.1338	0.3025
L × D × S	45	0.5020	0.6882	0.0116	0.4357	0.5020

Table 6. Harvest plant populations at six locations resulting from four seeding rates and averaged across four planting dates between late April and early June.

Seeding rate	Location					
	Ames	Crawfordsville	De Witt	Nashua	Nevada	Whiting
	plants ha^{-1}					
185,300	175,600†	151,200	189,600	155,400	179,500	176,000
308,900	280,900	258,100	262,100	260,100	269,500	271,800
432,400	354,000	348,200	355,800	354,100	342,700	330,700
556,000	420,500	393,000	407,800	471,600	436,600	390,000
LSD (0.05)			84,200			

†Means represent two years of data from Ames, Crawfordsville, De Witt, Nashua, and Nevada, and three years from Whiting.

Table 7. Seed yield, seeds m^{-2}, and seed mass response to four planting dates at six locations in Iowa between 2003 and 2006.

	Yield	Seed no.†	Seed mass	Harvest population	Return‡
	kg ha^{-1}	seeds m^{-2}	g 100 seeds^{-1}	plants ha^{-1}	$ ha^{-1}
Location					
Ames	3653	2338	14.0	307,700	709
Crawfordsville	3074	2251	12.4	287,600	586
De Witt	4653	2787	15.1	303,800	921
Nashua	3021	2026	15.8	310,300	574
Nevada	3377	2170	13.8	307,100	650
Whiting	5039	3032	14.9	292,100	1003
LSD (0.05)	1152	NS§	NS	NS	246
Planting date					
Late April	4202	2688	14.3	273,600	825
Early May	4044	2558	14.5	293,900	792
Late May	3818	2405	14.5	316,700	743
Early June	3147	2084	14.1	321,600	601
LSD (0.05)	227	172	NS	NS	48
Seeding rate					
185,300	3648	2367	14.2	171,200	741
308,900	3758	2409	14.3	267,100	742
432,400	3884	2476	14.4	347,600	746
556,000	3922	2484	14.5	419,900	732
LSD (0.05)	182	NS	0.1	15,000	NS

† Seed no. m^{-2} and seed mass data were not collected from Nashua in 2003.

‡ Income that is returned to management, accounting for the cost difference between seeding rates. Calculated as return = [seed yield × $0.213 kg^{-1}] – [(seeding rate/6600 seeds kg^{-1}) × $1.2 kg^{-1}]

§ NS = no significant differences at $P \leq 0.05$.

Table 8. Seed yield reductions between four planting dates at six locations in Iowa from 2003 to 2006.

Location	Late April–early May	Early May–late May	Late May–early June
	kg ha^{-1} wk^{-1}		
Ames	138b†	247b	634a
Crawfordsville	28b	223ab	403a
Nashua	161b	70b	512a
De Witt	48a	205a	76a
Nevada	82a	–327a	355a
Whiting	–39b	360a	441a
Mean	70	130	404
LSD (0.05)‡	NS§	NS	NS

† Values followed by the same letter within a location are not significantly different at $P \leq 0.05$

‡ LSD value for comparison between locations within each planting delay

§ NS = no significant differences at $P \leq 0.05$

Seed Yield

Locations did vary in yield potential (Table 5) as yield at Whiting and De Witt was greater than other locations ($P = 0.08$) (Table 7). Yield potential of the environment did not change the response to date of planting (Table 5). Averaged across locations no strong evidence existed to suggest that planting the last week of April rather than the second week of May increased yield significantly ($P = 0.16$). Late April planting was clearly superior to late May or early June planting (Table 7). At all locations the lowest yields occurred with June planting and yield reductions between late April and June were 41% at Ames, 32% at Crawfordsville, 24% at De Witt, 17% at Nashua, 12% at Nevada, and 24% at Whiting.

Rate of yield decline between planting dates was similar among locations (Table 8). Averaged across locations yield decreased at a rate of 70 kg ha^{-1} wk^{-1} between the late April and early May planting date and rates increased as planting was delayed, reaching 130 and eventually 404 kg ha^{-1} wk^{-1} between early May-late May and late May-early June, respectively. Within a specific location rate of yield decline between planting dates differed. At Ames, Crawfordsville, and Nashua, the rates were similar for the first two delays but increased between late May and early June planting. At De Witt and Nevada the rates were similar for all planting delays even though yields at Nevada increased at a rate of 327 kg ha^{-1} between early May and late May (Table 8). This unexpected response at Nevada to planting date was likely the result of early-season soil crusting in 2005 and severe drought conditions in 2006 (Table 4). These situations are not common and it is unlikely, based on the data from the nearby location in Ames to expect this response. Whiting was the only location where the yield decline rates were similar between early May-late May and late May-early June, averaging 382 kg ha^{-1} wk^{-1}. This similarity in rates indicates that a rapid yield decline started earlier in the season. Rate changes between planting dates were similar to reports by others in the upper Midwest that indicate yield declined at an increasing rate the longer planting was delayed (Grau et al., 1994; Lueschen et al., 1992; Oplinger and Philbrook (1992).

Planting in late April or early May was necessary to achieve maximum yield and illustrates that for most locations in Iowa there is a relatively large window of time, approximately 2 wk, to complete planting and achieve maximum yields. This finding is in agreement with previous planting date studies conducted in Iowa (Whigham, 1998a). A high-yield potential location such as Whiting did provide evidence that rapid yield decline does begin earlier and that the optimal time of planting may be narrower than at lower-yield potential locations. Research in the Upper Midwest has also shown that early planting is beneficial but the magnitude of the yield benefit is location and year specific (Lueschen et al., 1992).

Among 13 environments planted from late April to early June there was no planting date by seeding rate interaction (Table 5). Our data do not support increased seeding rates at later planting dates. This study did not test extremely late planting dates (later than 15 June) that may occur if replanting is necessary. Our research was similar to past studies that indicated a yield response to more plants ha^{-1} but only to the point where yield becomes independent of plant density (Duncan, 1986). Seeding rate did influence yield but did not interact with location or planting date (Table 5).

Optimal seeding rate varied among locations (Table 5). Separate equations were used at each location to predict the harvest plant population required to achieve yields that were 95% of the maximum yield of a location (Table 9). Ninety-five percent of the maximum yield was close to the LSD based on $P = 0.05$ and was representative of the point where nonsignificant yield differences occur. Establishment rates for seeding rates and harvest plant populations ranged from 0.57 to 0.84 and averaged 0.67. Four of the locations were seeded in 38-cm row spacing. Ames and Nevada are located in central Iowa and required final stands of 290,800 plants ha^{-1} with seeding rates of 345,700 seeds ha^{-1} for 95% of the maximum yield (Table

Table 9. Regression equations and predicted minimum harvest plant populations and seeding rates to achieve full yield potential and 95% of maximum yield for six locations in Iowa between 2003 and 2006.

Location	Equation†	R^2	Model significance	Maximum yield‡ Yield	Maximum yield‡ Harvest plant population	Maximum yield‡ Seeding rate	95% of maximum yield Yield	95% of maximum yield Harvest plant population	95% of maximum yield Seeding rate
				kg ha^{-1}	plants ha^{-1}	seeds ha^{-1}	kg ha^{-1}	plants ha^{-1}	seeds ha^{-1}
Ames	$y = -2430 + 483.2\ln$ (ppa§)	0.90	0.0501	3841	420,500	543,069	3648	290,100	343,700
Crawfordsville	$y = 3095\ [1 - e^{-0.000024\ (ppa)}]$	0.22	0.0004	3183	348,200	462,434	3024	157,300	173,200
De Witt	$y = 474 + 332.1\ln$ (ppa)	0.94	0.0286	4753	407,800	539,800	4515	192,500	197,500
Nashua	$y = 3099\ [1 - e^{-0.000016\ (ppa)}]$	0.83	0.0002	3152	354,100	422,595	2994	211,800	253,900
Nevada	$y = -2198 + 443.1\ln$ (ppa)	0.98	0.0103	3555	436,600	560,197	3377	291,400	347,700
Whiting	$y = 5109\ [1 - e^{-0.000018\ (ppa)}]$	0.55	0.0001	5219	390,000	543,178	4958	195,600	200,400

† Log linear or gompertz equations were selected based model significance and maximization of the coefficient of determination (R^2) and used to predict the harvest population necessary to reach 95% of maximum yield.

‡ Maximum yield and associated harvest population obtained at a location. Seeding rate was predicted based on linear establishment rate.

§ ppa = harvest plant population ha^{-1}.

9). Final populations of 194,000 plants ha^{-1} and seeding rates of 199,000 seeds ha^{-1} were necessary to achieve 95% of the maximum yield at the high-yield potential locations, Whiting and De Witt. Nashua and Crawfordsville were seeded in 76-cm row spacing and produced yields 95% of the maximum with harvest stands of 157,300 and 211,800 plants ha^{-1} with seeding rates of 173,200 and 253,900 seeds ha^{-1}, respectively.

Response to harvest plant populations for most locations was within the population range reported by Beuerlein (1988), Elmore (1991, 1998), Weber et al. (1966), and Wiggans (1939). Our study is the first study to evaluate locations with very different yield potentials and provided evidence that high-yield locations required lower harvest plant populations than lower yield-potential locations. Oplinger and Philbrook (1992) reported that yields in conventional tilled systems continued to increase at seeding rates >494,200 seeds ha^{-1}. Seeding rates this high were necessary to reach the maximum yield for most locations; however, because there was no difference between the two highest seeding rates (Table 7) the optimal seeding rate predicted for each location were considerably less (Table 9).

Accounting for additional seed costs ($22.40 ha^{-1} 123,500 seeds^{-1}), the economic return from the four seeding rate treatments was not significantly different (Table 7). Among locations the seeding rate of 185,300 seeds ha^{-1} had an economic return equal to other seeding rates because the reduction in seed cost offset the reduced seed yield. Harvest plant populations from the 185,300 seeding rate averaged 171,200 plants ha^{-1} averaged across locations. These populations would not be sufficient to achieve the highest yield, but due to increased seeds costs, represent the economic seeding rate. This economic seeding rate is less than current seeding rates regardless of row spacing. Previous studies have not reported economic seeding rates for the upper Midwest. As seed costs continue to increase, greater emphasis should be placed on economic seeding rates compared with seeding rates that produce the greatest yields.

Primary Yield Components

Number of seeds m^{-2} was similar among locations and correlated with yield even though differences among locations were >1000 seeds m^{-2}. Seeds m^{-2} was the yield component that showed a continual reduction to delayed planting and accounted for the yield decline from late April to late May planting. Similar to yield no reduction in seeds m^{-2} occurred at Nevada between early and late May planting. Seeding rates did not change seeds m^{-2} (Table 7).

Seed mass response to planting date varied by location and seeding rate (Table 5), but separating the location × planting date × seeding rate interaction by the slice statement in SAS, showed no conclusive trend to be evident. Seed mass was equal between the first two planting dates at Whiting and the first three at Nevada and De Witt (data not shown). By the June planting date, seed mass had declined 10% at Nevada, 8% at Whiting, and 3% at De Witt from the earlier planting dates. At Nashua and at Ames seed mass increased for the last two planting dates compared with the first two planting dates. Our data indicate that location conditions determine whether seed mass responds positively or negatively to delayed planting and is in agreement with previous research (Elmore, 1990; Anderson and Vasilas, 1985).

Range in seeds m^{-2} for locations and treatments was 1717 to 3463 seeds m^{-2} (102% difference) and average seed mass varied between 120 and 164 mg seed^{-1} (37% difference). These changes resulted in yield differences as great as 190%. A strong linear relationship ($R^2 = 0.89$) existed between seeds m^{-2} and yield (Fig. 1) but not between seed mass and yield (data not shown). Based on these data, seeds m^{-2} was the component that drove yield responses between planting dates. Regression analysis indicated that the response slope between seeds m^{-2} and yield was 1.93x and did run parallel to the reference lines of known seed mass (seed mass × seeds m^{-2} = yield). As seeds m^{-2} increased, seed mass also increased to further improve seed yield. Soybean in high-yield locations produced more seeds m^{-2} and a greater number of seeds did not limit seed fill. At both De Witt and Whiting the greatest number of seeds m^{-2} and the largest seeds occurred at the late April planting date (data not shown). One location (Nashua 2004) produced very large seeds (>160 mg seed^{-1}) at the two later planting dates, but yields were <3500 kg ha^{-1} due to low seeds m^{-2}. Greater seed mass has limited ability to increase seed yield and full yield potential is not attained due to a seeds m^{-2} limitation. As planting was delayed to late May or early June seeds m^{-2} was the yield component most notably affected and posed the greatest limitation to achieving high yields. Changes in seed mass were variable and location specific and are not the major yield limitation at later planting dates in the upper Midwest.

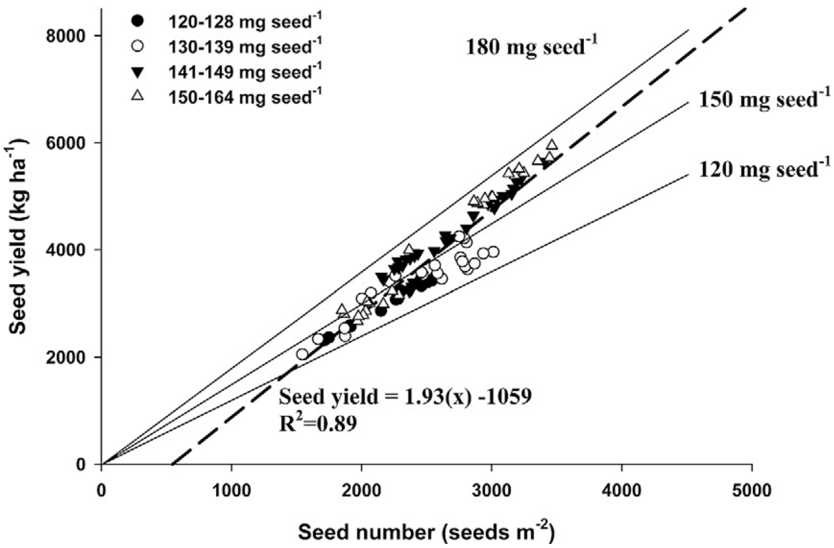

Fig. 1. Seed yield response to changes in seeds m^{-2} and seed mass at Ames, Crawfordsville, De Witt, Nashua, Nevada, and Whiting, IA, from 2003 to 2006. Solid lines are reference lines for three seed masses (mg $seed^{-1}$ × seeds m^{-2}). The dashed line is the regression line for all data points.

CONCLUSIONS

Planting soybean earlier than current practices is a management practice producers should use to increase yield in the upper Midwest, even with cool spring temperatures. Probability for spring frost does limit how early planting can occur and requires region-specific recommendations. Early planting consistently improved yield through an increase in seeds m^{-2} rather than improvements in seed mass. Yield increases were marginal by seeding rates >185,300 seeds ha^{-1}, did not vary by planting date, and yield improvements were offset by additional seed costs. Risks are associated with reduced seeding rates but as seed costs increase and since yield responses are small the focus must be placed on economic return rather than yield maximization.

ACKNOWLEDGMENTS

The authors thank Adriana Murillo-Williams and Jodee Stuart for their technical assistance. This research was funded by the Iowa Soybean Association.

REFERENCES

Andales, A.A., W.D. Batchelor, and C.E. Anderson. 2000. Modification of a soybean model to improve soil temperature and emergence date prediction. Trans. ASAE 43:121–129.

Anderson, L.R., and B.L. Vasilas. 1985. Effects of planting date on two soybean cultivars: Seasonal dry matter accumulation and seed yield. Crop Sci. 25:999–1004.

Beuerlein, J.E. 1988. Yield of indeterminate and determinate semidwarf soybean for several planting dates, row spacings, and seeding rates. J. Prod. Agric. 1:300–303.

Board, J.E., M.S. Kang, and B.G. Harville. 1999. Path analyses of the yield formation process for late-planted soybean. Agron. J. 91:128–135.

Board, J.E., and H. Modali. 2005. Dry matter accumulation predictors for optimal yield in soybean. Crop Sci. 45:1790–1799.

Bramlage, W.J., A.C. Leopold, and J.E. Specht. 1979. Imbibitional chilling sensitivity among soybean cultivars. Crop Sci. 19:811–814.

Carpenter, A.C., and J.E. Board. 1997. Branch yield components controlling soybean yield stability across plant populations. Crop Sci. 37:885–891.

Duffy, M., and D. Smith. 2006. Estimated cost of crop production in Iowa–2006. Ext. Bull. Fm 1712. Iowa State Univ., Ames.

Duncan, W.G. 1986. Planting patterns and soybean yields. Crop Sci. 26:584–588.

Egli, D.B. 1988. Plant density and soybean yield. Crop Sci. 28:977–981.

Egli, D.B. 1998. Seed biology and the yield of grain crops. CAB Int., New York.

Elmore, R.W. 1990. Soybean cultivar response to tillage systems and planting date. Agron. J. 82:69–73.

Elmore, R.W. 1991. Soybean cultivar response to planting rate and tillage. Agron. J. 83:829–832.

Elmore, R.W. 1998. Soybean cultivar responses to row spacing and seeding rates in rainfed and irrigated environments. J. Prod. Agric. 11:326–331.

Grau, C.R., E.S. Oplinger, E.A. Adee, E.A. Hinkens, and M.J. Martinka. 1994. Planting date and row width effect on severity of brown stem rot and soybean productivity. J. Prod. Agric. 7:347–351.

Hamman, B., D.B. Egli, and G. Koning. 2002. Seed vigor, soilborne pathogens, preemergent growth, and soybean seeding emergence. Crop Sci. 42:451–457.

Helms, T.C., E. Deckard, R.J. Goos, and J.W. Enz. 1996. Soybean seedling emergence influenced by days of soil water stress and soil temperature. Agron. J. 88:657–661.

Hoeft, R.G., E.D. Nafziger, R.R. Johnson, and S.R. Aldrich. 2000. Soybean as a crop. p. 31–59. *In* R.G. Hoeft et al. (ed.) Modern corn and soybean production. R.R. Donnelley and Sons, Chicago, IL.

Krell, R.K., L.P. Pedigo, J.H. Hill, and M.E. Rice. 2004. Bean leaf beetle (*Coleopteran: Chrysomelidae*) management for reduction of bean pod mottle virus. J. Econ. Entomol. 97:192–202.

Lam, W.F., and L.P. Pedigo. 2000. A predictive model for the survival of overwintering bean leaf beetles (*Coleopteran: Chrysomelidae*). Environ. Entomol. 29:800–806.

Lam, W.F., and L.P. Pedigo. 2001. Population dynamics of bean leaf beetles (*Coleopteran: Chrysomelidae*) in central Iowa. Environ. Entomol. 30:562–567.

Lueschen, W.E., J.H. Ford, S.D. Evans, B.K. Kanne, T.R. Hoverstad, G.W. Randall, J.H. Orf, and D.R. Hicks. 1992. Tillage, row spacing, and planting date effects on soybean following corn and wheat. J. Prod. Agric. 5:254–260.

Meyer, D.W., and M. Badaruddin. 2001. Frost tolerance of ten seedling legume species at four growth stages. Crop Sci. 41:1838–1842.

National Agriculture Statistics Service. 2007. Published estimates data base (PEDB). Available at http://usda.mannlib.cornell.edu/usda/nass/CropProd//2000s/2006/CropProd-11-09-2006.txt [accessed 12 Nov. 2006; verified 30 Jan. 2008]. USDA-NASS, Washington, DC.

Nice, G.R.W., N.W. Buehring, and D.R. Shaw. 2001. Sicklepod (*Senna obtusifolia*) response to shading, soybean (*Glycine max*) row spacing, and population in three management systems. Weed Technol. 15:155–162.

Oplinger, E.S., and B.D. Philbrook. 1992. Soybean planting date, row width, and seeding rate response in three tillage systems. J. Prod. Agric. 5:94–99.

Pedersen, P., and J.G. Lauer. 2003. Soybean agronomic response to management systems in the upper midwest. Agron. J. 95:1146–1151.

Pedersen, P., and J.G. Lauer. 2004. Response of soybean yield components to management system and planting date. Agron. J. 96:1372–1381.

Sadras, V.O. 2007. Evolutionary aspects of the trade-off between seed size and number in crops. Field Crops Res. 100:125–138.

SAS Institute. 2003. The SAS system for Windows. v. 9.1.3. SAS Inst., Cary, NC.

Stanger, T.F., and J.G. Lauer. 2006. Optimum plant population of Bt and Non-Bt corn in Wisconsin. Agron. J. 98:914–921.

Steinwand, A.L., and T.E. Fenton. 1995. Landscape evolution and shallow groundwater hydrology of a till landscape in Central Iowa. Soil Sci. Soc. J. 59:1370–1377.

Weber, C.R., R.M. Shibles, and D.E. Byth. 1966. Effect of plant population and row spacing on soybean development and production. Agron. J. 58:99–102.

Whigham, K. 1998a. What is the best soybean seeding rate? Integrated crop management newsletter. IC-480(7):56–57. Iowa State Univ. Ext. Serv., Ames.

Whigham, K. 1998b. Plant soybeans before mid-May. Integrated crop management newsletter. IC-480(6):46–47. Iowa State Univ. Ext. Serv., Ames.

Whigham, K., D. Farnham, J. Lundvall, and D. Tranel. 2000. Soybean replant decisions. Ext. Bulletin PM 1851. Iowa State Univ.

Wilcox, J.R., and E.M. Frankenberger. 1987. Indeterminate and determinate soybean responses to planting date. Agron. J. 79:1074–1078.

Wiggans, R.G. 1939. The influence of space and arrangement on the production of soybean plants. J. Am. Soc. Agron. 31:314–321.

Wrather, J.A., S.R. Koenning, and T.R. Anderson. 2003. Effect of diseases on soybean yields in the United States and Ontario (1999–2002). Plant Health Progress doi:10.1094/PHP-2003–0325–01-RV. Available at www.plantmanagementnetwork.org/pub/php/review/2003/soybean (verified 31 Jan. 2008).