GENETIC GAIN X MANAGEMENT INTERACTION IN SOYBEAN: SEEDING RATE EFFECT

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THESIS

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Abstract

Plant breeders have increased genetic yield potential of soybean during the past century. The plant characteristics which soybean breeders have selected that have contributed most to those yield gains are not well understood. The hypothesis states that plants from recently released cultivars can withstand increased plant population (inter-plant competition) more effectively than earlier released cultivars and the objective of this study is to test this hypothesis. Soybean cultivars released over the last 80 years were evaluated at high and low seeding rates in research trials conducted in Illinois, Indiana, Minnesota and Wisconsin. In Illinois and Indiana, 57 maturity group III cultivars released between 1923 and 2007 were compared, and in Minnesota and Wisconsin, 59 maturity group II cultivars released between 1928 and 2008 were compared by seeding at high (445,000 seeds ha^{-1}) and low (148,000 seeds ha^{-1}) rates. Seed yield was higher for the high seeding rate versus low seeding rate throughout all cultivars and years of release, but a larger difference was observed between seeding rates in newer cultivars. The yield increase came from an increased number of pods and seeds $plant^{-1}$, and improved harvest index for both seeding rates. Although the high seeding rate provided higher yields, the low seeding rate had a larger increase in yield $plant^{-1}$. This increase was due to newer cultivars having a greater branching ability at the low seeding rate while branching slightly decreased at the high seeding rate. I conclude newer cultivars are better able to compensate yield than older cultivars by producing more seed on branches under lower plant populations.

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Introduction

Soybean [*Glycine max* (L.) Merr.] has had an increasing yield trend since the early 1900s due to intensive breeding efforts and improvements in agronomic management practices (Hartwig, 1973). Soybean yield is determined by the combination of genetic, agronomic and environmental factors. The continued advancement of these factors is important for improving soybean yield potential and allowing growers to achieve the best economic return from their land. The role of improved genetics has been researched heavily over decades. However, the role of improved agronomic practices is not well understood. Since the USDA began recording national averages in 1924, soybean yield has improved 23.4 kg ha^{-1} yr^{-1} (USDA-NASS, 2012). However, when yield improvement was analyzed between 1972 and 1998, soybean yield increased 31.2 kg ha^{-1} yr^{-1} (Specht et al., 1999). According to Specht et al. (1999), genetic improvement accounts for 25-30 kg ha^{-1} yr^{-1} of the 31.2 kg ha^{-1} yr^{-1} linear increase.

Optimal seeding rates are crucial for growers to maximize their net income, and this is especially true currently due to increasing cost of soybean seed. Determination of optimal seeding rate lowers seeding costs, reduces lodging and minimizes disease problems in soybean (Boquet and Walker, 1980). Although this is well understood, the mechanisms for the observed responses to changing plant density are not (Egli, 1988). The optimal seeding rate varies and is used to determine the optimum harvest plant population for the plant community. Although the optimal seeding rate varies due to many factors, changing seeding rates affects growth dynamics of the soybean plant and the plant community.

Soybean plants must be able to produce optimal plant characteristics to maximize yield. Plant height (Luedders, 1977), number of nodes $plant^{-1}$, number of pods $node^{-1}$, number of seeds pod^{-1}, size and weight of seed (Woodworth, 1932) are all plant components believed to influence soybean yield. However, pod number unit area^{-1}, seeds pod^{-1} and seed weight are considered the three components of soybean seed yield and understanding their interrelationships is important (Pandey and Torrie, 1973). These plant characteristics have the ability to respond to different seeding rates to contribute to maximum yield potential.

Literature Review

History of Soybean

Domestication of soybean [*Glycine max* (L.) Merr.] occurred in the eastern half of North China in the eleventh century B.C. and continues to be one of the five staple crops in China along with rice, wheat, barley and millet (Gibson and Benson, 2005). For many decades, it was believed that the introduction of soybean to North America occurred in 1804. However in 1983, Hymowitz and Harlan stated that it was introduced in 1765 by Samuel Bowen. It was brought to America for manufacturing soy sauce and other products to be exported to England. Per Bowen's request, Henry Yonge was the first person to plant soybean in Savannah, Georgia as a green forage crop (Hymowitz and Harlan, 1983).

Although soybean had been introduced to North America in 1765, production did not expand until much later. Soybean was initially used as a forage crop until around the 1920s when production for seed started to increase in the United States (Sleper and Shannon, 2003). According to Hymowitz (1970), the Orient dominated soybean production during the first three decades of the twentieth century. It was not until the late 1940s and early 1950s that the United States finally surpassed the Orient in soybean production (Hymowitz, 1970). Currently, soybean ranks second in area planted behind corn in the United States with 30.4 million hectares planted in 2011 (USDA-NASS, 2012). Soybean also ranks second behind corn in Illinois crop production, and Illinois contributes 13.4% of the total soybean produced in the United States (USDA-NASS, 2012). Soybean also currently ranks third in value of all United States agricultural commodities with 10.6% share behind beef and corn (USDA-NASS, 2012).

Yield trends for many crops grown around the United States have continued to increase over time at production sites (USDA-NASS, 2012). Intensive breeding efforts and improvements in management practices have greatly impacted the increasing corn and soybean yield trends. Genetic selection for the best traits in soybean has been occurring since the introduction of the crop, but extensive breeding efforts did not occur until 1936 when the United States Regional Soybean Industrial Products Laboratory was established in Urbana, IL (Hartwig, 1973). Until the 1970s, soybean breeding was primarily done at state agriculture experiment stations or within the Agriculture Research Service of the United States Department of Agriculture. Private industry began heavily investing in soybean breeding after the Plant Variety Protection Act, passed in 1970, allowed intellectual property protection of crop varieties (Sleper and Shannon, 2003).

According to Pathan and Sleper (2008), increasing yield with improved qualities and increased resistance to biotic and abiotic stresses is the overall goal of plant breeding. When soybean yield was analyzed from 1924 to 1998, a 22.6 kg ha^{-1} $year^{-1}$ linear increase was realized. However, when the yield improvement was analyzed between 1972 and 1998, soybean yield increased at a rate of 31.2 kg ha^{-1} $year^{-1}$ (Specht et al., 1999). According to Specht et al. (1999), genetic improvement accounted for 25-30 kg ha^{-1} $year^{-1}$ of this 31.2 kg ha^{-1} $year^{-1}$ increase in national yields. Contrary to the conclusion by Specht et al. (1999) that yield increase has been linear, Voldeng et al. (1997) concluded yield gains from genetic improvement was a quadratic function. They proposed that prior to 1976 almost zero yield improvement was due to genetic improvements. They proposed yield improvement during this early time was likely due to better weed control due to the development of herbicides, improved cultural practices and increased soil fertility arising from fertilization of alternate-year crops (Luedders, 1977). Genetic yield improvement after this time was approximately 30 kg ha^{-1} $year^{-1}$, similar to the reports of Specht et al (1999). Since genetic improvement was not observed prior to 1976 but played a significant role after, they modeled a quadratic equation, showing a 0.5% genetic yield increase $year^{-1}$ (Voldeng et al., 1997).

Soybean Growth and Development

Soybean yield is determined by the combination of genetic, agronomic and environmental factors. The continued advancement of these factors is important for improving soybean yield potential and allowing growers to achieve the best economic return from their land. Specific components such as canopy coverage (Ma et al., 2001), branching ability (Carpenter and Board, 1997b), plant height, number of nodes $plant^{-1}$, number of pods $nodes^{-1}$, number of seeds pod^{-1}, size and weight of seed (Luedders, 1977; Woodworth, 1932) and seed oil and protein content (Chung et al., 2002) are thought to influence soybean yield.

Canopy Cover and Branching Ability

The interception of solar radiation and the utilization of radiant energy for plant biomass are the main processes in crop growth and yield. To maximize the crop growth and yield by intercepting solar radiation, crop biomass must accumulate early in the season which is accomplished by high population densities and branching ability. Since two thirds of branching occurs between R1 and R5 (Board and Settimi, 1986), higher populations densities are important early in the season to maximize light intercept and begin photosynthetic processes

(Purcell et al., 2002). When complete canopy coverage is accomplished by R1, maximum yields are more likely to be produced. Soybean has a significant reduction in yield if complete canopy ground coverage does not occur by R5 (Lee et al., 2008).

In a study by Carpenter and Board (1997a), four different plant populations were evaluated; 70,000 (low), 164,000 (medium), 189,000 (medium-high) and 234,000 (high) plants ha^{-1}. Branch pod number $plant^{-1}$, reproductive node number $plant^{-1}$, branch pod number $(reproductive\ node)^{-1}$, branch node number $plant^{-1}$ and branch weight $plant^{-1}$ were significant ($P \leq 0.05$) yield components across the four populations. The low population had greater branching ability compared to the medium population due to greater number of branch reproductive nodes $plant^{-1}$. The medium population had a comparable number of branch reproductive nodes $plant^{-1}$ as the high population but had a greater branch yield due to more pods reproductive $node^{-1}$. They concluded population effects on yield are mainly controlled by branch pods as they reported 3.78 g $plant^{-1}$ yield increase g^{-1} increase in branch dry matter (Carpenter and Board, 1997a). Total branch dry matter depends on the interplant competition of a population and the duration from R1 to R5. Lower populations have increased branch dry matter accumulation results from reduced interplant competition while higher populations have decreased branch dry matter due to increased interplant competition.

Since most branch dry matter does not accumulate until the reproductive stages, it is crucial for the stems of the soybean plant to produce a full canopy. Rapid early growth of the soybean plant allows for more light interception to maximize photosynthetically active radiation (PAR) and radiation use efficiency (RUE). Purcell et al. (2002) conducted a study to determine the effect that different plant populations had on light interception of soybean.

They hypothesized RUE would increase with increasing populations and that biomass would increase with increased PAR. The hypothesis was not supported in relation to increasing RUE. In fact, they found RUE decreased as plant populations increased. They had no explanation for the decrease, but they speculated it could be due to fallen leaves and petioles that were not included in their biomass sampling, or to limitations to the amount of nitrogen that could be fixed with increasing populations. Although their hypothesis for the RUE was not correct, the hypothesis for the PAR was supported. Biomass production as a result of intercepted PAR followed an asymptotic curve whereas the biomass increased, and the intercepted PAR increased until the intercepted value became very high and leveled out. This relationship occurred because light was no longer a limiting factor on crop yield once it reached high intercepted PAR levels (Purcell et al., 2002).

Plant Characteristics

Increasing soybean yield is the most important goal for both soybean breeders and growers. To maximize yield, soybean plants must be able to produce optimal plant characteristics which can provide increased yield potential. Plant height (Luedders, 1977), number of nodes plant^{-1}, number of pods node^{-1}, number of seeds pod^{-1}, size and weight of seed (Woodworth, 1932) are all plant components believed to influence soybean yield. Knowledge of the interrelationships of pod number unit area^{-1}, seeds pod^{-1} and seed weight is important because they are considered the three components of seed yield for soybean (Pandey and Torrie, 1973). Although many different yield components are affected by environmental factors and management practices, pods plant^{-1} is known to have the greatest response to these stresses (Pandey and Torrie, 1973). At lower populations, fewer plants are available to maximize soybean yield so more seed plant^{-1} must be produced to compensate for the lower population and to maintain an optimum total yield. To accomplish this, soybean plants can produce additional pods plant^{-1} (Pandey and Torrie, 1973). This concept is explained by Adams' theory that pods plant^{-1} and plants area^{-1} are negatively correlated. The theory suggests that with lower plants in a given area, the more pods a plant will be able to produce (Adams, 1967).

The height of soybean plants has also been well documented through prior research to determine its role in soybean yield potential. Prior to the 1970s, plant height was decreased as breeders selected for less lodging. After 1970, plant heights began to increase. This may have been due to lodging resistance efforts by soybean breeders. When breeding efforts become sufficient to achieve lodging resistance, taller plants would be more beneficial to maximize yield potential. Plant height and lodging are also the major plant traits that affect harvest losses. Data from different studies imply that effort by breeders to increase yield by avoiding mechanical harvest losses have been approached (Ustun et al., 2001). Understanding and improving these plant characteristics will be the driving force behind maintaining the increasing soybean yield trend.

Seeding Rate

Optimal seeding rates are crucial for growers to maximize their net income, and this is especially true currently due to increasing cost of soybean seed. Determination of optimal seeding rate lowers seeding costs, reduces lodging and minimizes disease problems (Boquet and Walker, 1980). Although this is well understood, the mechanisms responsible for the observed responses to changing plant density are not (Egli, 1988). While many research studies conclude that seeding rates are critical to maximizing soybean yield, others are still skeptical.

According to Lee et al. (2008), soybean yield is relatively insensitive to plant population with a wide range of seeding rates producing the same yield. Finding an optimum seeding rate is difficult because there are many factors that must be understood. Row spacing, seed placement and planter calibration, and the seed's germination rate affect the optimal seeding rate (Robinson and Conley, 2007). Conley and Santini (2007) recommended a seeding rate of 397,800 and 313,800 viable seeds ha^{-1} for 38- and 76- cm rows, respectively. However, Lee et al. (2008) conducted a study using seeding rates ranging from 43,000 viable seeds ha^{-1} to 560,000 viable seeds ha^{-1} and concluded that the optimal seeding rates were between 171,000 and 264,000 seeds ha^{-1}. Although the optimal seeding rate varies due to many factors, changing seeding rates affects growth dynamics of the soybean plant and the plant community.

The optimal seeding rate varies and is used to determine the optimum harvest plant population for the plant community. In the study by Carpenter and Board (1997a) previously described, the four populations were evaluated in regards to yield potential to determine an optimum planting population. Yield between the low vs. medium population showed a 12% difference with the medium population producing more yield. Yield in the medium vs. high population showed no difference in yield. Although the high populations had a similar yield response to the medium population, inputs for the high populations were greater than the medium population. Therefore, the medium population (164,000 plants ha^{-1}) was the optimal population throughout the study (Carpenter and Board, 1997a).

Lee et al. (2008) performed an experiment incorporating higher seeding rates than the study by Carpenter and Board that ranged from 43,000 viable seeds ha^{-1} to 560,000 viable seeds ha^{-1}. The goal of the study was to determine the optimal planting population and the economically optimal planting population. The optimum planting population for this study was defined as the population producing 95% of the predicted yield at the highest observed plant population (Edwards et al., 2005). This experiment was conducted using ten different soybean varieties with maturities ranging from 2.9 to 4.9. A normal planting date (May) and a late planting date (June) were used. Yield increased rapidly as population increased but reached maximum levels at relatively low populations. The optimum planting populations for May planting were 108,000 to 232,000 plant ha^{-1} and required seeding rates of 171,000 to 264,000 seeds ha^{-1}, much lower than the region's recommended seeding rates of 300,000 to 516,000 seeds ha^{-1} (Beuerlein and Dorrance, 2005; Heatherly and Elmore, 2004). Optimum planting populations for June were 238,000 to 282,000 plants ha^{-1} which were obtained with seeding rates of 266,000 to 307,000 seeds ha^{-1} (Lee et al., 2008). Optimum plant populations were higher in June because more plants were required to counteract the smaller plants often associated with later planting dates (Heatherly and Elmore, 2004).

In addition to yield, plant characteristics are affected by spatial differences within rows. In a study conducted by Lehman and Lambert (1960), spatial plant distribution was analyzed to determine the influence it had on branching ability. They used four different plant spacings within rows (13, 26, 52 and 78 plants m^{-1} of row). A final yield partition was collected from stem and branch seeds $plant^{-1}$ and pods $plant^{-1}$. Branch to stem yield ratios were obtained for these yield components. A ratio above one would provide evidence that branches were relatively more important than stems in overall yield while a ratio below one would provide evidence that stems were relatively more important. All spatial distributions had ratios below one showing the greater importance of the main stems compared to the branches (Lehman and Lambert, 1960). However, branching was still important for total seed yield in the plots with greater distance between plants. At 13 plants m^{-1} about as many pods and seeds were produced on branches versus on stems. Plant spacings of 52 and 78 plants m^{-1} had relatively few pods and seeds produced by the branches while only slightly more were produced at 26 plants m^{-1}. Seeds $plant^{-1}$, pods $plant^{-1}$ and branches $plant^{-1}$ reacted in similar manner when spatial distribution was changed. As the plant population decreased, the number of units of these characters increased. However, greater differences were observed at lower populations than at higher populations (Lehman and Lambert, 1960).

Research Justification

Soybean yield trends continue to climb with the introduction of new soybean cultivars with advanced genetics. Various agronomic practices implemented by growers have taken advantage of these genetics to maximize soybean yield. Seeding rate is one of the agronomic practices that can easily be adjusted to provide the best growing conditions. Finding an optimal seeding rate is difficult because it relies on many variables. However, determining how newer cultivars respond to high and low seeding rates compared to older cultivars is crucial to understand the direction advanced soybean breeding is driving the optimal seeding rate.

Research studies have been conducted on genetic gain of soybean and varying seeding rates but there is research lacking to demonstrate how varying seeding rates affect the genetic yield trend. The hypothesis of the experiment states that plants from recently released cultivars can withstand increased plant population (inter-plant competition) more effectively than earlier released cultivars and the objective of this study is to test this hypothesis. To understand how changing seeding rates have affected soybean cultivars over time and determining the plant characteristics that influence the changes and differences in yield, this experiment was set up with three objectives: i) to determine the effect of varying seeding rates on the soybean genetic yield gain, ii) to determine how plants at low seeding rates compensate yield, and iii) to determine plant characteristics associated with yield gain over year of release.

Materials and Methods

Field research was conducted to evaluate the influence of high and low seeding rates on soybean yield gain over time and the interaction of seeding rate and genetic yield gain. Trials were conducted in 2010 and 2011 at the University of Illinois Crop Sciences Research and Education Center in Urbana, Illinois (40°3’ N, 88°14’ W), the University of Wisconsin-Madison Arlington Agricultural Research Station in Arlington, Wisconsin (43°18’ N, 89°20’ W), Purdue University Throckmorton Purdue Agriculture Research Center in Lafayette, Indiana (40°17’ N, 86°54’ W) and the University of Minnesota Southern Research and Outreach Center in Waseca, Minnesota (44°4’ N, 93°31’ W). Location information and soil characteristics for the four locations are presented in Table 1. There was one field trial at each location and year for a total of eight sites. Cultivars were randomly seeded into blocks at either 445,000 seeds ha^{-1} (high) or 148,000 (low) seeds ha^{-1}. Emergence and harvest plant stands were recorded and analyzed to determine clear separation between the two seeding rates across maturity groups and year of release. Harvest plant stands were relatively consistent across the years of release throughout all locations. Final plant stands averaged 311,000 and 94,000 plants ha^{-1} for the high and low seeding rates, respectively. Within each seeding rate treatment block, the IL and IN locations planted 57 MGIII soybean cultivars released between 1923 and 2007, while the MN and WI locations planted 59 MGII soybean cultivars released between 1928 and 2008. There were 15 MGIII cultivars and 13 MGII cultivars replicated one time and randomly located within each block to estimate experimental error. Soybean cultivars were selected based on availability and performance during given release year. Pedigree information for all MG II and MG III cultivars used in this experiment can be found in Table 2a and 2b, respectively.

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

Location	Arlington, WI		Waseca, MN		Urbana, IL		Lafayette, IN	
Research Site	Arlington Agricultural Research Station 43°18’ N, 89°20’ W		Southern Research and Outreach Center 44°4’ N, 93°31’ W		Crop Sciences Research and Education Center 40°3’ N, 88°14’ W		Throckmorton Purdue Agricultural Center 40°17’ N, 86°54’ W	
Soil Series	Plano silt loam		Webster - Nicollet clay loam		Flanagan silt loam & Drummer silty clay loam		Throckmorton silt loam	
Soil Family	fine-silty, mixed, mesic Typic Argiudoll		fine-loamy, mixed, mesic Typic Endoaquoll & Aquic Hapludoll		fine-silty, mixed, mesic Typic Endoaquoll & fine, smectitic, mesic Aquic Argiudoll		fine-silty, mixed mesic mollic Oxyaquic Hapludalf	
Soil Fertility								
Phosphorus (mg kg^{-1})	44-56		32-37		23-34		39-66	
Potassium (mg kg^{-1})	166-173		165-185		122		138-146	
pH	6.9-7.1		5.9-7.1		5.8-6.1		6.0-6.1	
Organic Matter (g kg^{-1})	3.2		5.4-6.3		3.6-4.1		2.9-3.0	
Field Operations	2010	2011	2010	2011	2010	2011	2010	2011
Planting Date	4-May	5-May	18-May	19-May	15-May	12-May	10-May	17-May
Harvest Date	8-Oct	7-Oct	15-Oct	14-Oct	7-Oct	11-Nov	24-Sep	10-Oct

Table 2a. List of cultivars, year of release, plant introduction(PI) number, and pedigree for MG II cultivars

Cultivar	Year of Release	Maturity Group	PI Number†	Pedigree‡
Korean§	1928	II	PI548360	From China
Mukden§	1932	II	PI548391	P.I. 50523 (NE China)
Richland§	1938	II	PI548406	P.I. 70502-2 (NE China)
Hawkeye§	1947	II	PI548577	Mukden x Richland
Harosoy§	1951	II	PI548573	Mandarin (Ottawa)(2) x A.K. (Harrow)
Lindarin	1958	II	PI548589	Mandarin (Ottawa) x Lincoln
Harosoy 63	1963	II	PI548575	Harosoy (8) x Blackhawk
Hawkeye 63	1963	II	PI548578	Hawkeye (7) x Blackhawk
Amsoy	1965	II	PI548506	Adams x Harosoy
Corsoy§	1967	II	PI548540	Harosoy x Capital
Beeson	1968	II	PI548510	C1253 (Blackhawk x Harosoy) x Kent
Amsoy 71§	1970	II	PI548507	Amsoy (8) x C1253
Wells	1972	II	PI548630	C1266R (Harosoy x C1079) x C1253
Harcor	1975	II	PI548570	Corsoy x OX383 (Corsoy x 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) x Arksoy
Vickery	1978	II	PI548617	Corsoy (5) x (L65-1342 & Anoka x Mack)
Corsoy 79	1979	II	PI518669	Corsoy (6) x Lee 68
Beeson 80	1979	II	PI548511	Beeson (8) x Arksoy
Century§	1979	II	PI548512	Calland x Bonus
Amcor	1979	II	PI548505	Amsoy 71 x Corsoy
Private 2-11	1982	II	n/a	n/a
Century 84	1984	II	PI548529	Century (5) x Williams 82
Elgin	1984	II	PI548557	F4 selection from AP6 population
Preston	1985	II	PI548520	Schechinger S48 x Land O' Lakes Max
Private 2-15	1985	II	n/a	n/a
Burlison	1988	II	PI533655	F4 selection from K74-113-76-486 x Century
Private 2- 9	1988	II	n/a	n/a
Elgin 87	1988	II	PI518666	Elgin (5) x Williams 82
Conrad§	1988	II	PI525453	A3127 x Tri-Valley Charger
Jack§	1989	II	PI540556	Fayette x Hardin
Kenwood	1989	II	PI537094	Elgin x A1937
Private 2- 1	1989	II	n/a	n/a
Private 2- 2	1990	II	n/a	n/a
RCAT Angora	1991	II	PI572242	B152 x T8112
Private 2- 6	1991	II	n/a	n/a
Private 2- 5	1993	II	n/a	n/a
Private 2-10	1994	II	n/a	n/a
Private 2-16	1994	II	n/a	n/a
IA 2021	1995	II	n/a	Elgin 87 x Marcus
Savoy	1996	II	PI597381	Burlison x Asgrow A3733
Private 2-12	1996	II	n/a	n/a
Dwight§	1997	II	PI597386	Jack x A86-303014
Private 2-18	1997	II	n/a	n/a
IA 2038	1998	II	n/a	Pioneer 9301 x Kenwood
IA 2050	2000	II	n/a	Northrup King S24-92 x A91-501002
IA 2052	2000	II	n/a	Northrup King S24-92 x Parker
Loda§	2001	II	PI614088	Jack x IA 3003
Private 2- 4	2001	II	n/a	n/a
Private 2-17	2001	II	n/a	n/a
IA 2068	2003	II	n/a	AgriPro P1953 x LN94-10470
Private 2- 3	2004	II	n/a	n/a
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 x A00-711036
Private 2-13	2008	II	n/a	n/a
Private 2-14§	2008	II	n/a	n/a

† n/a, not applicable

‡ n/a, not available

§ Cultivars replicated within location

Table 2b. List of cultivars, year of release, plant introduction(PI) number, and pedigree for MG III cultivars

Cultivar	Year of Release	Maturity Group	PI Number†	Pedigree‡
Dunfield§	1923	III	PI548318	P. I. 36846 (NE China)
Illini§	1927	III	PI548348	Sel. from A.K. in 1920
AK (Harrow)§	1928	III	PI548298	Sel. from A.K. (by 1928)
Mandell	1934	III	PI548381	Sel. from Manchu in 1926
Mingo	1940	III	PI548388	Sel. from Manchu in 1924
Lincoln§	1943	III	PI548362	Mandarin x Manchu
Adams	1948	III	PI548502	Illini x Dunfield
Shelby	1958	III	PI548574	Lincoln (2) x Richland
Ford	1958	III	PI548562	Lincoln (2) x Richland
Ross	1960	III	PI548612	Monroe x Lincoln
Wayne§	1964	III	PI548628	L49-4091x Clark
Adelphia	1964	III	PI548503	C1070 x Adams
Calland§	1968	III	PI548527	C1253 x Kent
Williams§	1971	III	PI548631	Wayne x L57-0034 (Clark x Adams)
Woodworth§	1974	III	PI548632	Wayne x L57-0034
Private 3- 1§	1978	III	n/a	n/a
Cumberland	1978	III	PI548542	Corsoy x Williams
Oakland	1978	III	PI548543	L66L-137 (Wayne x L57-0034) x Calland
Pella	1979	III	PI548523	L66L-137 x Calland
Williams 82§	1981	III	PI518671	Williams (7) x Kingwa
Private 3-15	1983	III	n/a	n/a
Zane	1984	III	PI548634	Cumberland x Pella
Harper	1984	III	PI548558	F4 sel. from an unknown diallel-cross pop.
Chamberlain§	1986	III	PI548635	A76-304020 x Land O Lakes Max
Private 3- 2	1986	III	n/a	n/a
Resnik	1987	III	PI534645	Asgrow A3127(4) x L24
Pella 86	1987	III	PI509044	From backcross of Pella(5) x Williams 82
Private 3- 9	1989	III	n/a	n/a
Private 3-10	1990	III	n/a	n/a
Private 3-16	1991	III	n/a	n/a
Dunbar	1992	III	PI552538	Platte x A3127
Thorne	1992	III	PI564718	A80-344003 x A3127BC3F2-1
Private 3-17	1992	III	n/a	n/a
Private 3-18	1993	III	n/a	n/a
Private 3-19	1994	III	n/a	n/a
Macon§	1995	III	PI593258	Sherman x Resnik
IA 3004	1995	III	n/a	Northrup King S23-03 x A86-301024
Maverick	1996	III	PI598124	LN86-4668 (Fayette x Hardin) x Resnik(3)
Private 3- 4	1996	III	n/a	n/a
Private 3-11	1996	III	n/a	n/a
Pana	1997	III	PI597387	Jack x Asgrow A3205
Private 3- 5	1997	III	n/a	n/a
Private 3-12	1997	III	n/a	n/a
Private 3- 6	1998	III	n/a	n/a
IA 3010	1998	III	n/a	Jaques J285 x Northrup King S29-39
Private 3- 7§	1999	III	n/a	n/a
Private 3-20	2000	III	n/a	n/a
U98-311442	2001	III	n/a	A94-773014 x Bell
IA 3014	2001	III	n/a	LN90-4366 x IA3005
Private 3- 8§	2002	III	n/a	n/a
IA 3023	2003	III	n/a	Dairyland DSR-365 x Pioneer P9381
NE3001	2004	III	n/a	Colfax x A91-701035
Private 3-13§	2004	III	n/a	n/a
IA 3024	2004	III	n/a	A97-553017 x Pioneer YB33A99
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

† n/a, not applicable
‡ n/a, not available
§ Cultivars replicated within location

The experiment was replicated by environment, defined as location within year, for each maturity group. Management methods and site characteristics are described by location.

Illinois Location

In 2010, trials were on Flanagan silt loam (fine, smetitic, mesic Aquic Argiudoll). In 2011, trials were on Drummer Silty Clay Loam (fine-silty, mixed, super-active, mesic Typic Endoaquoll). Both trials were grown following a corn crop harvested for grain. Seed beds were prepared using one pass fall chisel followed by one pass spring mulch tillage followed by one pass spring mulch tillage with deep-herbicide incorporation. Trials were planted with an Almaco four-row plot planter with John Deere MaxEmerge units. Planted plot size was 3.1m x 4.6m. Plots were harvested with an Almaco SPC 20 Plot Harvester (Almaco, Nevada, IA). Harvested plot size was 1.5m x 4.1m.

Weeds were controlled using pre-emergence and post-emergence herbicides to eliminate competition factors. To control early season weeds in 2010 and 2011, sulfentrazone and imazethapyr were applied prior to planting at a rate of 0.19 kg a.i. ha^{-1} and 0.04 kg a.i. ha^{-1}, respectively. To control later emerging weeds in 2010, clethodim was applied at V5 at a rate of 0.22 kg a.i. ha^{-1}. In 2011, sodium salt of bentazon and sethoxydim were applied at V5 at a rate of 0.74 kg a.i. ha^{-1} and 0.22 kg a.i. ha^{-1}, respectively. In addition to herbicide control, plots were kept weed free by manual hoeing throughout the growing season.

Wisconsin Location

In 2010 and 2011, trials were on Plano Silt Loam (fine-silty, mixed, super-active mesic Typic Argiudoll). Both trials were grown following a corn crop harvested for silage. Seed beds were prepared using one pass fall chisel followed by one pass spring field cultivation followed by one pass spring soil finisher. Trials were planted using a custom built planter with John Deere components. Planted plot size was 3.1m x 4.6m. Plots were harvested with an Almaco Plot Harvester (Almaco, Nevada, IA). Harvested plot size was 1.5m x 4.1m.

Weeds were controlled using pre-emergence and post-emergence herbicides to eliminate competition factors. To control early season weeds in 2010 and 2011, S-metolachlor and ammonium salt of imazethapyr were applied prior to planting and incorporated in the soil at a rate of 1.39 kg a.i. ha^{-1} and 0.06 kg a.i. ha^{-1}, respectively. In 2010 and 2011, plots were maintained weed free after emergence by cultivation and manual hoeing throughout the growing season.

Indiana Location

In 2010 and 2011, trials were on Throckmorton silt loam (fine-silty, mixed, super-active, mesic mollic Oxyaquic Hapludalf). Both trials were grown following a corn crop harvested for grain. Seed beds were prepared using one pass fall chisel followed by a two pass spring field cultivation in 2010 and one pass fall chisel followed by one pass spring field cultivation in 2011. Trials were planted using a custom built planter with Kinze components. Planted plot size was 3.1m x 4.6m. Plots were harvested with a Kincaid 8-XP plot harvester (Kincaid, Haven, KS). Harvested plot size was 1.5m x 4.1m.

Weeds were controlled using pre-emergence and post-emergence herbicides to eliminate competition factors. To control early season weeds in 2010, cloransulam-methyl was applied prior to planting and incorporated into the soil at a rate of 0.04 kg a.i. ha^{-1}. In 2010, all weed control after emergence was done by manual hoeing. To control early season weeds in 2011, flumioxazin and chlorimuron ethyl were applied prior to planting and incorporated into the soil at a rate of 0.06 kg a.i. ha^{-1} and 0.02 kg a.i. ha^{-1}, respectively. To control late emerging weeds in 2011, sethoxydim and ammonium salt of imazethapyr were applied at V5 at a rate of 0.22 kg a.i. ha^{-1} and 0.06 kg a.i. ha^{-1}, respectively. In addition to herbicide control, plots were kept weed free by manual hoeing throughout the growing season.

Minnesota Location

In 2010, trials were on Webster clay loam (fine-loamy, mixed, super-active, mesic Typic Endoaquoll). In 2011, trials were on Nicollet clay loam (fine-loamy, mixed, super-active, mesic Aquic Hapludoll). Both trials were grown following a corn crop harvested for grain. Seed beds were prepared using one pass fall chisel followed by one pass spring cultivation. Trials were planted using an Almaco SeedPro Vacuum Planter. Planted plot size was 3.1m x 4.6m. Plots were harvested with an Almaco Plot Harvester (Almaco, Nevada, IA). Harvested plot size was 1.5m x 4.1m.

Weeds were controlled using pre-emergence and post-emergence herbicides to eliminate competition factors. To control early season weeds in 2010 and 2011, trifluralin, saflufenacil and imazethapyr were applied prior to planting and incorporated in the soil at a rate of 1.68 kg a.i. ha^{-1}, 0.02 kg a.i. ha^{-1} and 0.07 kg a.i. ha^{-1}, respectively. To control late emerging weeds in 2010 and 2011, ammonium salt of imazamox was applied at V5 at a rate of 0.04 kg a.i. ha^{-1}. In addition to herbicide control, plots were kept weed free by manual hoeing throughout the growing season.

Soybean Sampling and Analysis

To provide evidence of genetic gain for the high and low seeding rates over the year of release, 1m of row was hand harvested at maturity. Plants were cut using a garden clipper at soil level at Urbana and Waseca locations. Total plant number collected was recorded for each plot. Branches were removed from stems in the field and collected as separate samples. Samples were air dried for a week to allow them to obtain consistent moisture.

Dry weights were recorded for stem biomass of the cut plot samples. Heights of each harvested stem were measured to the top reproductive node and averaged throughout the sample of each plot. Stem node number was counted for each plant in a plot, recorded and averaged. Using the height and stem node number, internode length was calculated. Pods were counted for the entire meter and recorded. Total pod number was divided by the number of plants in the sample to determine pods $stem^{-1}$. Stem node number and pod counts were used to calculate the number of pods $node^{-1}$. After data sampling, pods were hand harvested and seeds were cleaned using sieves to remove unwanted plant parts and other debris. Seeds were counted using a computerized seed counter (Agriculex, Guelph, Ontario, Canada) and weighed to determine the mass $seed^{-1}$.

To determine branching contribution to overall yield, branch biomass was weighed $plot^{-1}$. Pods were counted, hand harvested, and samples were cleaned as described for stems seeds. Seeds were counted and weighed to determine the mass seed^{-1}. Branch data were compared to stem data to determine if genetic advances have occurred in branching and seed mass. Stem and branch biomass and seed weights were combined. Harvest index was determined from these values expressed as a ratio of total seed weight plot^{-1} to total plant biomass plot^{-1} and expressed as a percentage.

The remaining center rows in the plots were mechanically harvested. Seed mass and moisture were collected, and yield was adjusted to a moisture content of 130 g kg^{-1}. Yield was also adjusted to account for the 1 meter sampled row removed for destructive plant sampling for yield component data. Yield data were analyzed over year of release and seeding rate to determine if newer cultivars could withstand higher seeding rates.

Yield data and plant characteristics were subjected to a mixed-effect regression analysis using the PROC MIXED procedure in SAS Version 9.2 (SAS Institute Inc., Cary, NC). Prior research has expressed genetic yield gain trends linearly (Specht et al., 1999) or quadratically (Voldeng et al., 1997) over year of release. A linear mixed-model provided the best fit for this experiment therefore yield data and plant characteristics were regressed linearly over release year. Yield, seed yield plant^{-1}, seed yield stem^{-1} plant^{-1}, seed yield branch^{-1} plant^{-1}, height stem^{-1}, nodes stem^{-1} plant^{-1}, pods stem^{-1} node^{-1}, seeds stem^{-1} pod^{-1}, seeds branch^{-1} pod^{-1}, and harvest index were analyzed using a consistent model. The fixed effects analyzed were seeding rate, year of release, maturity group and their respective interactions. Yield data and plant characteristics were regressed over year of release to evaluate change over time for each of the two seeding rates. The seeding rate by year of release interaction was examined to determine if differences in the rate of yield change existed between the seeding rates. Maturity group was used to determine if there was any yield level differences between MG II and MG III. Variables were removed from the model if deemed insignificant by the -2 log likelihood method to present a simplified model for analyzed data when possible.

Results and Discussion

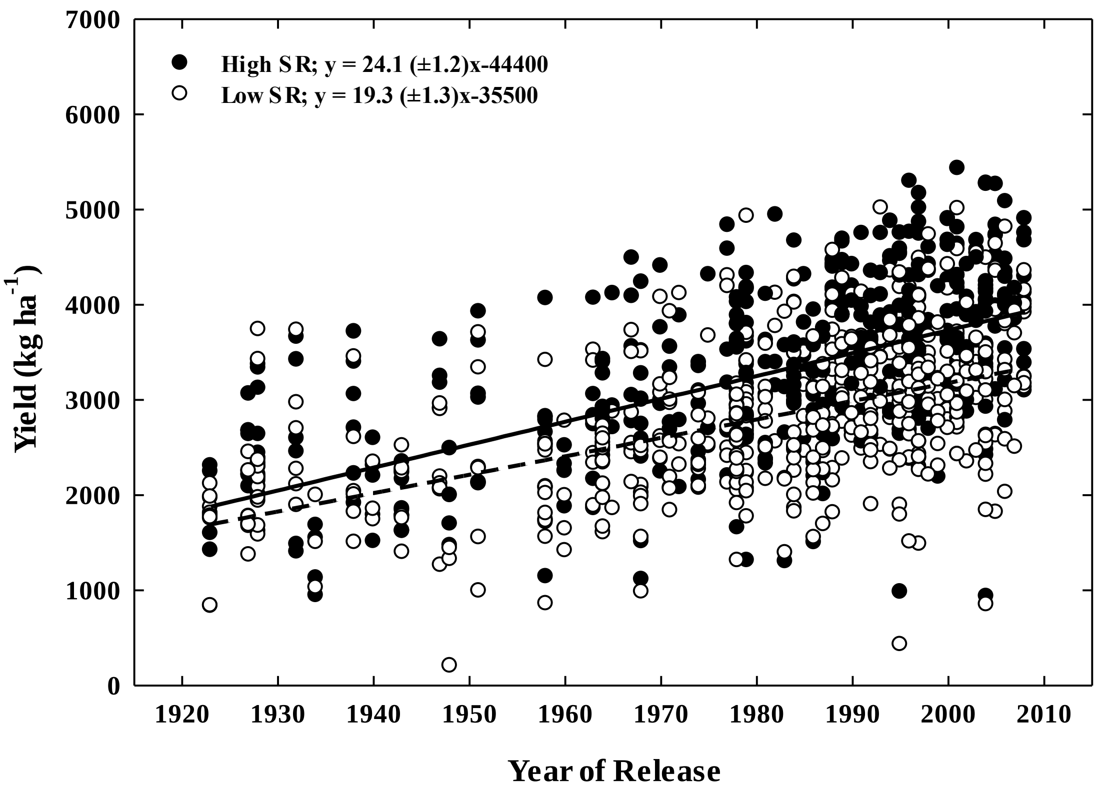
Influence of Maturity Group (MG)

Across all dependent variables in the experiment, there was no difference between MG II and MG III cultivars examined. Effects of MG, MG x year of release, MG x seeding rate and MG x year of release x seeding rate interactions ($P>0.05$) had no effect on yield ($P=0.61$), seed yield plant^{-1} ($P=0.39$), stem nodes plant^{-1} ($P=0.33$), stem pods node^{-1} ($P=0.13$), branch seeds pod^{-1} ($P=0.73$), stem seed weight plant^{-1} ($P=0.36$), branch seed weight plant^{-1} ($P=0.37$) and harvest index ($P=0.95$). Therefore a reduced model excluding maturity group and respective interactions was used for these dependent variables. Height plant^{-1} was not recorded for MG II cultivars so MG was not involved in final models for analyzed variables. Stem seeds pod^{-1} was not affected by MG ($P=0.76$), MG by year of release and MG by year of release by seeding rate. MG by seeding rate was significant ($P=0.01$) for stem seeds pod^{-1} but was left out of the model due to insignificance in all other factors analyzed.

Seed Yield

More recently released cultivars produced higher seed yield ha^{-1} than previously released cultivars ($P<0.001$) for both seeding rates (Fig. 1). Yield was always higher in the higher seeding rate, however, there was an interaction between seeding rate and year of release ($P<0.05$). Cultivars in the high seeding rate increased seed yield ha^{-1} at 24.1 ± 1.2 kg yr^{-1} while cultivars in the low seeding rate increased seed yield ha^{-1} at 19.3 ± 1.3 kg yr^{-1} (Fig. 1).

Figure 1. Regression of yield (kg ha^{-1}) over cultivar year of release at high (solid) and low (dashed) seeding rates in 2010 and 2011



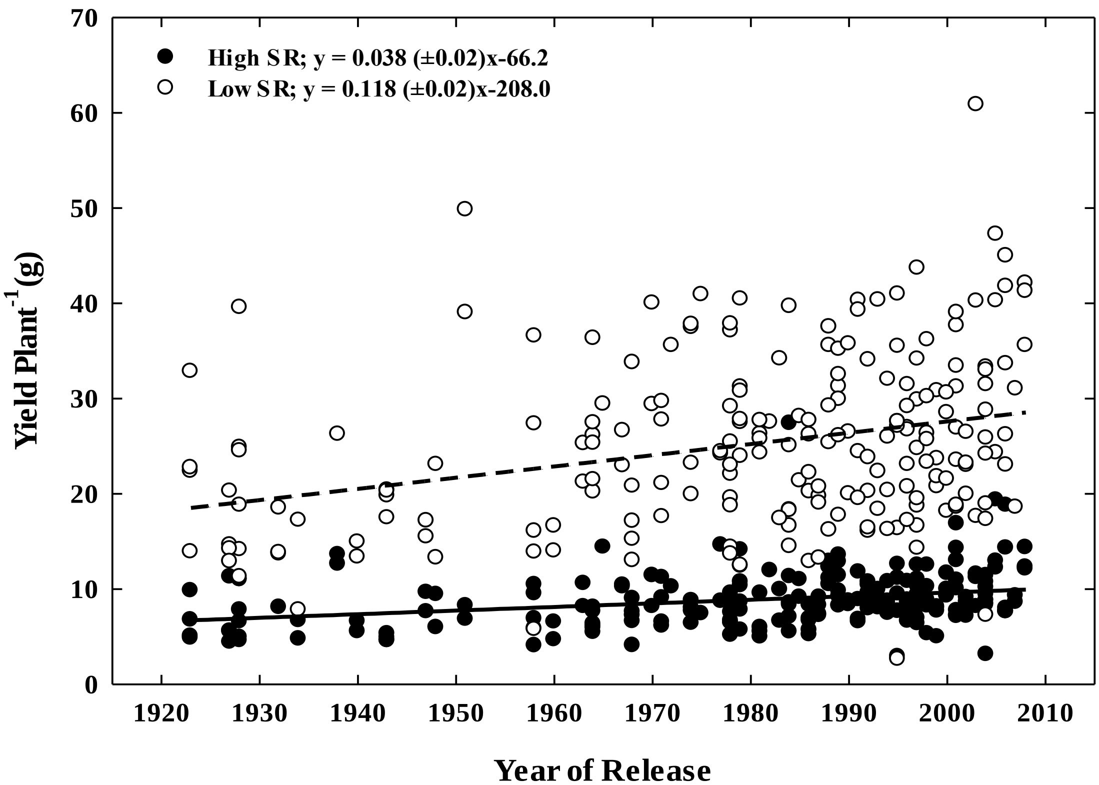
An increase in genetic yield gain over time has been well documented by various other researchers (Luedders, 1977; Specht et al., 1999; Wilcox, 2001). Our research demonstrated a 4.8 kg ha^{-1} yr^{-1} greater yield gain for cultivars planted at the higher seeding rate versus the low seeding rate. Therefore, it appears newer cultivars are genetically better equipped to produce higher yield in canopies with higher interplant competition compared to cultivars released in earlier years.

Seed Yield Plant^{-1}

More recently released cultivars also expressed higher seed yield plant^{-1} ($P<0.001$) than previously released cultivars (Fig. 2). Seed yield plant^{-1} was always higher in the low seeding rate versus the high seeding rate ($P<0.001$), however, there was a significant ($P=0.001$) interaction between seeding rate and year of release (Fig. 2). Cultivars in the low seeding rate increased seed yield plant^{-1} at 0.118 ± 0.02 g yr^{-1} while cultivars in the high seeding rate increased seed yield plant^{-1} at 0.038 ± 0.02 g yr^{-1} (Fig. 2).

Seed yield and yield components were not only examined on a plant^{-1} basis, but plant productivity was differentially examined by plant stems and plant branches. Seed yield stem^{-1} plant^{-1} increased across cultivar year of release (Fig. 3a). Cultivars in the low seeding rate produced more seed yield stem^{-1} plant^{-1} compared to cultivars in the high seeding rate. However, yield produced on the main stem increased at the same rate, 0.048 g yr^{-1}, for both the high and low seeding rates (Fig. 3a).

Figure 2. Regression of yield plant^{-1} (g) over cultivar year of release at high (solid) and low (dashed) seeding rates in 2010 and 2011



The low seeding rate had higher branch yield plant^{-1} compared to the high seeding rate ($P<0.001$). For branch seed yield plant^{-1}, the low seeding rate provided a significant increase over year of release while the high seeding rate had a slight decrease (Fig. 3b). Branch seed yield plant^{-1} was also affected by seeding rate. The low seeding rate achieved greater branch yield plant^{-1} compared to the high seeding rate ($P<0.001$). The interaction between seeding rate and year of release on branch seed yield plant^{-1} was significant ($P<0.001$) as the low seeding rate increased at a rate of 0.071 g yr^{-1} while the high seeding rate decreased 0.003 g yr^{-1}.

Cultivars planted at the low seeding rate produced 0.08 g yr^{-1} greater yield gain plant^{-1} than those planted at the high seeding rate providing evidence that newer cultivars planted at a low seeding rate are able to better compensate by producing higher yield plant^{-1} than older cultivars. The increase in seed yield stem^{-1} plant^{-1} across cultivar year of release (Fig. 3a) is consistent with the overall yield and yield plant^{-1} results. Increased seed yield stem^{-1} plant^{-1} over cultivar release year has allowed higher yields for high and low seeding rates. Although an increase for both seeding rates was reported for seed yield stem^{-1} plant^{-1}, it does present the ability for low seeding rates to compensate yield as seen with the overall yield plant^{-1}. The greater branch yield plant^{-1} of the low seeding rate is consistent with findings by Lehman and Lambert who discovered that as plant populations decreased, branch seeds plant^{-1} increased (1960). Since there was an interaction between the seeding rates and year of release for the seed yield branch^{-1} plant^{-1}, it is evident that the increased ability of new cultivars to compensate yield at the low seeding rate compared to the high seeding rate is due to higher yield potential of branches.

Figure 3a. Regression of stem seed yield plant^{-1} (g) over cultivar year of release at high (solid) and low (dashed) seeding rates in 2010 and 2011

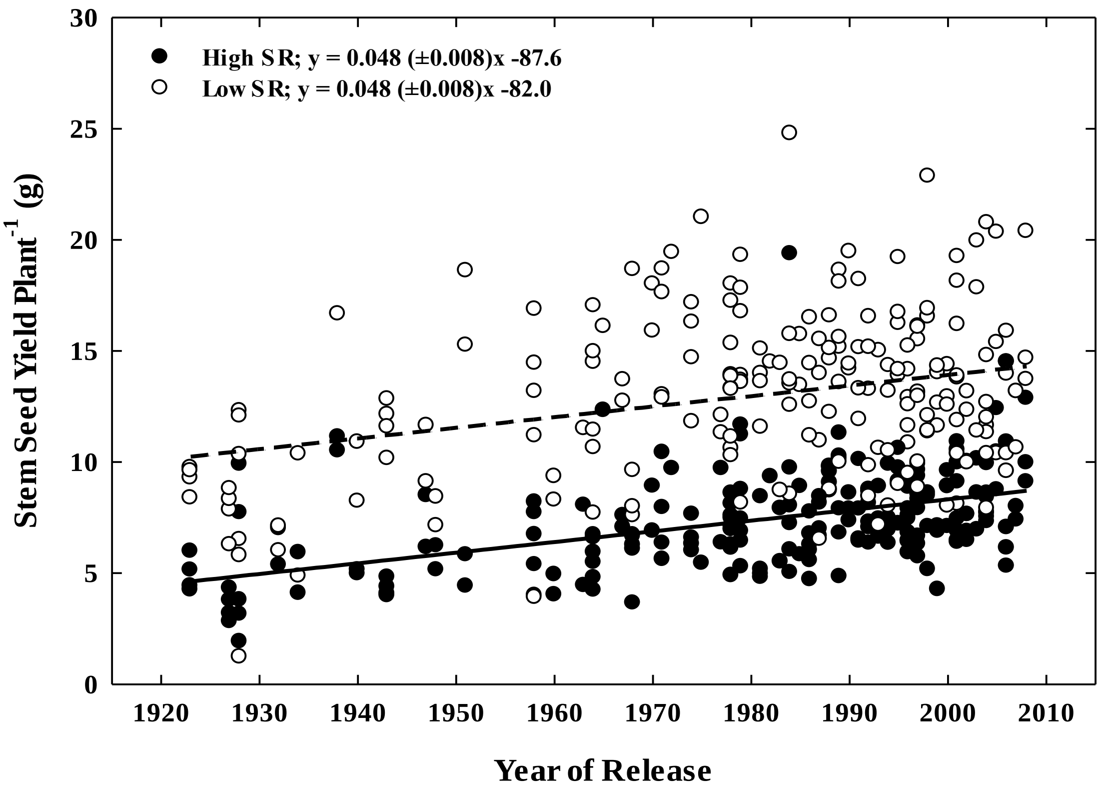
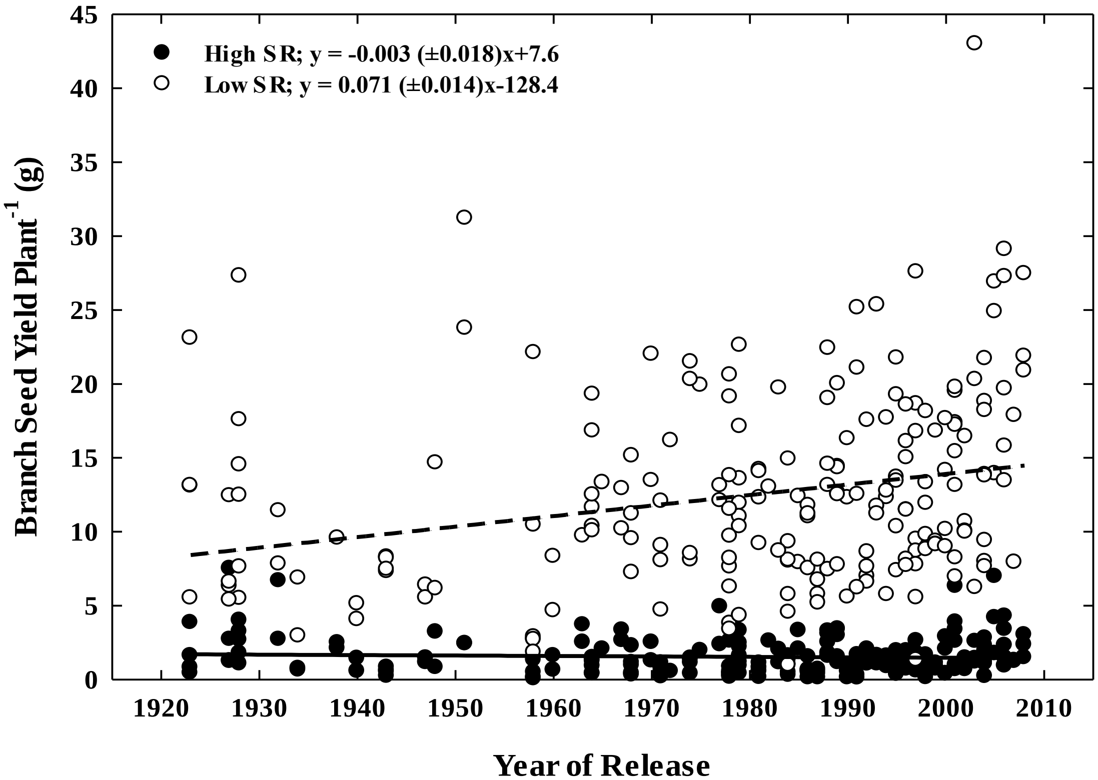


Figure 3b. Regression of branch seed yield plant^{-1} (g) over cultivar year of release at high (solid) and low (dashed) seeding rates in 2010 and 2011



Plant Characteristics

Stem height was only recorded for MG III cultivars. Stem height decreased for the high and low seeding rates across year of release at a rate of 0.21 and 0.28 cm yr^{-1}, respectively (Fig. 4). Seeding rate did not have an effect on height $stem^{-1}$ $plant^{-1}$ (P=0.051) but remains in the final model because the interaction between seeding rate and year of release was significant (P=0.044) (Fig. 4). As mentioned above, plant height decreased at a slightly faster pace over year of release in the low seeding rate versus the high seeding rate.

Nodes $stem^{-1}$ increased by 0.014 nodes yr^{-1} for both the high and low seeding rates across year of release (Fig. 5). As both seeding rates had the same increase yr^{-1}, there was no interaction between the seeding rate and year of release therefore the year of release by seeding rate interaction was excluded from the final model. However, there was a seeding rate effect (P=0.022) observed as the low seeding rate averaged 4 more nodes $stem^{-1}$ $plant^{-1}$ than the high seeding rate over cultivar year of release.

An increase in stem pods $node^{-1}$ was observed at the high and low seeding rates over cultivar year of release at a rate of 0.006 pods $node^{-1}$ yr^{-1} (Fig. 6). Seeding rate was significant (P<0.001) as the low seeding rate produced an average of 0.6 more pods $node^{-1}$ for each year of release. The lack of interaction between year of release and seeding rate indicated that both seeding rates showed the same response across cultivars.

Seeds pod^{-1} increased over year of release for stems and branches at the high and low seeding rates. Stem seeds pod^{-1} increased at a rate of 0.0034 seeds pod^{-1} yr^{-1} (Fig. 7a) and branch seeds pod^{-1} (Fig. 7b) increased 0.0022 seeds pod^{-1} yr^{-1} at both seeding rates. The low seeding rate had more seeds pod^{-1} than the high seeding rate on stems and branches. Stems

Figure 4. Regression of stem height (cm) over cultivar year of release at high (solid) and low (dashed) seeding rates in 2010 and 2011

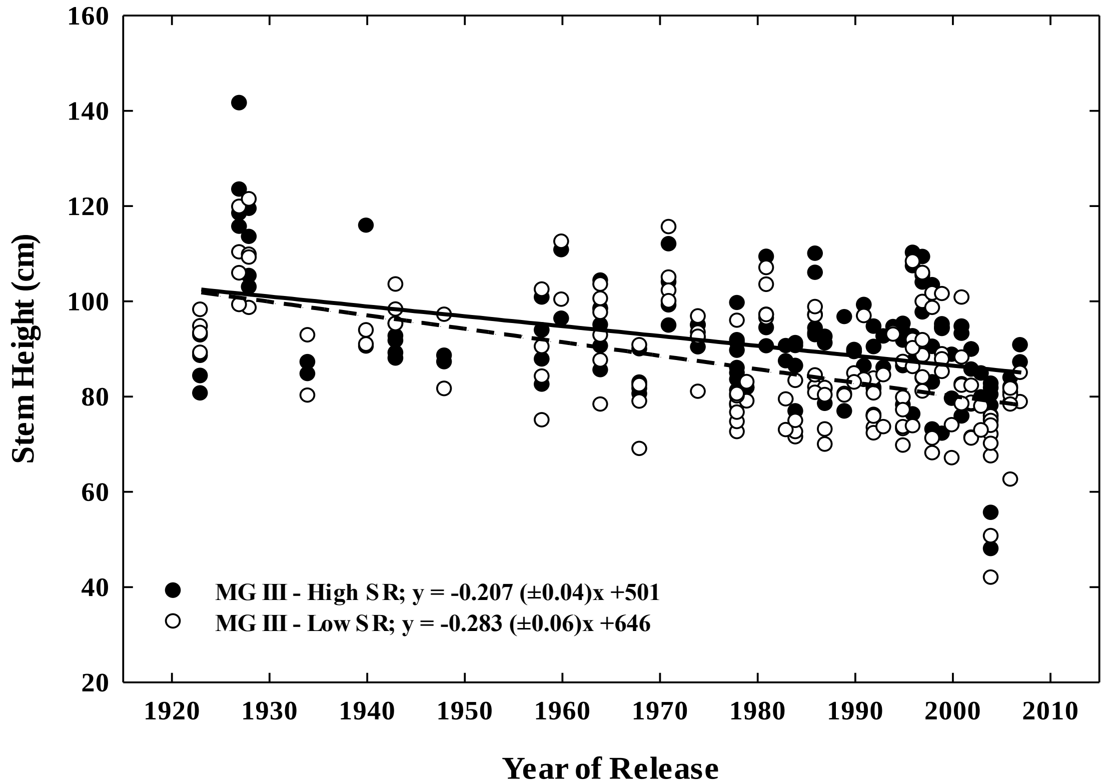


Figure 5. Regression of stem nodes plant^{-1} (#) over cultivar year of release at high (solid) and low (dashed) seeding rates in 2010 and 2011

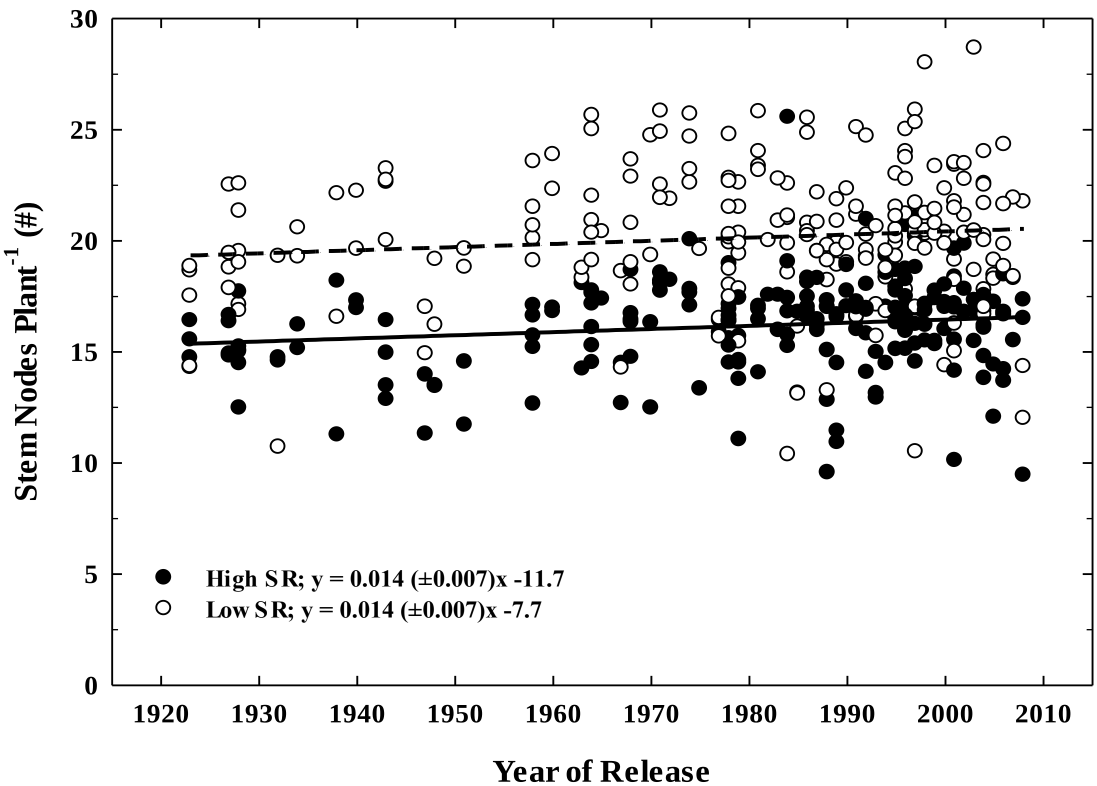


Figure 6. Regression of stem pods node⁻¹ (#) over cultivar year of release at high (solid) and low (dashed) seeding rates in 2010 and 2011

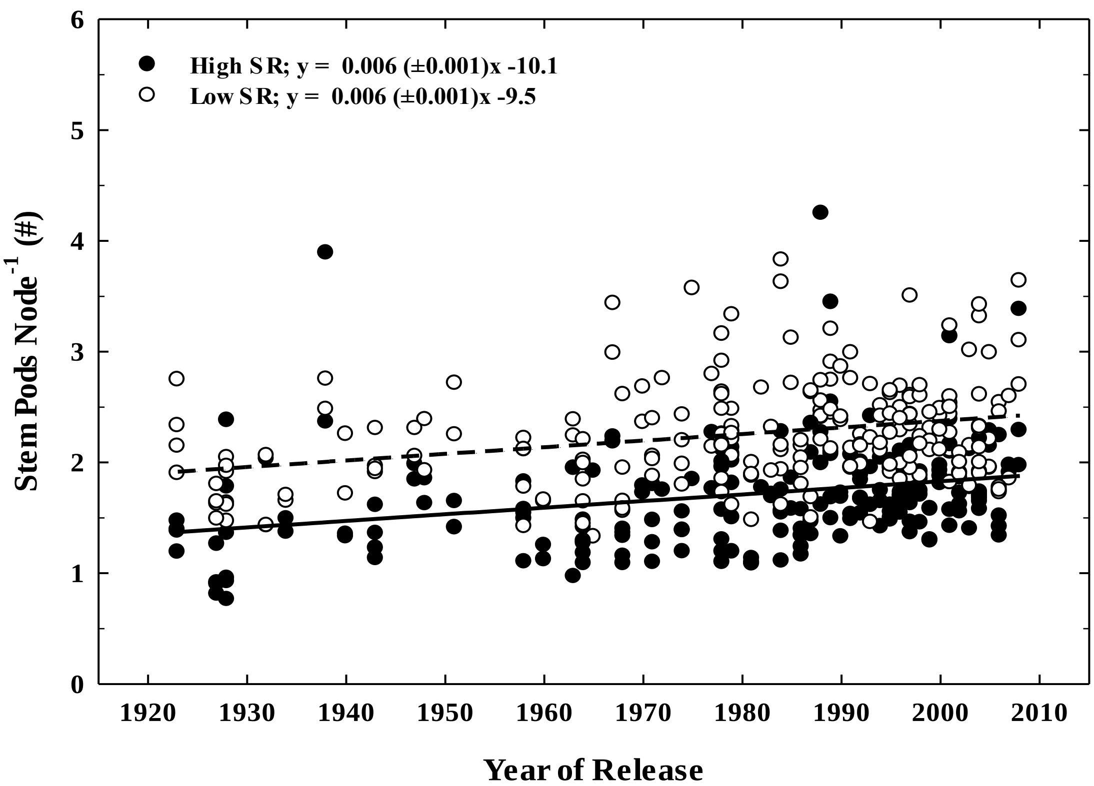


Figure 7a. Regression of stem seeds pod^{-1} (#) over cultivar year of release at high (solid) and low (dashed) seeding rates in 2010 and 2011

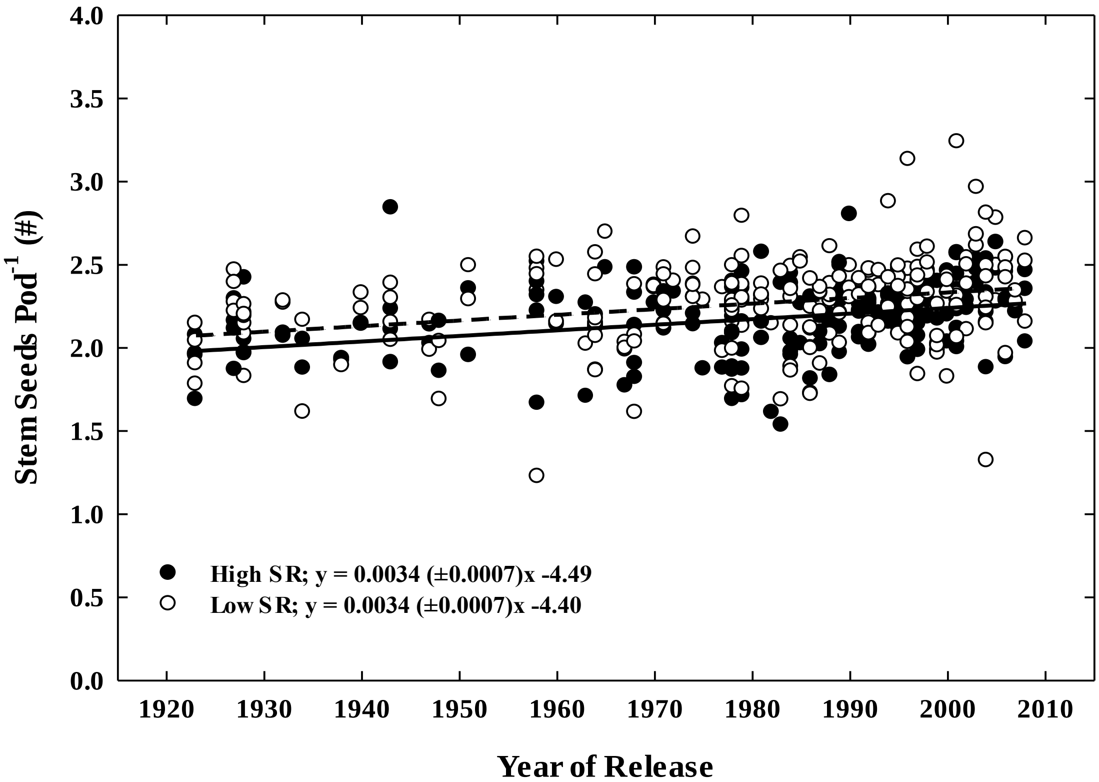
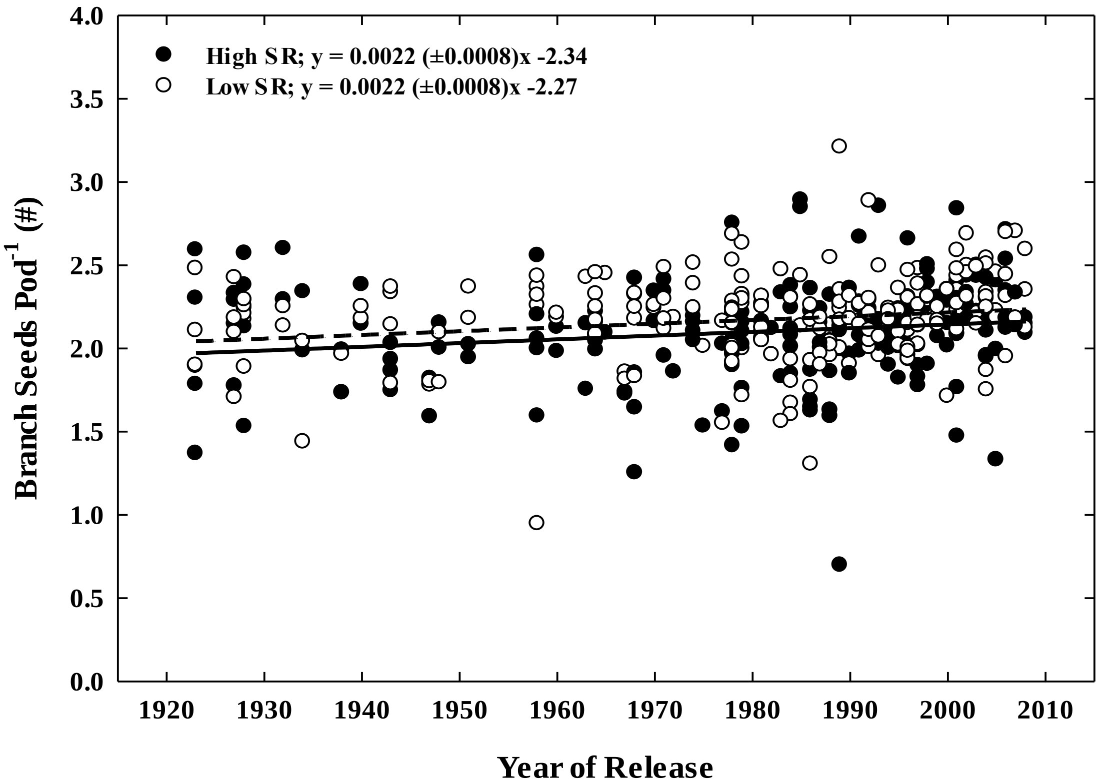


Figure 7b. Regression of branch seeds pod⁻¹ (#) over cultivar year of release at high (solid) and low (dashed) seeding rates in 2010 and 2011



had 0.09 and branches had 0.07 more seeds pod^{-1} at the low seeding rate compared to the high seeding rate.

Stem height results here are similar to those reported by Ustun et al. (2001), and indicate that breeders have achieved shorter plants to prevent lodging, therefore improving yield. Plant height is one of the most important plant characteristics in yield potential as plants can lodge from becoming too tall causing mechanical harvest losses and disease pressure (Ustun et al., 2001). Since the stem height decreased and number of stem nodes increased, the internode length has been shortened by breeding efforts over time.

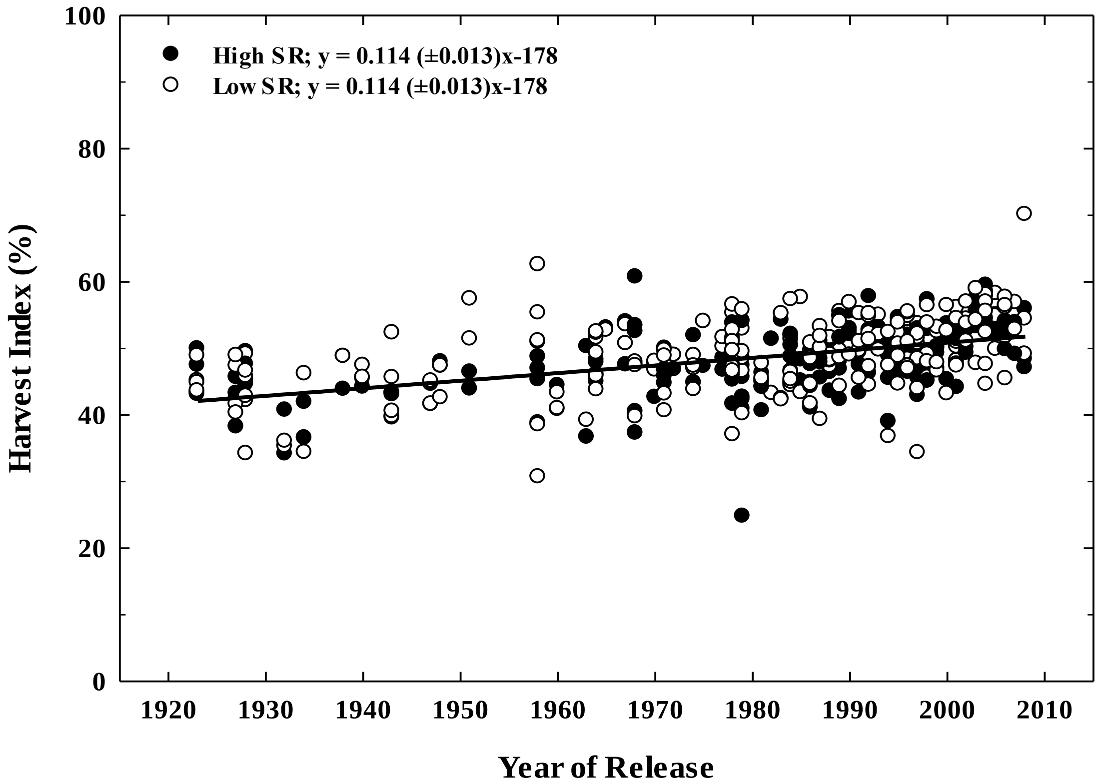
Stem pods node^{-1} also increased with newer cultivars. Since there was an increased number of nodes stem^{-1} plant^{-1}, pod number increased at a higher rate when viewed in a plant^{-1} basis rather than node^{-1} (data not shown). Pods plant^{-1} is known to respond better to stresses from environmental factors and management practices than any other plant characteristic. At lower plant populations, plants must produce more seed to compensate yield and this is most readily done by producing more pods (Pandey and Torrie, 1973).

Shorter plant heights and greater number of nodes plant^{-1} conclude that newer cultivars have developed shorter internode lengths. Since there has been a slight increase in the number of pods node^{-1} and the number of nodes stem^{-1} plant^{-1} has increased, there are more total pods produced plant^{-1} in newer cultivars. This follows Adams' theory that pods plant^{-1} and plants area^{-1} are negatively correlated (1967). The increase in stem and branch seeds pod^{-1} coupled with this increase in total pods plant^{-1} provide evidence that newer cultivars have the ability to develop more seed plant^{-1} compared to older cultivars.

Harvest Index

Seeding rate did not influence harvest index. However, harvest index increased across year of release for high and low seeding rate at 0.114 ± 0.013 % yr^{-1} (Fig. 8). Harvest index is the measure of the weight of a harvested product (seeds) as a percentage of the total plant weight so higher harvest index indicates better plant efficiency of energy resources. Harvest index has improved over years of successful soybean breeding, but appears to be un-influenced by plant population.

Figure 8. Regression of harvest index (%) over cultivar year of release at high (solid) and low (dashed) seeding rates in 2010 and 2011



Summary and Conclusion

Research and on-farm documentation have provided evidence that soybean breeders have continuously developed higher yielding soybean cultivars over time. Implementing optimum management practices helps these improved soybean cultivars to reach their maximum yield potential. Seeding rate is one management practice that growers can manipulate to strive for higher yields and greater profit margins. Seeding rates vary by growers in an attempt to achieve high yields; however, determining an optimum seeding rate is difficult because soybean cultivars have the ability to adjust their growth habits to account for various spatial distributions.

The data from this study show that the high seeding rate provided better yields compared to the low seeding rate across all cultivar years of release. The reason for the examined yield difference between the high and low seeding rates was due to an increased number of plants area^{-1} in the high seeding rate. Yield for the high and low seeding rates increased over time while the high seeding rate had a slightly faster progression. This yield gain provides evidence that soybean breeders have successfully improved soybean traits to provide greater yield in both high and low seeding rates.

Although the high seeding rate had a greater overall yield, the low seeding rate expressed greater yield plant^{-1} increase over time. The low seeding rate increased 0.118 g yr^{-1} while the high seeding rate only increased 0.038 g yr^{-1}. However, the increase in stem seed yield plant^{-1} for the high and low seeding rates progressed at the same rate (0.048 g yr^{-1}). Therefore the increase in seed yield plant^{-1} over cultivar year of release was due to greater increase in the branch seed yield plant^{-1} at the low (0.071 g yr^{-1}) compared to the high (-0.003 g

yr^{-1}) seeding rates. From these data, it is evident that extensive soybean breeding has developed soybean cultivars with better branching ability and a greater capacity to compensate yield when plant stand is reduced.

From the results of this experiment, it is evident that soybean breeders are continuing to increase the soybean yield trend over time. Through successful breeding efforts to generate higher yields, breeders have reduced height and increased nodes $stem^{-1}$ $plant^{-1}$, stem pods $node^{-1}$ and stem and branch seeds pod^{-1}. Harvest index has continued to improve suggesting that newer soybean cultivars are spending more energy on generating seed as opposed to biomass compared to older cultivars. Changing seeding rate from high to low had an effect on the growth habits of the soybean plants. Soybean plants in the high seeding rate produced majority of the seed on the main stem while the low seeding rate compensated lower plant stands by producing relatively equal seed on the stems and branches. Soybean breeders moving forward should look to continue these improvements while determining how well newer cultivars perform under different seeding rates as growers strive to get a better understanding for optimum seeding rates.

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Appendix

Yield

Table A1. Type 3 tests of fixed effects for yield differences

Effect[a]	Type 3 Tests of Fixed Effects			
	Num DF	Den DF	F Value	Pr > F
SR	1	88.7	14.81	0.0002
YR	1	110	321.85	<.0001
SR*YR	1	88.9	16.4	0.0001

[a] Abbreviations: SR = seeding rate; YR = year of release

Yield Plant^{-1}

Table A2. Type 3 tests of fixed effects for yield plant^{-1} differences

Effect[a]	Type 3 Tests of Fixed Effects			
	Num DF	Den DF	F Value	Pr > F
SR	1	138	8.46	0.0042
YR	1	140	32.42	<.0001
SR*YR	1	138	10.56	0.0015

[a] Abbreviations: SR = seeding rate; YR = year of release

Table A3a. Type 3 tests of fixed effects for stem seed yield plant^{-1} differences

Effect[a]	Type 3 Tests of Fixed Effects			
	Num DF	Den DF	F Value	Pr > F
SR	1	2.74	164.96	0.0016
YR	1	67.1	37.7	<.0001

[a] Abbreviations: SR = seeding rate; YR = year of release

Table A3b. Type 3 tests of fixed effects for branch seed yield plant^{-1} differences

Effect[a]	Type 3 Tests of Fixed Effects			
	Num DF	Den DF	F Value	Pr > F
SR	1	178	13.34	0.0003
YR	1	71.9	10.98	0.0014
SR*YR	1	178	15.63	0.0001

[a] Abbreviations: SR = seeding rate; YR = year of release

Stem Height

Table A4. Type 3 tests of fixed effects for stem height differences

Effect[a]	Type 3 Tests of Fixed Effects			
	Num DF	Den DF	F Value	Pr > F
SR	1	58.2	3.97	0.0511
YR	1	56.8	19.36	<.0001
SR*YR	1	58.3	4.25	0.0438

[a] Abbreviations: SR = seeding rate; YR = year of release

Stem Nodes Plant^{-1}

Table A5. Type 3 tests of fixed effects for stem nodes plant^{-1} differences

Effect[a]	Type 3 Tests of Fixed Effects			
	Num DF	Den DF	F Value	Pr > F
SR	1	2.06	41.53	0.0215
YR	1	76	4.35	0.0405

[a] Abbreviations: SR = seeding rate; YR = year of release

Stem Pods Node^{-1}

Table A6. Type 3 tests of fixed effects for stem pods node^{-1} differences

Effect[a]	Type 3 Tests of Fixed Effects			
	Num DF	Den DF	F Value	Pr > F
SR	1	3.91	99.34	0.0006
YR	1	87.7	19.37	<.0001

[a] Abbreviations: SR = seeding rate; YR = year of release

Seeds Pod^{-1}

Table A7a. Type 3 tests of fixed effects for stem seeds pod^{-1} differences

Effect[a]	Type 3 Tests of Fixed Effects			
	Num DF	Den DF	F Value	Pr > F
SR	1	240	33.52	<.0001
YR	1	90.2	24.22	<.0001

[a] Abbreviations: SR = seeding rate; YR = year of release

Table A7b. Type 3 tests of fixed effects for branch seeds pod^{-1} differences

Effect[a]	Type 3 Tests of Fixed Effects			
	Num DF	Den DF	F Value	Pr > F
SR	1	130	8.44	0.0043
YR	1	74.3	7.89	0.0064

[a] Abbreviations: SR = seeding rate; YR = year of release

Harvest Index

Table A8. Type 3 tests of fixed effects for harvest index differences

Effect[a]	Type 3 Tests of Fixed Effects			
	Num DF	Den DF	F Value	Pr > F
YR	1	83.9	73.34	<.0001

[a] Abbreviations: YR = year of release