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RESEARCH

Genetic Gain × Management Interactions in Soybean: I. Planting Date

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ABSTRACT

Planting date is a commonly manipulated management practice in soybean [*Glycine max* (L.) Merr.] production; however, the impacts of past and ongoing agronomic improvements, such as earlier planting, on genetic yield improvement and associated changes in seed protein and oil have not been evaluated. The objectives of this study were to determine if a 30-d difference in planting date affected measured rates of genetic improvement in (i) yield, (ii) seed mass, and (iii) seed protein and oil in the midwestern United States. Research was conducted at Arlington, WI, Urbana, IL, and Lafayette, IN, during 2010 and 2011, using 59 Maturity Group (MG) II cultivars (released 1928–2008) at Wisconsin, and 57 MG III cultivars (released 1923–2007) at Illinois and Indiana, with targeted planting dates of 1 May and 1 June. Earlier planting provided higher yields (+3.1 kg ha^{-1} yr^{-1}) than late planting in MG III soybean. Seed protein concentration decreased linearly over cultivar year of release at a rate of 0.191 (± 0.069) g kg^{-1} yr^{-1} for MG II, and 0.242 (± 0.063) g kg^{-1} yr^{-1} for MG III. Seed oil concentration increased over year of release at a rate of 0.142 (± 0.037) g kg^{-1} yr^{-1} for MG II, and 0.127 (± 0.039) g kg^{-1} yr^{-1} for MG III. The interaction between planting date and cultivar year of release for MG III yield suggested that the trend toward earlier planting is one agronomic improvement that, when coupled with genetic improvement, has provided a synergistic increase in on-farm soybean yields in the midwestern United States.

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Abbreviations: MG, Maturity Group.

Soybean [*Glycine max* (L.) Merr.] yields in the United States have improved at a rate of 23.4 kg ha^{-1} yr^{-1} since national yield data were first reported in 1924 (USDA-NASS, 2011). The persistence of this annual on-farm yield gain has been attributed to continued cultivar improvement via plant breeding and the periodic adoption of improved agronomic practices by U.S. producers (Specht and Williams, 1984). The contribution of genetic yield gain toward overall yield improvement in soybean has been well documented. However, the relative contribution of individual agronomic advancements remains unclear. Specht et al. (1999) summarized a number of previous genetic gain studies, and based on these studies, reported that the average annual increase in soybean yield due to genetic improvements ranged from 10 to 30 kg ha^{-1} yr^{-1} (Boerma, 1979; Luedders, 1977; Specht and Williams, 1984; Voldeng et al., 1997; Wilcox et al., 1979). Even with such a wide range, the relative contribution of genetic improvement in the United States (Maturity Group [MG] IV or earlier) was estimated by Specht and Williams (1984) to be 12.5 kg ha^{-1} yr^{-1}, among hybridized cultivars released post-1940 in their research.

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About half of yield gain in soybean can be attributed to genetic improvement. The remaining half is hypothesized to be the result of improved agronomic practices and the potentially synergistic interaction of advances in both agronomics and genetics. Researchers have speculated that a number of changes in agronomic practices have contributed to soybean yield improvement. These include: (i) earlier planting dates (Heatherly and Elmore, 2004; Johnson, 1987; Specht et al., 1999), (ii) narrower row spacing (Heatherly and Elmore, 2004; Specht et al., 1999; Voldeng et al., 1997), (iii) higher seeding rates (Voldeng et al., 1997), (iv) improved weed control and herbicide use (Luedders, 1977; Specht et al., 1999; Voldeng et al., 1997), and (v) reduced harvest losses (Specht et al., 1999). Arguably, the most important and cost-free cultural management decision that a grower can make to maximize grain yield is to sow soybean at a calendar date appropriate for the latitude of production (Cartter and Hartwig, 1963; Robinson et al., 2009). Optimum planting date in the northern United States ranges from early to mid-May (Heatherly and Elmore, 2004). Recent literature suggests that planting in late April can help maximize yields in the Midwest, although seeding soybean before then is not recommended because of increased risk of seedling exposure to frost and no documented yield advantage when compared to late-April and early-May plantings (De Bruin and Pedersen, 2008a; Robinson et al., 2009). Planting dates in the midwestern United States have consistently trended toward earlier calendar dates (USDA-NASS, 2011). However, further research is needed to determine the potential contribution of planting date to soybean yield enhancement, given that yields are also rising due to genetic improvement.

In most circumstances, soybean yield declines steadily when planting is delayed after mid-May. In Iowa, yield loss resulting from delayed planting averaged 130 kg ha^{-1} wk^{-1} (18.6 kg ha^{-1} d^{-1}) between early and late May and then 404 kg ha^{-1} wk^{-1} (57.7 kg ha^{-1} d^{-1}) between late May and early June (De Bruin and Pedersen, 2008a). Soybean yields in Nebraska declined at a linear rate of 119 kg ha^{-1} wk^{-1} (17 kg ha^{-1} d^{-1}) in 2003 and 301 kg ha^{-1} wk^{-1} (43 kg ha^{-1} d^{-1}) in 2004 as planting date was delayed from early May to mid-June (Bastidas et al., 2008). Delayed planting results in decreased plant height (Bastidas et al., 2008; Wilcox and Frankenberger, 1987), decreased pods plant^{-1} (Anderson and Vasilas, 1985; Elmore, 1990), decreased pods m^{-2} (Pedersen and Lauer, 2004; Robinson et al., 2009), and decreased seeds per unit area (Pedersen and Lauer, 2004), all leading to lower yields. Delayed planting also influences seed protein and oil, frequently resulting in increased seed protein concentration and decreased seed oil concentration (Kane et al., 1997; Pendleton and Hartwig, 1973; Robinson et al., 2009). Lower protein and higher oil concentrations were also associated with more recently released soybean cultivars when compared to older cultivars (Wilcox et al., 1979), although this preliminary observation has yet to be documented with a comprehensive group of cultivars representing a wide range of release years. Seed mass has been shown to decrease (Anderson and Vasilas, 1985; Elmore, 1990), increase (Bastidas et al., 2008), or not change (Pedersen and Lauer, 2004; Wilcox and Frankenberger, 1987) over a range of planting dates. Further research efforts with a greater number of cultivars might help resolve the impact of planting date on seed mass.

Clearly, genetic gain has played an important role in soybean yield improvement over time, but the genetic improvement made by breeders does not account for all of the on-farm improvement in yield to date. Understanding the role of agronomic advancements in past soybean yield gain is key to determining past sources of yield gain, and will ensure that yield improvements will continue to occur in the future. Furthermore, synergistic interactions between agronomic improvements and genetic gain are also assumed to have played a role in past soybean yield gain, and the contribution of these interactions must be discerned and verified. The shift toward earlier planting is just one of many agronomic practices that has changed over time and may be a contributing factor to the yield improvement realized by U.S. soybean growers. The comprehensive study described in this paper, utilizing over 115 public and proprietary cultivars in two maturity groups, was aimed at examining the interaction between planting date and the measured rate of genetic improvement over time. This rich set of soybean cultivars, released over eight decades, provided a unique opportunity to study the impact of early and late planting on the derived estimates of genetic yield improvement. We hypothesized that earlier soybean planting provided a production system environment more favorable for the expression of genetic yield potential in newer cultivars. If so, then the estimated rate of genetic yield gain would be expected to be greater with earlier planting than with later planting (i.e., a synergistic interaction). It is expected that seed mass and seed protein and oil have also been influenced by earlier planting dates and have changed over time as a result of both breeding efforts and earlier planting. To understand the effects of earlier planting on soybean yield gain, seed mass, and seed protein and oil over time in MG II and MG III cultivars in the north-central United States, the objectives of our study were twofold: (i) to compare overall yield, yield response *to*, and measured rates of yield gain over time among previously released soybean cultivars *between* two planting dates, 1 May and 1 June; and (ii) to compare changes in soybean mass and seed protein and oil among previously released soybean cultivars at two planting dates, 1 May and 1 June.

Table 1. Experimental details with respect to test sites, soils, and dates of planting and harvest.

	Arlington, WI		Urbana, IL		Lafayette, IN	
	Arlington Agricultural Research Station		Crop Sciences Research and Education Center		Throckmorton Purdue Agricultural Center	
Location of research site	43°18′ N, 89°20′ W		40°3′ N, 88°14′ W		40°17′ N, 86°54′ W	
Soil series	Plano silt loam		Flanagan silt loam and Drummer silty clay loam		Throckmorton silt loam	
Soil family	Fine-silty, mixed, mesic Typic Argiudoll		Fine-silty, mixed, mesic Typic Endoaquoll and fine, smectitic, mesic Aquic Argiudoll		Fine-silty, mixed, mesic mollic Oxyaquic Hapludalf	
Soil fertility						
Phosphorus (mg kg^{-1})	44–56		23–34		39–66	
Potassium (mg kg^{-1})	166–173		122		138–146	
pH	6.9–7.1		5.8–6.1		6.0–6.1	
Organic matter (g kg^{-1})	3.2		3.6–4.1		2.9–3.0	
Field operations	**2010**	**2011**	**2010**	**2011**	**2010**	**2011**
Planting date (May PD treatment)	4 May	5 May	15 May	12 May	10 May	17 May
Planting date (June PD treatment)	1 June	6 June	14 June	8 June	4 June	12 June
Harvest date (May PD treatment)	8 Oct.	17 Oct.	7 Oct.	11 Oct.	24 Sept.	11 Oct.
Harvest date (June PD treatment)	13 Oct.	17 Oct.	7 Oct.	11 Oct.	4 Oct.	11 Oct.
Planting date difference (d)	28	32	30	27	25	26

MATERIALS AND METHODS

Research was conducted in 2010 and 2011 at Arlington, WI, Urbana, IL, and Lafayette, IN. Location-specific information and soil characteristics for the three sites can be found in Table 1. In both years, soybean followed corn [*Zea mays* (L.)] harvested for grain at the Illinois and Indiana locations, whereas soybean followed corn harvested for silage at the Wisconsin location. All locations were fall-chiseled, and prepared in the spring with field cultivation (Wisconsin, Indiana) or mulch tillage (Illinois). Fertility and pest management at each location was performed according to local university management recommendations. At each location, cultivars were seeded at two planting dates, with 1 May and 1 June as the desired target dates. The 1 May planting date (early) was selected to represent planting dates growers currently use, whereas the 1 June (late) planting was selected to represent planting dates more commonly used in the past (USDA-NASS, 2011). In both years, weather and soil moisture conditions resulted in planting occurring later than the target dates, though a 25- to 32-d differential in planting date was still achieved (Table 1).

At the Wisconsin location, 59 MG II soybean cultivars released over eight decades, from 1928 to 2008 were planted, whereas at the Illinois and Indiana locations, 57 MG III soybean cultivars released from 1923 to 2007 were planted. The cultivars used in the experiment, along with plant introduction number and pedigree information, are provided in Table 2. Each cultivar used in the experiment was unique, novel, or widely grown during the time period of introduction. Cultivars included plant introductions grown about 80 yr ago, along with public and proprietary cultivars derived from further cycles of selection and breeding since then. Seed used for the experiment came from public and private seed sources, with seed increases of all cultivars occurring during the 2009 and 2010 growing seasons. Seed of the MG II cultivars was increased at the University of Nebraska–Lincoln (Lincoln, NE); whereas seed of the MG III cultivars was increased at the University of Illinois at Urbana–Champaign (Urbana, IL). To provide an estimate of experimental error, 13 MG II cultivars and 15 MG III cultivars were replicated twice within each planting date, for a total of 72 plots per planting date treatment in each maturity group. A limited number of cultivars were chosen for replication due to limited seed supply and field space constraints. Replicated cultivars within each maturity group were evenly distributed across years of release. The experiment was replicated by environment, defined as location within year, for each maturity group.

Plots were mechanically seeded in four rows, spaced 76 cm apart, at a rate of 370,650 untreated seeds ha^{-1}. Planted plot dimensions at all locations were 3.1 m wide by 4.6 m long. Plant populations were recorded for all plots at the V1 (first trifoliolate) and R8 (95% pod maturity) stages, as defined by Fehr and Caviness (1977). The center two rows of each plot were mechanically harvested a few days after R8. Grain weight and moisture data were collected simultaneously at harvest so that seed yield could be expressed on a 130 g kg^{-1} seed moisture content basis. Grain subsamples (approximately 500 g) were collected from each plot for seed protein and oil concentration analysis. Seed protein and oil contents were determined using a Perten DA 7200 Feed Analyzer (Perten Instruments, Stockholm, Sweden). Seed mass (100-seed weight) was estimated by weighing a grain sample collected from each harvested plot.

Yield, seed mass, and seed protein and oil data were subjected to a mixed-effect regression analysis using the PROC MIXED procedure in SAS Version 9.2 (SAS Institute Inc., Cary, NC). Models were constructed for maturity groups separately. The main effects of planting date, cultivar year of release, and the planting date × year of release interaction were treated as fixed effects. Environment and cultivar, along with the planting date × environment, planting date × cultivar, and planting date × environment × cultivar interactions were considered to be random effects. Cultivar was assigned as a random

Table 2. List of soybean cultivars, year of release, maturity group, plant introduction (PI) number, and pedigree.

Cultivar	Year of release	Maturity group	PI No.	Pedigree
Dunfield†	1923	III	PI548318	P.I. 36846 (NE China)
Illini†	1927	III	PI548348	Selection from A.K. in 1920
Korean†	1928	II	PI548360	From China
AK (Harrow)†	1928	III	PI548298	Selection from A.K. (by 1928)
Mukden†	1932	II	PI548391	P.I. 50523 (NE China)
Mandell	1934	III	PI548381	Selection from Manchu in 1926
Richland†	1938	II	PI548406	P.I. 70502-2 (NE China)
Mingo	1940	III	PI548388	Selection from Manchu in 1924
Lincoln†	1943	III	PI548362	Mandarin × Manchu
Hawkeye†	1947	II	PI548577	Mukden × Richland
Adams	1948	III	PI548502	Illini × Dunfield
Harosoy†	1951	II	PI548573	Mandarin (Ottawa)(2) × A.K. (Harrow)
Lindarin	1958	II	PI548589	Mandarin (Ottawa) × Lincoln
Shelby	1958	III	PI548574	Lincoln (2) × Richland
Ford	1958	III	PI548562	Lincoln (2) × Richland
Ross	1960	III	PI548612	Monroe × Lincoln
Harosoy 63	1963	II	PI548575	Harosoy (8) × Blackhawk
Hawkeye 63	1963	II	PI548578	Hawkeye (7) × Blackhawk
Wayne†	1964	III	PI548628	L49-4091 × Clark
Adelphia	1964	III	PI548503	C1070 × Adams
Amsoy	1965	II	PI548506	Adams × Harosoy
Corsoy†	1967	II	PI548540	Harosoy × Capital
Beeson	1968	II	PI548510	C1253 (Blackhawk × Harosoy) × Kent
Calland†	1968	III	PI548527	C1253 × Kent
Amsoy 71†	1970	II	PI548507	Amsoy (8) × C1253
Williams†	1971	III	PI548631	Wayne × L57-0034 (Clark × Adams)
Wells	1972	II	PI548630	C1266R (Harosoy × C1079) × C1253
Woodworth†	1974	III	PI548632	Wayne × L57-0034
Harcor	1975	II	PI548570	Corsoy × OX383 (Corsoy × Harosoy 63)
Private 2-7	1977	II	n/a‡	n/a
Private 2-8	1977	II	n/a	n/a
Wells II	1978	II	PI548513	Wells (8) × Arksoy
Vickery	1978	II	PI548617	Corsoy (5) × (L65-1342 and Anoka × Mack)
Private 3-1†	1978	III	n/a	n/a
Cumberland	1978	III	PI548542	Corsoy × Williams
Oakland	1978	III	PI548543	L66L-137 (Wayne × L57-0034) × Calland
Corsoy 79	1979	II	PI518669	Corsoy (6) × Lee 68
Beeson 80	1979	II	PI548511	Beeson (8) × Arksoy
Century†	1979	II	PI548512	Calland × Bonus
Amcor	1979	II	PI548505	Amsoy 71 × Corsoy
Pella	1979	III	PI548523	L66L-137 × Calland
Williams 82†	1981	III	PI518671	Williams (7) × Kingwa
Private 2-11	1982	II	n/a	n/a
Private 3-15	1983	III	n/a	n/a
Century 84	1984	II	PI548529	Century (5) × Williams 82
Elgin	1984	II	PI548557	F_4 selection from AP6 population
Zane	1984	III	PI548634	Cumberland × Pella
Harper	1984	III	PI548558	F_4 selection from an unknown diallel-cross population
Preston	1985	II	PI548520	Schechinger S48 × Land O'Lakes Max
Private 2-15	1985	II	n/a	n/a
Chamberlain†	1986	III	PI548635	A76-304020 × Land O'Lakes Max
Private 3-2	1986	III	n/a	n/a
Resnik	1987	III	PI534645	Asgrow A3127(4) × L24
Pella 86	1987	III	PI509044	From backcross of Pella(5) × Williams 82
Burlison	1988	II	PI533655	F_4 selection from K74-113-76-486 × Century
Private 2-9	1988	II	n/a	n/a
Elgin 87	1988	II	PI518666	Elgin (5) × Williams 82
Conrad†	1988	II	PI525453	A3127 × Tri-Valley Charger
Jack†	1989	II	PI540556	Fayette × Hardin
Kenwood	1989	II	PI537094	Elgin × A1937

Table 2. Continued.

Cultivar	Year of release	Maturity group	PI No.	Pedigree
Private 2-1	1989	II	n/a	n/a
Private 3-9	1989	III	n/a	n/a
Private 2-2	1990	II	n/a	n/a
Private 3-10	1990	III	n/a	n/a
RCAT Angora	1991	II	PI572242	B152 × T8112
Private 2-6	1991	II	n/a	n/a
Private 3-16	1991	III	n/a	n/a
Dunbar	1992	III	PI552538	Platte × A3127
Thorne	1992	III	PI564718	A80-344003 × A3127BC3F2-1
Private 3-17	1992	III	n/a	n/a
Private 2-5	1993	II	n/a	n/a
Private 3-18	1993	III	n/a	n/a
Private 2-10	1994	II	n/a	n/a
Private 2-16	1994	II	n/a	n/a
Private 3-19	1994	III	n/a	n/a
IA 2021	1995	II	n/a	Elgin 87 × Marcus
Macon†	1995	III	PI593258	Sherman × Resnik
IA 3004	1995	III	n/a	Northrup King S23-03 × A86-301024
Savoy	1996	II	PI597381	Burlison × Asgrow A3733
Private 2-12	1996	II	n/a	n/a
Maverick	1996	III	PI598124	LN86-4668 (Fayette × Hardin) × Resnik(3)
Private 3-4	1996	III	n/a	n/a
Private 3-11	1996	III	n/a	n/a
Dwight†	1997	II	PI597386	Jack × A86-303014
Private 2-18	1997	II	n/a	n/a
Pana	1997	III	PI597387	Jack × Asgrow A3205
Private 3-5	1997	III	n/a	n/a
Private 3-12	1997	III	n/a	n/a
IA 2038	1998	II	n/a	Pioneer 9301 × Kenwood
Private 3-6	1998	III	n/a	n/a
IA 3010	1998	III	n/a	Jaques J285 × Northrup King S29-39
Private 3-7†	1999	III	n/a	n/a
IA 2050	2000	II	n/a	Northrup King S24-92 × A91-501002
IA 2052	2000	II	n/a	Northrup King S24-92 × Parker
Private 3-20	2000	III	n/a	n/a
Loda†	2001	II	PI614088	Jack × IA 3003
Private 2-4	2001	II	n/a	n/a
Private 2-17	2001	II	n/a	n/a
U98-311442	2001	III	n/a	A94-773014 × Bell
IA 3014	2001	III	n/a	LN90-4366 × IA3005
Private 3-8†	2002	III	n/a	n/a
IA 2068	2003	II	n/a	AgriPro P1953 × LN94-10470
IA 3023	2003	III	n/a	Dairyland DSR-365 × Pioneer P9381
Private 2-3	2004	II	n/a	n/a
NE3001	2004	III	n/a	Colfax × A91-701035
Private 3-13†	2004	III	n/a	n/a
IA 3024	2004	III	n/a	A97-553017 × Pioneer YB33A99
IA 2065	2005	II	n/a	n/a
Private 2-19	2005	II	n/a	n/a
Private 2-20	2005	II	n/a	n/a
IA 2094	2006	II	n/a	AgriPro X0121B74 × A00-711036
Private 3-22	2006	III	n/a	n/a
Private 3-23	2006	III	n/a	n/a
Private 3-14	2007	III	n/a	n/a
Private 2-13	2008	II	n/a	n/a
Private 2-14†	2008	II	n/a	n/a

† Cultivars replicated within location.

‡ n/a, not applicable.

Table 3. Mean monthly air temperature and total monthly precipitation at Arlington, WI, Urbana, IL, and Lafayette, IN, during the 2010 and 2011 growing seasons, and during the past 30 yr.

	Arlington, WI			Urbana, IL			Lafayette, IN		
	2010	2011	30 yr	2010	2011	30 yr	2010	2011	30 yr
Air temperature (°C)									
April	10.4	6.2	7.1	15.1	11.9	11.1	14.9	11.6	10.7
May	15.3	13.4	13.2	18.3	16.9	16.9	18.1	17.1	16.6
June	19.7	19.6	18.7	23.8	22.8	22.3	23.3	22.6	21.8
July	22.9	24.0	20.8	25.2	26.8	23.8	24.4	26.0	23.4
August	22.2	21.0	19.6	25.1	24.1	23.0	24.3	22.7	22.4
September	15.6	14.5	15.2	19.7	17.5	19.0	19.4	17.1	18.8
Precipitation (mm)									
April	107.5	106.4	88.9	48.5	214.6	93.5	72.9	192.6	86.6
May	88.9	55.4	93.7	78.5	121.9	124.2	72.6	113.4	117.9
June	169.4	98.8	118.9	198.6	106.7	110.2	95.0	92.8	115.6
July	222.8	64.3	105.7	90.7	39.9	119.4	66.3	45.5	103.6
August	114.0	39.9	99.1	40.1	44.7	99.8	42.2	26.3	100.1
September	50.5	96.5	89.9	76.7	70.9	79.5	24.1	82.8	71.2

effect due to the fact that those selected for the experiment were chosen from a larger group of cultivars available over the eight decades. Fixed effects were tested for significance ($P < 0.05$) using the appropriate F test. Final models were a function of the model fit statistics (AIC, BIC, −2 Res Log Likelihood), as well as biological interpretation. Simple correlation coefficients were calculated using the PROC CORR procedure in SAS Version 9.2 (SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

Environment

Except for the month of July, average air temperatures were lower in 2011 than in 2010 at all locations (Table 3). At the Wisconsin location, 2010 could be characterized as an above-average rainfall year, whereas 2011 was a year with very low mid-season (July–August) rainfall and less than normal early- and late-season rainfall. In Wisconsin, the combination of above-average temperature and precipitation in 2010 led to record state soybean yields. At the Illinois and Indiana locations, early-season precipitation (April–May) was greater in 2011 than in 2010. Mid-season (July–August) precipitation at both Illinois and Indiana was well below the 30-yr average for both years, with drier conditions prevailing in 2011 than in 2010. Excess soil moisture was the most important factor resulting in actual planting dates not matching the targeted dates.

Yield

A comparison of mixed-effect regression models indicated that a linear mixed model provided the most appropriate fit to the observed trends in yield over year of release. Previous studies evaluating genetic yield gain in soybean have regressed yields either linearly (Boerma, 1979; De Bruin and Pedersen, 2008b; Specht and Williams, 1984; Wilcox, 2001) or quadratically (Voldeng et al., 1997) over year of release. Specht and Williams (1984) used multiple linear regressions within a maturity group to represent genetic gain over shorter periods of time while assessing the influence of different breeding methods on genetic gain. There was not sufficient evidence in the present study of curvilinearity in the change in yield over time, so a linear model was fitted to the yield data for each planting date.

Within maturity groups, more recently released cultivars exhibited higher yields ($P < 0.001$) than earlier released cultivars (Fig. 1). Simple correlation coefficients for yield and cultivar year of release ranged from 0.62 to 0.72 (Table 4). For MG II (Fig. 1a), there was no evidence of an interaction between planting date and cultivar year of release ($P > 0.05$). The rate of gain for soybean yield over time was 18.5 (± 1.57) kg ha^{-1} yr^{-1}. One possible explanation for the lack of an interaction between planting date and cultivar year of release in Wisconsin was that in both 2010 and 2011, record and above-average state soybean yields were documented.

For MG III (Fig. 1b), cultivar yield was influenced by planting date ($P < 0.05$); on average, cultivars planted in May provided superior yields. For the June planting, the rate of gain was 19.6 (± 1.74) kg ha^{-1} yr^{-1}, whereas it was increased +3.10 (± 1.41) kg ha^{-1} yr^{-1} for the May planting. A 3.10 kg ha^{-1} yr^{-1} greater rate of annual yield gain in cultivars planted in May vs. June indicates that newer cultivars responded more positively to earlier planting than cultivars released in earlier years. The synergistic interaction between planting date and year of release, along with significantly higher yields in May-planted soybean, provide evidence that trends toward earlier planting over time have contributed to soybean yield improvement and support the hypothesis that earlier planting over time by soybean growers in the midwestern United States has impacted on-farm yield gain in MG III soybean. Furthermore, the greater yield levels obtained with May planting in this study confirm recent planting date recommendations in

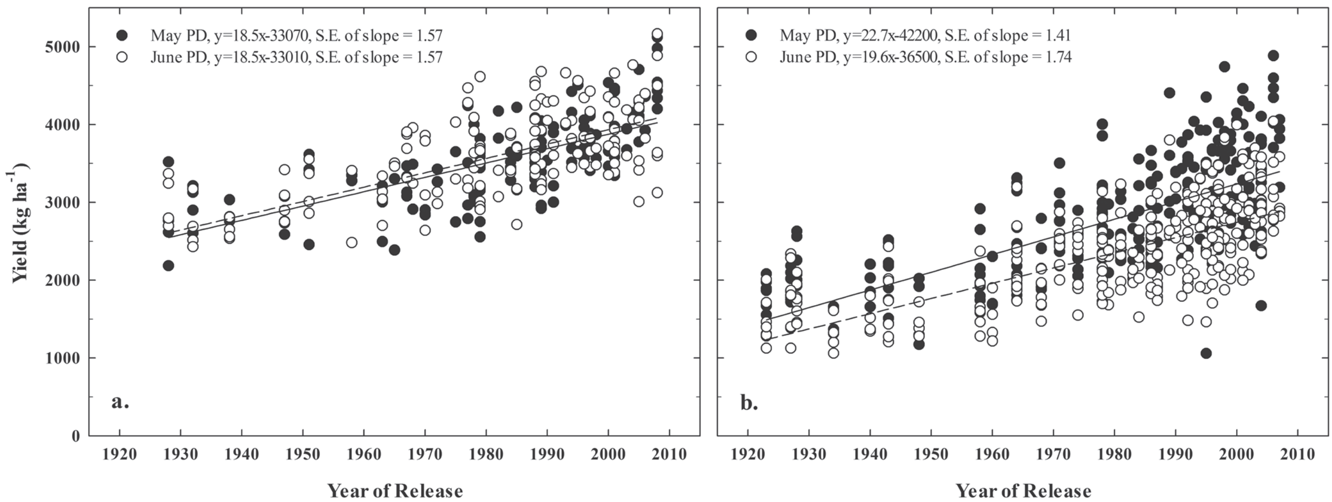

Figure 1. Regression of (a) Maturity Group (MG) II and (b) MG III seed yield (kg ha^{-1}) over soybean cultivar year of release at May (solid) and June (dashed) planting dates (PD) in 2010 and 2011.

Table 4. Simple linear correlation coefficients (r) between yield, seed mass, seed protein concentration, seed oil concentration, and cultivar year of release for Maturity Group (MG) II and MG III cultivars at May and June planting dates (PD) during 2010 and 2011.

	Seed mass	Protein	Oil	Year of release	Seed mass	Protein	Oil	Year of release
	MG II, May PD				MG II, June PD			
Yield	−0.08	−0.05	0.10	0.72***	−0.03	0.04	−0.21*	0.62***
Seed mass	–	0.14	−0.10	−0.04	–	0.26**	−0.24**	−0.19*
Protein	–	–	−0.78***	−0.26**	–	–	−0.77***	−0.31***
Oil	–	–	–	0.27***	–	–	–	0.27**
	MG III, May PD				MG III, June PD			
Yield	0.25***	0.12*	−0.08	0.67***	0.22***	−0.11	0.26***	0.68***
Seed mass	–	0.14*	0.00	0.22***	–	0.04	0.10	0.32***
Protein	–	–	−0.78***	−0.23***	–	–	−0.76***	−0.24***
Oil	–	–	–	0.23***	–	–	–	0.31***

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the <0.001 probability level.

the midwestern United States, with maximization of yields realized when using early-May planting dates (De Bruin and Pedersen, 2008a; Robinson et al., 2009; Specht, 2010).

The MG III cultivars exhibited a greater positive mean yield response to earlier planting when compared to MG II cultivars. Although the number of days between the May and June planting dates was similar (~30 d) at the MG III sites vs. the MG II sites, the difference between the targeted and actual June planting dates was, on average, about 8.5 d later for the MG III sites vs. only 2.5 d for the MG II sites. The 6-d greater delay in June planting at the MG III sites was an artifact of our May planting date establishment issues at these locations. The additional delay at MG III sites may have lessened the yield levels obtained with June plantings, though yields in delayed May plantings at the same sites may also have been lessened, influencing the response to planting date. In any case, these data show that earlier planting is more imperative for MG III than MG II cultivars, as later planting appears to limit the expression of genetic yield potential and reduce yield to a greater degree in MG III cultivars. The magnitude of yield response to early planting is very location and year specific (De Bruin and Pedersen, 2008a), and the environmental differences across locations and years in this study may not only underlie mean yield differences between the maturity groups but also yield response to planting date between maturity groups.

Plant populations at establishment (V1) and harvest (R8) for the two planting dates were not statistically different from one another for both maturity groups and did not impact harvested yields (data not shown). The similarities in plant populations indicated that stand establishment was not compromised with early planting into cooler, wetter soils with untreated seed. Comparable results were reported by De Bruin and Pedersen (2008a), who also found no decrease in harvest plant populations

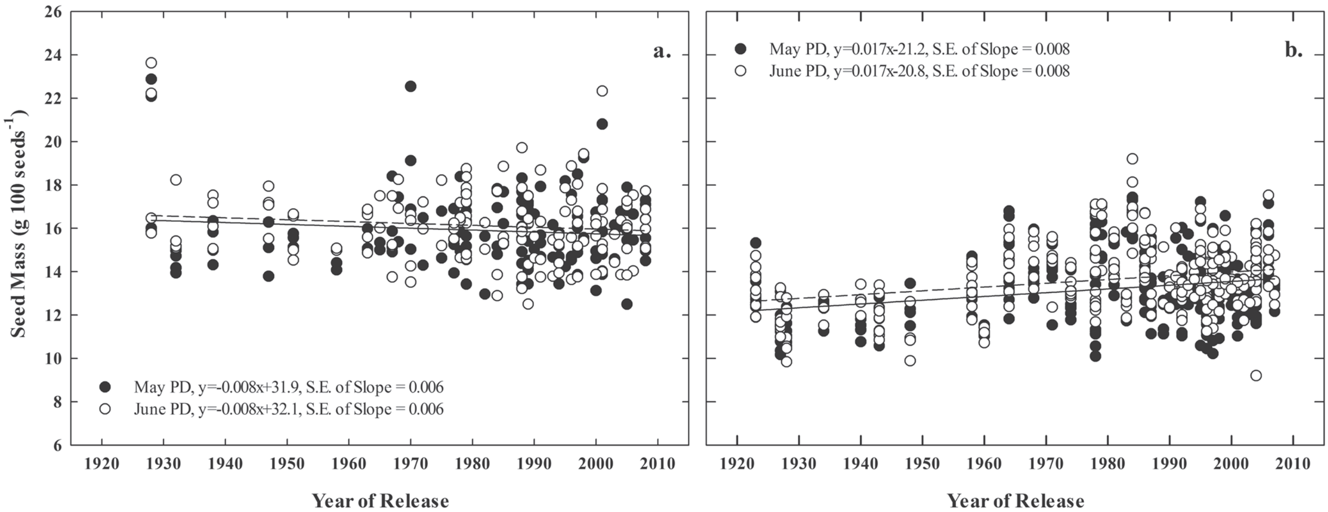

Figure 2. Regression of (a) Maturity Group (MG) II and (b) MG III seed mass (g 100 seeds^{-1}) over soybean cultivar year of release at May (solid) and June (dashed) planting dates (PD) in 2010 and 2011.

with earlier planting, though a study conducted 20 yr ago by Oplinger and Philbrook (1992) found that plant populations decreased with earlier planting.

Seed Mass

Mean seed mass was higher in MG II than MG III cultivars. There was no evidence of an effect of planting date or cultivar year of release on seed mass (i.e., 100-seed weight) for the MG II cultivars (Fig. 2a). However, there was an effect of cultivar year of release ($P < 0.05$) on seed mass for MG III cultivars (Fig. 2b), as seed mass increased 0.017 (± 0.008) g yr^{-1}.

Specht and Williams (1984) found an annual increase in 100-seed mass of 0.10 g yr^{-1} across all maturity groups (MG 00–IV) studied, although regression slopes for seed mass over year of release were not significantly different from zero in MG II and MG III soybean. Previous studies have shown that no consistent relationship between seed mass and cultivar year of release exists (Boerma, 1979; Morrison et al., 2000; Voldeng et al., 1997). Morrison et al. (2000) reported that breeders have improved yield over time by increasing the number of seeds per plant, not by increasing seed mass. In the present study, seed mass response did not differ appreciably by planting date, with similar seed mass recorded in both May and June planting for MG II and MG III cultivars. These results are in agreement with previous research suggesting that delayed planting date has little or no effect on soybean seed mass (Pedersen and Lauer, 2004; Wilcox and Frankenberger, 1987), although other studies have exhibited both increased (Bastidas et al., 2008) and decreased (Anderson and Vasilas, 1985; Elmore, 1990) seed mass with delayed planting. The conflicting results of the effect of planting date on soybean seed mass can likely be attributed to the variability of seed mass among cultivars and maturity groups (Robinson et al., 2009; Specht and Williams, 1984; Voldeng et al., 1997) and the influence of location-specific environmental conditions during the mid- to late seed fill period on seed mass (Ball et al., 2000; De Bruin and Pedersen, 2008a; Elmore, 1990). Both of these factors were observed in this study.

Seed Protein and Oil

Seed protein concentration decreased ($P < 0.05$) linearly over cultivar year of release for both MG II and MG III (Fig. 3). For MG II (Fig. 3a), the rate of decrease was 0.191 (± 0.069) g kg^{-1} yr^{-1} and for MG III (Fig. 3b.) it was 0.242 (± 0.063) g kg^{-1} yr^{-1}. The annual decline in seed protein concentration coincided with an improvement in seed oil concentration within maturity groups. Seed oil concentration in our study increased ($P < 0.01$) over cultivar year of release (Fig. 4). Within MG II (Fig. 4a), the rate of increase was 0.142 (± 0.037) g kg^{-1} yr^{-1}, whereas it was 0.127 (± 0.039) g kg^{-1} yr^{-1} in MG III (Fig. 4b). Trends in decreasing seed protein and increasing seed oil concentrations over time have been previously noted using a very small subset of MG II cultivars; however, no patterns in MG III protein and oil concentrations over time were documented in the same study (Wilcox et al., 1979). Subsequent evaluation of high-yielding, elite soybean lines from the Uniform Soybean Test produced no consistent trends over time in seed protein and oil concentrations among the MG II and MG III cultivars examined (Wilcox, 2001). Although patterns in seed protein and oil content over time have been unclear, the changes in soybean seed protein and oil over time across maturity groups in the current study agree favorably with the well-documented relationship of seed protein and oil concentration being negatively correlated (Hartwig and Kilen, 1991; Hymowitz et al., 1972; Panthee et al., 2005; Sebern and Lambert, 1984; Watanabe and Nagasawa, 1990; Wilcox and Guodong, 1997; Wilson, 2004; Yaklich et al., 2002). Simple correlation coefficients

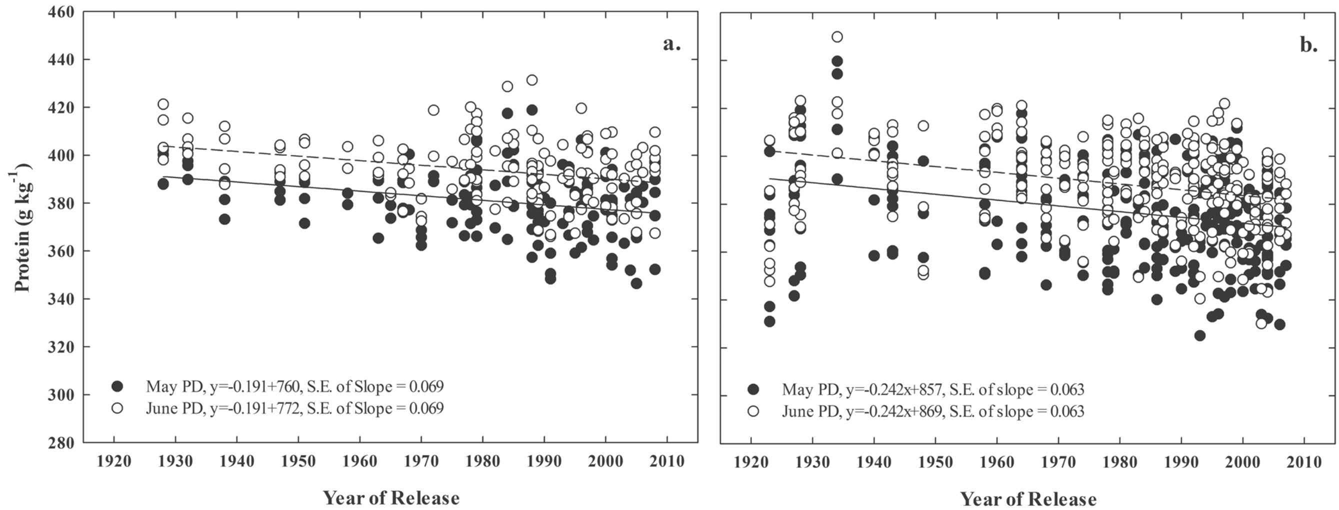

Figure 3. Regression of (a) Maturity Group (MG) II and (b) MG III seed protein concentration (g kg^{-1}) over soybean cultivar year of release at May (solid) and June (dashed) planting dates (PD) in 2010 and 2011.

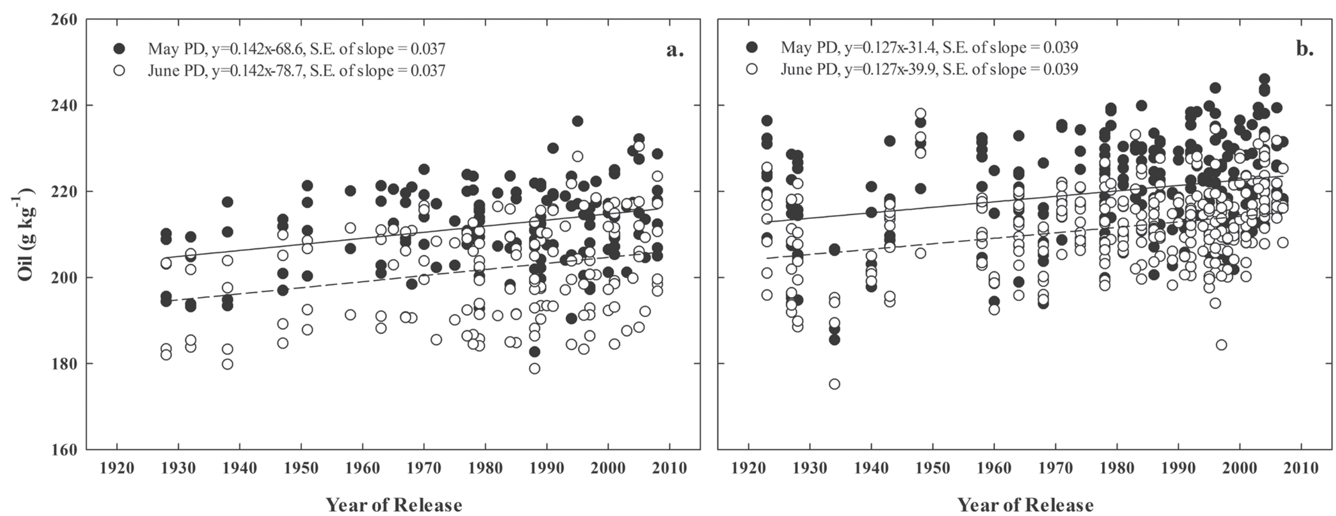

Figure 4. Regression of (a) Maturity Group (MG) II and (b) MG III seed oil concentration (g kg^{-1}) over soybean cultivar year of release at May (solid) and June (dashed) planting dates (PD) in 2010 and 2011.

ranged from −0.76 to −0.78 for seed protein and seed oil concentration in the present study (Table 4).

Within MG II, seed protein concentration was higher ($P < 0.05$) in June- than in May-planted soybean (Fig. 3), whereas seed protein concentration in MG III was unaffected by planting date. There was no evidence of an effect of planting date on seed oil concentration (Fig. 4). These results are in partial agreement with literature that has shown lower seed protein and higher seed oil concentrations with earlier planting (Heatherly and Elmore, 2004; Kane et al., 1997; Pendleton and Hartwig, 1973; Robinson et al., 2009). Delayed planting has occasionally produced no definitive response in the seed constituents of protein and oil in MG II (Pedersen and Lauer, 2003) and MG III (Bastidas et al., 2008) soybean. Seed oil and protein concentrations are primarily dictated by genetic factors such as cultivar selection and maturity group (Kane et al., 1997; Yaklich et al., 2002), and environmental factors such as temperature (Robinson et al., 2009) and moisture availability (Dornbos and Mullen, 1992) during the reproductive phases of growth, particularly R5 to R6. It is likely that genotypic and environmental variability are the principal drivers behind the occasional absence of response to delayed planting observed in other research.

In the current study, the ratio of the slopes suggested that for each 1-unit increase in seed oil content there was a 1.35-unit decrease (MG II) or a 1.91-unit decrease (MG III) in seed protein content. These values agree favorably with published literature. Specht et al. (1999) established that in most cases, a 1-unit increase in oil content is accompanied by a 2-unit decrease in protein content across soybean maturity groups. A 1:1 relationship was documented in shorter-maturing Canadian cultivars (Voldeng et al., 1997), a ratio substantially more balanced than the 1:2 ratio noted by Specht et al. (1999) and our observed ratios. From the observed trends in seed protein and oil across

MG II and MG III soybean, we speculate that breeders have unintentionally reduced seed protein concentration over time while focusing on the principal selection criterion, greater yield. It has been suggested that the increase in seed oil concentration and decrease in seed protein concentration over time are due to the positive and negative correlation of seed protein and oil with yield, respectively (Hartwig and Kilen, 1991; Wilcox and Guodong, 1997).

CONCLUSIONS

Soybean breeders have effectively increased yield by continuing to release higher yielding cultivars over time. Earlier planting provided higher yields (+3.1 kg ha^{-1} yr^{-1}) than late planting for MG III soybean. The apparent synergistic interaction between earlier planting and cultivar year of release suggested that yields of more recently released cultivars respond more positively to the practice of earlier planting in MG III environments. We conclude that trends toward earlier planting in the midwestern United States, combined with genetic yield gain, have contributed to on-farm yield improvement in MG III soybean. Within maturity groups, mean seed mass levels were similar at early and late plantings and were resistant to change over time. Breeding efforts within maturity groups increased seed oil concentration and decreased seed protein concentration. We suspect that the changes in soybean seed protein and oil are primarily a by-product of breeders selecting for yield and not necessarily for seed protein and oil.

Considering the greater yield response of newer cultivars to early planting, it may be beneficial for breeders to employ strategies in their breeding programs to exploit this synergistic interaction. Incorporating early planting trials into breeding nurseries may provide soybean breeders with the opportunity to make valuable progress that would otherwise go unnoticed in breeding settings where later planting to avoid spring frost, among other environmental uncertainties, is a standard practice. Other synergistic agronomic × genetic yield gain interactions conceivably exist. Successfully identifying and exploiting these synergies may provide soybean breeders and agronomists with tools that can facilitate greater yield improvement.

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