SOYBEAN GROWTH AND YIELD RESPONSE TO INTERPLANT COMPETITION
RELIEF IN VARIOUS PLANT DENSITY ENVIRONMENTS

BY

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THESIS

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**ABSTRACT**

Soybeans have the ability to regulate growth and yield component production in response to changes in plant population and competition. Previous research has addressed these issues from various aspects, however, there is a lack of information regarding how interplant competition affects plant size variability, or how different sized plants respond to different plant density environments, or how plants respond to competition relief at various developmental stages. Research was conducted in Urbana, Illinois to examine yield component and growth variability by plant density, interplant competition, and cohort size. Two soybean cultivars (AG3803 and AG3205) were established at initial plant densities of 15, 30, 45 and 60 plants $m^{-2}$. Large and small cohorts were selected visually at four growth stages (V3, V6, R2, and R4) to be relieved of competition (-) (i.e. thinned) to 5.3 plants $m^{-2}$, while similar sized (large or small) cohorts remained in the level of competition of the initial seeding density all season. Plant height, growth stage, and number of nodes were recorded at each respective thinning time for, both, cohorts relieved of competition, and cohorts that remained in competition. At maturity, yield component (pod count, seed count, seed mass) data were collected and analyzed as differences between levels of competition. Plants recovered by increasing total seed yield plant$^{-1}$ for all timings and initial population densities when densities were thinned (interplant competition reduced). Earlier thinning times increased plant$^{-1}$ seed yield by increasing pods plant$^{-1}$ while seed mass contributed to yield compensation at the last thinning time. These results improve the understanding of soybean crop communities, and the relationship between plant density and plant size variability.

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# TABLE OF CONTENTS

## Introduction

Annual soybean yields have increased nationwide and in Illinois by 10.9 and 13.6 kg ha$^{-1}$ year$^{-1}$ respectively, over the last 15 years (USDA NASS). This increase has come from a combination of genetic improvements, the introduction of biotechnology, and improved cultural practices. Selective breeding has also improved grain composition, increased pest tolerance, and increased yield potential. The utilization of newer biotechnology techniques has also allowed soybean breeders to insert traits into soybean germplasm. This has subsequently simplified weed management for soybean growers. While the yield potential of soybean is genetically determined, achieving full yield potential also requires an optimum environment. Therefore, a soybean grower's best opportunity to maximize yield is proper cultivar selection, and the maintenance of adequate fertility and other environmental conditions to the best of their ability. Ever since soybean has been a major crop, there has been ongoing research to determine that optimum environment. In general, aside from cultivar selection and adequate fertility, manipulation of soybean planting date, seeding rate, row spacing, and weed control are major agronomic factors that are routinely studied as they can significantly influence yield potential and economic return. This research considers previous efforts and advances our understanding of the process between competing plants with in a soybean canopy.

**Literature Review**

**History of Soybean**

Domestication of soybean (*Glycine max*) began in Eastern Asia in the 11th century B.C, and continues today to be the foundation of East Asian nutrition and cuisine (Hymowitz and Newell, 1981). Soybeans were first introduced to America in 1765 by Samuel Bowen for use as a green forage crop (Hymowitz and Harlan, 1983). In the early 1900's the United States Department of Agriculture began testing and promoting soybeans as a forage crop. By the 1920's, soybean production expanded into the Corn Belt and began to shift toward grain production. Then, by 1941, soybean grain hectares exceeded forage hectares for the first time (Probst and Judd, 1973). In 1950, the United States grew 6 million all purpose hectares of soybean, and by 2010, that number had increased 5 fold and soybean was the 3rd most valuable agricultural commodity following beef and maize (USDA NASS, 2010). Today, soybeans are among the three principal field crops in the U.S. along with maize and wheat (USDA NASS, 2010)

Soybeans are a valuable resource for both oil and protein and are used for a wide variety of consumer uses today. Soybean oil can be separated into industrial and edible products. Edible uses include margarine, shortenings, salad oils, deserts, and drug manufacturing, while industrial uses include soaps, inks, putty, insecticides, adhesives, linoleum, and lectin. Soybean meal is used for livestock feed, fish and pet feed, fertilizers, and protein concentrates. Soybean meal can also be used as soy flour for baked goods, cereals, and baby food (Hauck et al., 1972). In 2009, the United States produced 38% of the world's soybeans on 31.4 million hectares. The average yield was 2.96 metric tons hectare$^{-1}$ making gross revenue over $30 billion (USDA NASS, 2010). Of that total, Illinois produced 3.8 million hectares of soybeans valued over $4 billion (USDA NASS, 2010).

**Soybean Agronomics**

The agronomic practices of soybean are best optimized when a systematic approach to management is utilized with the understanding of soil types, climate conditions, pest concerns, fertility requirements, and equipment capacities for a producers operation. Producers can only plan ahead for, or react to, the conditions they have for many of these factors. However, the agronomic factors most easily controlled by the grower include when the crop is planted, how many seeds are planted, and in what row spacing, or arrangement, the seeds are placed. A review of literature for these agronomic factors follows.

*Planting Date*

Cartter and Hartwig (1963) stated that no single cultural factor was more important to soybean production than planting date. Regardless of other advancements in soybean production in the last 50 years, planting date still has significant and varying effects on soybean yield from year to year (Egli and Cornelius, 2009). Concerns with planting soybean too early include cold and wet soils which have the potential to delay emergence (Major et al., 1975), reduce plant stands (Oplinger and Philbrook, 1992), and cause poor seedling health (Hamman et al., 2002). Moreover, planting soybeans too early, such as early-April, or too late, such as July can result in premature flowering as a result of inadequate photoperiod (Board and Hall, 1983). On the other hand, delayed planting tends to reduce the number of days from emergence to flowering (Pedersen and Lauer, 2004a), push both vegetative and reproductive growth into less favorable environmental conditions (Egli and Bruening, 2000; Egli and Cornelius, 2009), and ultimately reduce yield potential by reducing season length. While many studies focus on calendar date, Hoeft et al. (2000) recommended to not begin planting soybeans before soil temperature reaches 10° C or above regardless of calendar date. According to the Illinois

Climate Network (ICN, 2011) 8 of the last 10 growing seasons in Illinois have had an average 10-cm deep soil temperature above 10° C that would satisfy the requirement for April planting.

For many years it was generally accepted that soybean yield could be maximized when planted during the month of May in the Corn Belt. This historical view was supported by Egli and Cornelius (2009). They conducted a meta-analysis study of 28 soybean planting date experiments which were conducted between 1960 and 2005. Their analysis included research studies with more than one year of data, and with at least three planting dates divided into three regions: Midwest, Upper South, and Deep South. Their results supported the notion that soybean yields in the Midwest begin to rapidly decline when planted after 30 May, 7 June in the Upper South, and 27 May in the Deep South. Delayed planting in the Midwest showed 0.7 percent decrease in yield day$^{-1}$ when planted after the optimal date of 30 May. The Upper South had 1.2% decline and the Deep South a 1.1% decline in yield day$^{-1}$ when planting was delayed after the optimal dates of 7 June, and 27 May, respectively. Early planting, before the optimal date, in both the Midwest and Upper South did not differ from zero. However, in the Deep South there was a 0.54 percent day$^{-1}$ yield decrease when planting before the optimal date. Only 23% of the April and early-May planting dates showed significant yield increases over later planting dates, which showed no consistent advantage for early planting, in contrast to a significant penalty for planting after the day of rapid decline (Egli and Cornelius, 2009).

While results from Egli and Cornelius (2009) seem conclusive, much of the data in their meta-analysis were nearly three decades old and may not reflect newer soybean genetics. More recent planting date research was conducted in Indiana in 2006 and 2007 by Robinson et al. (2009). The target planting dates were late-March, early-April, late-April, early-May, late-May, and early-June. In 2006, yields were similar from late-March through the middle of May. However, once planting was delayed past the middle of May, yields declined by 31.4 kg ha$^{-1}$

day$^{-1}$.  In the second year, 2007, maximum yields were again achieved between the late-April and early-May plantings.  Overall, yields were reduced by 13% and 25% when planting was delayed to early-June versus planting in late-April through early-May (Robinson et al., 2009).

Additional research in Iowa was conducted from 2003 to 2006 across 13 environments; target planting dates were the fourth week of April, the second week of May, the fourth week of May, and the second week of June.  There was no yield difference in planting in late-April versus early-May.  Yield reductions of 130 kg ha$^{-1}$ wk$^{-1}$ began when planting was delayed between early- and late-May.  Yield reductions reached 404 kg ha$^{-1}$ wk$^{-1}$ when planting was delayed from late-May through early-June.  According to their research, April planting does not influence plant establishment, and in order to achieve maximum yield in most parts of Iowa, planting between late-April and early-May is necessary (De Bruin and Pedersen, 2008a).

In summary, producers have a relatively broad window to complete planting before yield is significantly affected.  According to the literature, high yields can be achieved in the Midwest by planting in late-April or early-May (De Bruin and Pedersen, 2008; Pedersen and Lauer, 2004b; Robinson et al., 2009), or from early-May to late-May (Beaver and Johnson, 1981; Egli and Cornelius, 2009; Elmore, 1990).  Ultimately, soybean yield decreases most rapidly when planting is delayed beyond the end of May (Beaver and Johnson, 1981; De Bruin and Pedersen, 2008; Egli and Cornelius, 1990; Elmore, 1990; Pedersen and Lauer, 2004b; Robinson et al., 2009).  However, one could also hypothesize newer cultivars have become more responsive to earlier planting dates as more-recent data describes (De Bruin and Pedersen, 2008; Pedersen and Lauer, 2004b; Robinson et al., 2009), compared to earlier work (Beaver and Johnson, 1981; Egli and Cornelius, 2009; Elmore, 1990).  Nonetheless, many producers in the Corn Belt begin planting soybeans after corn planting is complete despite both positive and negative effects of early or late planting (De Bruin and Pedersen, 2008a).

*Row Widths and Seeding Rates*

There are two general concepts often used to explain the relationship between row spacing, plant density, and crop yield. The first concept is maximum crop yield can only be achieved if the crop community is able to produce sufficient leaf area to provide maximum light interception during reproductive growth (Shibles and Weber, 1966). Second, equidistant plant spacing maximizes yield because it minimizes interplant competition (Wiggans, 1939).

Most soybeans in the Midwest are grown in rows spaced 18- to 76-cm apart. Typically, plant-to-plant spacing within a row is adjusted according to row-to-row spacing (row width) so overall plant density remains constant. This adjustment is made in order to produce a complete canopy that is capable of maximizing light interception, while maintaining adequate plant-to-plant spacing. An advantage of narrow row spacing is more equidistant plant spacing that leads to an increase in canopy leaf area development and greater light interception earlier in the growing season (Shibles and Weber, 1966; Weber et al., 1966). According to Johnson (1987), when light is the limiting factor in crop production, equidistant plant spacing results in maximum yields. Quicker canopy development is also an advantage of narrow-rows as this has been found to enhance weed management (Buhler and Hartzler 2004, Heatherly and Elmore, 2004; Young et al. 2001), decrease stored water loss due to evaporation (Hoeft et al. 2000), and increase plant establishment (De Bruin and Pedersen, 2008b; Oplinger and Philbrook, 1992). However, other researchers have found that rapid canopy closure can increase the use of stored soil water, via transpiration, therefore, leaving less available water during the critical period of pod-fill (Heatherly and Elmore, 2004; Johnson, 1987; Taylor, 1980).

The cost of soybean seed has increased by 230% since 1996 (Anonymous, 2010), and this increase in cost has generated the need to define optimum seeding rates to maximize profit in addition to producing a final plant population that is capable of producing maximum yields.

In general, soybean seed yield is relatively insensitive to plant population, as a wide range of seeding rates typically produce the same yield (Lee et al., 2008). This is often a result of soybeans ability to regulate branch production in response to available space within the canopy (Carpenter and Board, 1997a,b). Conversely, as seeding rates are increased above what is considered optimum, interplant competition typically increases (Elmore, 1998), and plant stand uniformity decreases.

The majority of the research reported to date has evaluated the effect of seeding rates and row spacing collectively to determine the effect of each, or both, on soybean seed yield. Cox and Cherney (2011) compared soybean seed yield within three row-spacing and four seeding rates in 2008 and 2009 at Cornell University, New York. Seed yield was compared in 19-, 38-, and 76-cm rows, and at 321,000; 371,000; 420,000; and 469,000 seeds ha$^{-1}$. Narrow rows increased seed yield linearly as 19-cm (3.37 Mg ha$^{-1}$) rows out yielded 38-and 76-cm rows by 0.25 and 0.51 Mg ha$^{-1}$ or 8 and 18% respectively. Seed yield showed a quadratic response to seeding rate. Soybean seed yield increased by 7% as seeding rates increased from 321,000 seeds ha$^{-1}$ (3.04 Mg ha$^{-1}$) to 420,000 seeds ha$^{-1}$ (3.25 Mg ha$^{-1}$), but then declined by 4% of the optimum seeding rate as seeding rates were increased to 469,000 seeds ha$^{-1}$ (3.12 Mg ha$^{-1}$) with no row spacing interaction. From these data one might conclude that soybeans can compensate seed yield at lower seeding rates with equidistant plant spacing to the level, or above the level, of higher plant densities in wider rows where plants are more likely to compete with one another.

De Bruin and Pedersen (2008b) conducted similar row spacing and seeding rate experiments from 2004 to 2006 at three locations in Iowa. This research evaluated the effect of 38- and 76-cm wide rows, and seeding rates of 185,000; 309,000; 432,000; 556,000 seeds ha$^{-1}$ on seed yield. They found that 38-cm row spacing increased yield by an average of 5% across

three locations for three years.  Maximum yield was achieved with a final harvest population of 462,200 plant ha$^{-1}$.  However, >95% of the maximum yield could be achieved with a final harvest population as low as 258,600 plants ha$^{-1}$ or, stated differently, reducing seeding rates by 45% resulted in >95% of maximum yield (De Bruin and Pedersen (2008b).  Therefore, one might conclude that reduced row spacing is more economically significant than increasing seeding rates when trying to increase yield.

Elmore (1998) conducted a study over five site years in Nebraska from 1986 to 1988.  He used seeding rates  of 111,000; 345,000; 580,000; and 815,000 seeds ha$^{-1}$,  row spacings of  25-, 50-, and 76-cm , and irrigated versus non-irrigated.  Soybean yield response to row spacing varied depending on site, irrigation, and cultivar.  However, the 50-cm rows yielded the highest or at least as high as the highest at each site, in both water regimes, and across all five cultivars.  Seeding rates showed a positive response to an Increase from 111,000 to 345,000 seeds ha$^{-1}$ as yield was elevated by 315 kg ha$^{-1}$ averaged over all other factors.  Also, yield was not different as seeding rates were increased from 345,000 to 815,000 plants ha$^{-1}$ (Elmore, 1998).

In contrast, Oplinger and Philbrook (1992) conducted separate studies to measure the effect of row spacing and seeding rate on soybean seed yield in Wisconsin from 1983 to 1986.  The first study focused on row spacing in addition to tillage practices and planting date, while the second study focused on seeding rate also in addition to tillage only.  The results of the first experiment showed a 6.5% yield advantage to 19-cm rows versus 76-cm rows when averaged across three planting dates and three tillage systems (no-till, reduced-till, and conventional tillage).  The seeding rates examined were 123,000; 250,000; 370,000; 495,000; 618,000; and 741,000 seeds ha$^{-1}$.  Maximum yield was achieved at a planting density of 618,000 seeds ha$^{-1}$. However, seeding rates of 495,000 and 741,000 seeds ha$^{-1}$ produced yields that were not different.  Harvest plant stands were reported, and they found that plant stands as low as

343,000 plants ha$^{-1}$ achieved maximum yields. Reducing that plant stand by 18% to 280,000 plants ha$^{-1}$ resulted in yields that achieved >95% of the maximum yield. An even greater reduction to 215,000 plants ha$^{-1}$ still achieved >80% of the maximum yield. Additionally, their research indicated seeding rates should be increased by 32% when planting no-till or in reduced-till situations versus conventional till (Oplinger and Philbrook, 1992).

Bullock et al. (1998) conducted research that focused on soybean yield response to row spacing. Soybeans were planted in 38-, 76-, and 114-cm wide rows, and plant stands were thinned to 450,000 plants ha$^{-1}$ between V1 and V2. They reported seed yield increased as row spacing decreased, such that narrow rows (38-cm) out yielded 76- and 114-cm rows by 8 and 20%, respectively. In addition, 76-cm rows out yielded 114-cm rows by 12% (Bullock et al., 1998).

The work previously discussed evaluated indeterminate cultivars in the Mid-West and Upper-Midwest. However, Egli (1988) conducted research in Kentucky in 1985 and 1986 to determine the effect of plant density on both determinate and indeterminate cultivars on seed yield. Individual plants were grown in a variety of densities, ranging from 6,000 to 240,000 plants ha$^{-1}$. He found that seed yield increased linearly with increases in population up to 15,000 plants ha$^{-1}$ in indeterminate cultivars, whereas determinate cultivars increased seed yield linearly in relation to increases in population up to 30,000 plants ha$^{-1}$. This suggests that no interplant competition exists up to 15,000 plants ha$^{-1}$ in indeterminate soybeans or 30,000 plants ha$^{-1}$ in determinate cultivars. In addition, 95% photosynthetically active radiation (PAR) interception at growth stage R5 was achieved at a density as low as 51,000 and 33,000 plants ha$^{-1}$ in 1985 and 1986, respectively for the indeterminate cultivar. At these densities there was a sharp reduction in the rate of yield increase, suggesting that interplant competition has begun at some level. Maximum yield was achieved at 73,000 plants ha$^{-1}$. Therefore, one might assume

that plant densities above those required to maximize light interception may be required for maximum yields. The determinate cultivar responded differently in that 95% PAR interception, was achieved by R5, and maximum yields were achieved at the same density of 61,000 plants ha$^{-1}$.

Pedersen and Lauer (2003) found inconsistent response to row spacing in Wisconsin from 1997-2001. Their research focused on the influence of crop rotation sequence, tillage, and row spacing on soybean seed yield. There were inconsistent responses to row spacing between years resulting in at least one growing season where 19-, 38-, and 76-cm rows each produced optimal yields (Pedersen and Lauer, 2003). That is in contrast to other reports (Bullock et al., 1998; Cox and Cherney, 2001; De Bruin and Pedersen, 2008b; Elmore, 1998; Egli, 1988).

In conclusion, the spatial distribution of plants within a crop community can influence soybean seed yield. The research presented above suggests that maximum yield, or at least 95% of maximum yield, has been achieved in a range of seeding rates from 73,000 to 815,000 seeds ha$^{-1}$ (Cox and Cherney, 2011; De Bruin and Pedersen, 2008b; Egli, 1988; Elmore, 1998; and Oplinger and Philbrook, 1992). Therefore, supporting Lee et al. (2008), that soybean yield is relatively unresponsive to seeding rates. In addition, most research reports a positive yield response to decreasing row spacing to less than 16-cm (Bullock et al., 1998; Cox and Cherney, 2011; De Bruin and Pedersen, 2008 b; Elmore, 1998; Egli, 1988), and is agreement with Wiggans (1939), that soybeans typically produce highest yields in a uniform distribution due to minimization of interplant competition. However, others reported no response to row spacing (Pedersen and Lauer, 2003), and suggests focusing on other strategies to increase soybean seed yield. In addition to the literature presented, Lee et al. (2008) came to the conclusion that economically optimum plant populations could be 7 to 33% less than the optimum plant populations due to increasing seed costs. Therefore, one might hypothesize seeding rates

below current practices could be used to lower seed cost without reducing net profit. This hypothesis is of increasing interest due to the increase in seed costs for soybean producers today.

**Competition**

Competition can be defined as two or more plants demanding common environmental resources in excess of supply. In general, competition can be categorized into two types. Inter-specific competition occurs between multiple species and is usually demonstrated as competition between a desired crop and weeds. Intra-specific, or interplant competition, is when common resources are limited for all the plants of a similar specie, such as between the established crop plants with a given crop canopy. Individual plant productivity is typically limited by competition for light, water, soil nutrients or a combination of each (Buhler and Hartzler, 2004). Competition for light exists when plants are large enough to shade one another, while competition for soil resources can begin soon after germination (Weiner and Thomas, 1986). Within a crop community, plants growing under a canopy not only experience a reduction in the amount of irradiance, but also a reduction in the quality of light as chlorophyll preferentially absorbs red (R) light and reflects far-red (FR) light, thereby the R : FR decreases as sunlight moves through the crop canopy (Kasperbauer, 1987). The decrease in the amount of R light in relation to the amount of FR light thus results in an environmental cue for plants to detect neighbor plants before canopy closure (Green-Tracewicz et al., 2011). That cue typically leads to a response in plant growth. Many plant species respond to a reduction in R : FR with increased apical dominance, decreased branching, stem extension and internode elongation (Green-Tracewicz et al., 2011). In contrast to aboveground competition for a single resource, light, plants compete for multiple soil resources, including water and other essential mineral

nutrients.  Competitive stress created by competition in plant stands may be expressed by increased mortality, reduced seed production, and reduced growth rate (Board, 2000).

In soybean research, most work investigating the effect of competition has been on interspecies competition, or competition from weeds.  It is common knowledge that competition between crops and weeds cause significant losses to soybean producers every year.  The precise impact of weed competition on grain yield would be difficult to document since damage typically varies within fields, between fields, within and between regions, and between years (Buhler and Hartzler, 2004).  However, it has been estimated that weed interference annually reduces U.S. crop yield by 12% (Paoletti and Pimentel, 2000).  Based on the 2010 value of all U.S. crops, $192.5 billion (USDA), a 12% yield reduction translates to economic losses in excess of $15 Billion in the U.S.

In order to implement an adequate weed management strategy, it is essential to determine the period of soybean growth when weed interference is most detrimental.   Van Acker et al. (1993) addressed these issues at three locations in southern Ontario, Canada.  Their work determined the critical period of weed control in soybean generally consists of two parts: one being the critical weed-free period, and the second being the critical time of weed removal.  They found the critical weed-free period to be consistent and relatively short.  According to their research, when weed competition was eliminated from emergence to the fourth node growth stage, or approximately 30 days after emergence, yield losses were not more than 2.5%.  However, the critical time for weed removal (CTWR) varied across locations and years, and ranged from V2 to R3, or approximately 9 to 38 days after emergence (DAE), to prevent a yield loss of more than 2.5%.  If a 5% yield loss is deemed acceptable then the CTWR ranged from V3 to R3-R5, or 16-50 DAE.  In addition, a 10% yield loss would have a CTWR range of V4 to Harvest, or 22-74 DAE.  Therefore, one can conclude that yield losses from weed competition are evident

early in the growing season, and depending on the level of yield loss deemed acceptable, weeds should be controlled before V4 and continue through harvest.

Similar research was conducted by Knezevic et al. (2003) from 1999 to 2001 at two locations in Nebraska to determine the effect of row spacing on the critical time for weed removal (CTWR). This research found that the CTWR increases as row-spacing increases. They found that 19-, 38-, and 76-cm rows have a CTWR of the $3^{rd}$, $2^{nd}$, and $1^{st}$ trifoliate, respectively. These findings support conclusions by Van Acker et al. (1993), in that inter-specific competition begins early in the growing season. They also found that competition begins earlier in wide row soybeans versus narrow row soybeans, and that weeds allowed to compete all season long can reduce soybean yields by 44 to 84%.

Harder et al. (2007) conducted research similar to Knezevic et al. (2003) in Michigan during the 2004 and 2005 growing seasons. However, their research not only focused on the effect of row width, but also on seeding rates, and weed emergence and proliferation. They also found when weeds competed all season long, they reduced soybean seed yield by 46-66%. In addition, they found 19-cm wide rows reduced weed emergence more than 76-cm wide rows, after a postemergence glyphosate application to 10-cm weeds. This supported Knezevic et al. (2003) that soybeans in narrow rows are better competitors with weeds.

To further investigate weed interference on soybean seed yield, research was conducted by Nordby et al. (2007) to determine soybean cultivar competitiveness with weeds between different maturities and canopy characteristics. Their experiment was conducted at five locations in Illinois during the 2005 growing season. The authors found wide-canopy cultivars were not more competitive with weeds than narrow-canopy cultivars. However, later maturing cultivars were able to achieve higher yields even when weeds were removed later in the growing season compared to earlier maturing cultivars. They attributed the yield increase to

the increased light interception, and increased canopy closure which reduced the amount of light reaching the soil surface thereby reducing weed seed germination and survival (Nordby et al., 2007).

Green-Tracewicz et al. (2011) examined soybean shade avoidance and its effects on plant branching and on variability in biomass and yield plant[−1] during the 2007 and 2008 growing season at the University of Guelph in Guelph Ontario, Canada. They observed a shade avoidance response in soybean seedlings due to a reduction in the R : FR by comparing weedy and weed-free plots. Soybean plants grown in weedy conditions, or low R:FR conditions, had increased height, internode length, and shoot : root ratios. Plants grown in low R:FR conditions also had less root biomass, total plant biomass, and leaf area. These differences occurred as early as V2 when the weed-free treatment had generated 36% more root biomass, and they continued until seed-fill (R5). Moreover, total biomass, seed number, and seed yield at R5 was increased for the weed-free treatment by 30, 14, and 12%, respectively. Most of the increased seed yield came as a result of increased branches, and pod plant[−1] (Green-Tracewicz et al. 2011). Their research conclusions agreed with Van Acker et al. (1993) and Knezevic et al. (2003) in that weed interference begins during the very early stages of vegetative growth.

In summary, there is significant evidence to support the fact that soybean-weed interactions can negatively impact seed yield, and in severe cases, by as much as 84% (Harder et al., 2007; Knezevic et al., 2003). It is suggested that in order to prevent yield losses to weed competition, weeds should be controlled early in the vegetative stages and remain controlled throughout the early part of the reproductive stages (Van Acker et al., 1993). Inter-specific competition begins earlier in the growing season for soybean grown in wide rows versus narrow rows (Knezevic et al., 2003), and later maturing cultivars tolerate weed competition better than early maturing cultivars (Nordby et al., 2007). Soybeans respond to weed competition growing

taller in an attempt to avoid shading (Green-Tracewicz, 2001), this can result in an increase in plant lodging and increasing harvest difficulties.

In contrast to the many studies investigating competition between soybean and weeds, there has been very limited research reported to identify the effects of interplant competition, or competition between soybean plants in a shared environment. Duncan (1986) advanced two postulates to explain the effect of soybean plant relations on seed yield. He proposed that (i) there is a range of plant densities where soybean seed yield increases with no increase in light interception by the crop canopy, and (ii) that, within limits, seed yield will increase with increases in vegetative mass during the seed initiation period, with all other conditions remaining the same. In addition, Duncan described three phases of soybean yield response to increased plant density. Phase I covers the range of plant densities where there is no interplant competition and seed yield is directly proportional to plant density, or yield per plant is constant. Phase II begins at a plant density great enough to intercept nearly all of the insolation at full canopy, and ends at a density where further increase in density results in no increase in seed yield. Phase III includes all plant densities where seed yield is not increased by an increase in density. Phase I and II are separated by that range of densities where interplant competition increases. These postulates provide a framework to evaluate seed yield response of a soybean community in relation to changing plant densities.

**Yield Recovery**

Soybean plants have a unique ability to regulate growth in relation to multiple conditions. In other words, phenotypic plasticity has been observed in soybean crop communities in response to seeding rate (Board, 2000; Carpenter and Board, 1997a,b), and row spacing (Knezevic et al., 2003). Soybeans have the ability to make adjustment to available space which allows soybean communities to achieve optimum yields over a broad range of plant

arrangements.  However, the mechanism responsible for this yield compensation is not fully understood (Carpenter and Board, 1997a,b; Egli, 1988).

In general, soybean seed yield can be determined by the product of biomass (BM) and harvest index (HI).  Acknowledging that soybean HI is constant in most environments (Spaeth et al., 1984), maximizing BM should produce the highest yields.  This is consistent with work done by Duncan (1986), who proposed that, the greater the total dry matter (TDM) the greater the yield, as long as the TDM is produced before seed initiation.  Furthermore, it has been suggested that optimal crop growth rate (CGR), or dry matter (DM) production, resulted when leaf area index (LAI) is sufficient (3.0-3.5) to achieve near maximum light interception (LI), 95%, by R5 (Shibles and Weber, 1965; Weber et al., 1966).

Alternatively, yield can also be considered a function of four basic factors, commonly called 'yield components', which include seed mass, number of seeds pod$^{-1}$, number of pods plant$^{-1}$, and number of plants per given area.  Identifying which yield components contribute the most to yield and yield compensation under given crop management situations would help understand necessary management to achieve optimal yields.  Moreover, an increased understanding of how yield components and growth dynamic factors regulate soybean yield in response to plant population could improve cultivar development to optimize yield at low populations.  In addition, that could also provide producers with indicators of optimal populations (Carpenter and Board, 1997a).

In order to determine which yield components contribute the most to yield or yield recovery Carpenter and Board (1997a) conducted research in Louisiana on determinate growth soybeans in 1994 and 1995.  This research focused on soybean branch yield components and how soybeans controlled yield stability across three plant populations (70,000; 164,000; and 234,000 plants ha$^{-1}$).  They found that maximum yields were 4078 kg ha$^{-1}$ and were achieved at

164,000 plants ha⁻¹.  However, reducing that stand by 58% to 70,000 plants ha⁻¹ only resulted in

a 12% yield decrease.  On the other hand, increasing plant density by 43%, to 234,000 plant ha⁻¹,

resulted in no yield increase.  They found that yield stability in this experiment is explained by an

increase in seed yield per plant.  The seed yield increase per plant came from an increase in pod

production per branch.  The increase in branch pods resulted from an increase in branch DM per

plant, where branch DM accounted for 13.6; 13.1; and 9.6% of the TDM at the low, medium,

and high populations, respectively.   Furthermore, the increase in branch DM was positively

correlated with increased branch node number, and branch reproductive node number.

Greater branch DM per plant was explained by greater DM per plant which could be associated

with reduced interplant competition (Carpenter and Board, 1997a).  The higher plant densities

showed a reduction in total plant DM that resulted in decreased DM partitioning to branches,

and subsequently less branch nodes and reproductive nodes to produce seed yield.

Similarly, Board (1985) conducted research in Louisiana during 1981 and 1982 to

determine the yield components associated with soybean yield reductions at between optimal

(mid-May) and non-optimal (early-April and mid-June) planting dates.  He found that the yield

components associated with seed yield reductions at non-optimal planting dates differed with

early and late planting dates.  Yield reductions associated with early-April planting were mostly

accounted for by a reduction in branch nodes and the proportion of branch nodes that became

fertile.  However, yield reductions for the late (mid-June) planting date were attributed to fewer

branch numbers that resulted in fewer branch pods and seeds.  Regardless of early or late

planting seed yield reductions at non-optimal planting dates were associated with a reduction in

branch rather than main stem yield components (Board, 1985).

Carpenter and Board (1997b) compared growth dynamic factors that contribute to yield

stability versus yield component contributions to yield recovery.  From this research, they found

that yield stability came from equilibration of CGR and TDM production per square meter across populations by R1. This was achieved by greater light interception efficiency (LIE) and net assimilation rate (NAR) in the lower populations as they were twice that of the highest population during vegetative growth. Maintenance of CGR and TDM partitioning was critical in yield compensation, and most equilibration occurred during the vegetative period (Carpenter and Board, 1997b).

Moreover, Board (2000) conducted similar research in Louisiana during the 1995 and 1996 growing seasons. This research focused on how LIE affected yield compensation at various plant densities (80,000; 145,000; and 390,000 plants ha$^{-1}$). At 14 DAE CGR per plant was similar across populations, indicating that little to no interplant competition occurred during the first two weeks of growth. At 21 DAE crop growth rate compensation began in low versus higher plant populations. Plant density had no effect on seed yield, and similar yields were achieved by an equilibration of CGR across populations by R1 and TDM equilibration by R5. Equilibration of CGR was a result of greater NAR by plants in lower densities that was created by greater LIE during the vegetative period. Equilibration of DM was accomplished by an increase in relative leaf area expansion rate (RLAER) that was a result of dry matter partitioning to branches. The increase in branch production resulted in an increase in pods per branch. These results indicate that growth dynamic factors early in the vegetative period are essential for yield compensation between low and high populations. In order for lower populations to express the ability to recover yield, producers must avoid stresses that prevent lower populations to reach CGR comparable with higher populations (Board, 2000).

The response of soybean yield components in relation to management system and planting date was investigated by Pedersen and Lauer (2004a) at two locations in Wisconsin (Arlington Agricultural Research Station, Hancock Agricultural Research Station) from 1997 to

2000.  Their experiment included three soybean cultivars, two tillage systems (conventional, no-tillage), with and without irrigation, and early- and late-May planting dates.  The experiment was seeded at 432,000 seed ha$^{-1}$, and plants were hand harvested at 21, 42, 63, 84, 105, and 126 DAE.  The yield components measured were: harvest index, seed number per square meter, pod number per square meter, seeds per pod, and seed mass.  Similar yield component development was observed for each management system before 84 DAE or the beginning of pod set, and up to 105 DAE for all treatments with the exception of planting date.  In the end management system did have an effect on yield component production.  Management systems produced seed mass ranging from 10.5 to 16.5 g 100 seed$^{-1}$, seed number from 2878 to 3824 seeds m$^{-2}$, pod number from 1182 to 1571 pods m$^{-2}$, and seeds per pod from 2.36 to 2.49 seeds per pod (Pedersen and Lauer, 2004).  Furthermore, planting date had an effect on soybean yield components with the early planting date (early-May) having greater overall yield (7%), seed number (11%), pod number (14%), and harvest index (1%) than the late-May planting date.  The late-May planting date increased seed per pod by 2.5% and seed mass was not significant.  Tillage systems differed at Arlington as no-till systems out yielded conventional systems by 7%.  No-till systems also had greater seed mass (16%), while conventional tillage systems had greater seed number (12%) and pod number (12%).  Between tillage systems, seed per pod and harvest index were not significant.  Irrigation had no effect on yield or any of the other yield components, except a 1% yield increase in seed per pod by irrigating.  Yield components and their development differed by cultivar, but the ability of compensation was more affected by year than by management system or planting date (Pedersen and Lauer, 2004).

The impact of whole plant removal on soybean seed yield was investigated by Conley et al. (2008) from 2003 to 2005 at one location in Indiana and one location in Nebraska.  In Indiana, soybeans were seeded at 390,000 seeds ha$^{-1}$ in 38-cm rows and in Nebraska they were seeded

at 381,000 seeds ha^{-1} in 80-cm rows.  At both locations, stands were reduced by 0; 25; 50; and

75%, at V3, V6, R1, and R3.5.  Base seed yields were lower in Indiana at 4000 kg ha^{-1}, when

compared with seed yields of 4500 kg ha^{-1} achieved in Nebraska.  Seed yields decreased as

stands were reduced at both locations.  The rate of yield loss differed by location, timing of plant

removal, and percentage of stand reduction.   In general, yield loss increased as plant

development and the percentage of plants removed increased.  According to their results, yield

losses ranged from 2-33%, among 50 and 75% stand removal treatments, when plants were

removed at V3 and V6, respectively (Conley et al., 2008).  When plants were removed at R1 and

R3.5, yield reductions were more severe ranging from 3% to 60% among the same stand

removal treatments.  Yield was not reduced when 25% stand loss occurred at V3, V6, or R1.

Seed mass was only affected by plant removal at R3.5 at the Indiana site where seed mass

increased as the percentage of plants removed increased.  At 75% plant removal seed mass

increased 14.2% (Conley et al., 2008).  Although seed mass increased as plants were removed, it

was not enough to compensate to full yield potential as yield loss levels reached 60%.  In

addition, Conley et al. (2008) suggests that yield loss may occur when plant stands are reduced

as early as V3, however, plants can recover yield losses at or before R1, if there is a final plant

population of 247,500 plants ha^{-1} or more (Conley et al., 2008).

In summary, the ability of soybean plants to compensate yield is associated with many

factors including vegetative growth and yield component adjustments, or a combination of

both.  The increase in individual plant performance related to vegetative adjustments is due to

an increase in LIE and NAR in the lower populations that resulted in CGR equilibration by R1

(Board, 2000; Carpenter and Board, 1997a) and by equilibration of TDM production before seed

fill initiation (R5).  The seed yield increase came from an increase in TDM that allowed more DM

to be partitioned to branches thereby increasing the number of pods branch[-1] (Board, 1985;

Carpenter and Board, 1997b). Early planting can reduce the proportion of branch nodes that became fertile, while late planting can reduce branch node number (Board, 1985). Early planting was also found to increase seed yield, while late planting increased seed mass (Pedersen and Lauer, 2004a). Tillage systems also have an effect on yield component production such that conventional tillage increases seed and pod numbers while no-till systems have higher seed mass (Pedersen and Lauer, 2004a). The combination of the factors affecting soybean seed yield production emphasizes the complexity of individual soybean plant compensation and seed yield recovery, however, according to Conley et al. (2008) plants can recover yield loss at or before R1 if there is a at least a final plant population of 247,500 plants ha$^{-1}$.

**Research Justification**

Soybean plants have the ability to regulate growth and yield production by individual plants in response to their surrounding environment.  Research previously reported provides evidence that the spatial distribution of soybean plants within a crop community can influence soybean performance.  This has been reported based on the collective response of "whole-plant" soybean communities where gross-level factors such as maximizing light interception before reproductive growth and minimizing inter-specific and interplant competition are critical components for determining an appropriate plant distribution to maximize overall yield. However, very little research has been reported that has attempted to explain soybean plant response within a community.  As soybean plant densities increase, variability of plant size also increases, however few research studies characterize this variability.  As soybean plant densities increase, plant variability increases due to competition, and in ultra-high seeding rates, competition can be elevated to the point of plant mortality.  The responses to high densities include plants growing taller, lodging more, branching less, and ultimately producing less pods and seeds per plant.  Alternatively, as soybean plant densities decrease, soybean plants compensate for open space by producing more branches, and in theory, more pods and seeds per plant.  However, limited research has investigated how much variability in plant size exists in different seeding density environments, how different sized plant cohorts (small versus large) respond to interplant competition, or the effect of plant removal to stimulate compensatory plant growth and yield among soybean communities.  There is also a lack of information regarding if small "non-productive" plants can compensate yield similar to large, presumably "more-productive" cohorts following plant removal.  The main objectives of this research were to determine the effect of seeding density on plant size variability, the ability of individual plants to recover yield following neighboring plant removal, and determine whether small cohorts can

compensate growth and yield at similar levels to that of large cohorts.  My hypothesis is that plant growth and yield variability will increase as soybean densities increase and as interplant competition relief is delayed, and that both small and large cohorts will increase individual plant growth and yield following competition relief, however, small cohorts will not recover as well as large cohorts.  I expect that the results of this study will provide useful and currently lacking information on the effects of plant size variability and the differences in the ability of small and large cohorts to increase plant growth and yield following an event in which stands are reduced.

**Materials and Methods**

<u>Field Sites</u>

Three field research trials, two in 2009 and one in 2010, were conducted at the University of Illinois Crop Sciences Research and Education Center in Urbana, Illinois (40:5:36.0204N,88:13:46.1454W).  In 2009, both studies were established in Drummer silty clay loam (Fine-silty, mixed, superactive, mesic Typic Endoaquoll) soil in different fields. These trials were also established 12 days apart, and thus were treated as independent experimental environments.  In 2010, the study was on a Flanagan silty loam (Fine, smectitic, mesic Aquic Argiudolls).  All three trials were grown following a corn crop, in fields that had been in a long-term corn-soybean rotation.  Prior to planting each year, the seedbed was prepared by deep ripping in the fall corn residue, followed by one pass with a field cultivator in the spring.  Trials were planted with a four-row cone planter with 76-cm row spacing (Almaco, Nevada, Iowa). Planting dates, harvest dates, monthly rainfall, heat unit accumulation, and solar radiation accumulation for all three trials can be found in Table 1.  Soil types, fertility, pH, and soybean cyst nematode egg counts are presented in Table 2.

Preemergence and postemergence herbicides were used to control weeds throughout the growing season in all trials to eliminate inter-species competition.  Prior to planting in 2009, cloransulam –methyl, alachlor, and glyphosate were applied preemergence at 0.0097 kg a.i. ha$^{-1}$, 0.37 kg a.i. ha$^{-1}$, and 0.87 kg a.e. ha$^{-1}$, respectively.  To control later emerging weeds, the same rate of glyphosate was also applied postemergence at the V3 soybean growth stage in each trial. In 2010, early season weeds were controlled with sulfentrazone and imazethapyr applied preemergence at 0.35 kg a.i. ha$^{-1}$ and 0.07 kg a.i. ha$^{-1}$, respectively, followed by 0.87 kg a.e. ha$^{-1}$ glyphosate postemergence at V4.  In addition to herbicidal control, plots were kept weed     free     by     hand     for     the     remainder     of     the     growing     season.

Table 1. Harvest dates, and accumulated Julian Days, precipitation, heat units, and solar radiation from planting date to date of harvest for the three field trials located in Urbana, Illinois 2009 and 2010.

| Planting Date | Thinning/Harvest Growth Stage | | | | |
|---|---|---|---|---|---|
| | V3 | V6 | R2 | R4 | R8 |
| | Harvest Date | | | | |
| 5/19/2009 (A) | 6/24/2009 | 7/1/2009 | 7/13/2009 | 8/14/2009 | 10/14/2009 |
| 6/1/2009 (B) | 7/5/2009 | 7/20/2009 | 7/31/2009 | 8/27/2009 | 11/2/2009 |
| 5/10/2009 | 6/10/2010 | 6/23/2010 | 7/7/2010 | 7/20/2010 | 9/22/2010 |
| | Days After Planting | | | | |
| 5/19/2009 (A) | 37 | 44 | 56 | 88 | 149 |
| 6/1/2009 (B) | 35 | 50 | 61 | 88 | 155 |
| 5/10/2009 | 32 | 45 | 59 | 72 | 136 |
| | Accumulated Precipitation (mm) | | | | |
| 5/19/2009 (A) | 128 | 130 | 232 | 301 | 547 |
| 6/1/2009 (B) | 145 | 231 | 264 | 375 | 626 |
| 5/10/2009 | 118 | 255 | 258 | 316 | 456 |
| | Accumulated Heat Units (MGDD) | | | | |
| 5/19/2009 (A) | 767 | 929 | 1186 | 1869 | 2768 |
| 6/1/2009 (B) | 760 | 1078 | 1312 | 1902 | 2630 |
| 5/10/2009 | 593 | 937 | 1275 | 1623 | 3260 |
| | Accumulated Solar Radiation (MJ m$^{-2}$) | | | | |
| 5/19/2009 (A) | 512 | 690 | 920 | 1646 | 2910 |
| 6/1/2009 (B) | 757 | 1082 | 1347 | 1899 | 2764 |
| 5/10/2009 | 655 | 955 | 1369 | 1641 | 3020 |

Table 2. Soil types, phosphorus levels, potassium levels, pH, and soybean cyst nematode egg counts for trial locations in Urbana, IL 2009 and 2010.

| | Location | | |
| --- | --- | --- | --- |
| | Urbana 2009 (A) | Urbana 2009 (B) | Urbana 2010 |
| Soil type | Drummer silty clay loam | Drummer silty clay loam | Flanagan silt loam |
| Subgroup | Typic Endoaquoll | Typic Endoaquoll | Aquic Argiudolls |
| Organic Matter (%) | 4.1 | 3.0 | 4.0 |
| Phosphorus (ppm) | 68 | 36 | 110 |
| Potassium (ppm) | 258 | 153 | 278 |
| Soil pH | 6.5 | 6.5 | 6.8 |
| Soybean Cyst Nematode egg counts (100 cc of soil)$^{-1}$ | 720 | 3920 | 1280 |

## Experimental Design and Statistical Analysis

In each of the three TRIAL, the experimental design was a split plot where whole-plot treatments have a 2x4 factorial combination in a randomized complete block design with four replications. The main plot factors examined were glyphosate-resistant CULTIVAR (AG3803 and AG3205) (Monsanto Company, St. Louis, Missouri) and SEEDING DENSITY (15, 30, 45, and 60 seeds m$^{-2}$). Main plots were 6.5 m long by 6 m wide and consisted of 8 soybean rows spaced 76-cm apart (Table 3). The sub-plot treatments have a 2x4 factorial combination of plant COHORT size (large, small) and THINNING TIME (V3, V6, R2, R4) (Fehr and Caviness, 1977). Large and small cohorts were visually selected to represent the variability of plant sizes as they pertained to the established cultivar and seeding density at the time of plant growth stage treatments examined. To evaluate the effect of interplant competition, all the studied variables are expressed as the difference between measurements from plant stands thinned to a population of 5.3 plants m$^{-2}$ (competition removed, (-)) and plants that remained in the initial plant densities (according to seeding density treatments (+)) all season.

The linear model used for the statistical analysis of the dependent variables was

$$y_{ijklmn} = \mu + a_i + b_{(i)j} + d_k + a_i d_k + \phi_l + a_i \phi_l + d_k \phi_l + a_i d_k \phi_l + Error(1) +$$

$$\lambda_m + a_i \lambda_m + d_k \lambda_m + a_i d_k \lambda_m + \phi_l \lambda_m + a_i \phi_l \lambda_m + d_k \phi_l \lambda_m + a_i d_k \phi_l \lambda_m +$$

$$\theta_n + a_i \theta_n + d_k \theta_n + a_i d_k \theta_n + \lambda_m \theta_n + a_i \lambda_m \theta_n + d_k \lambda_m \theta_n + a_i d_k \theta_n \lambda_m + \phi_l \theta_n +$$

$$a_i \phi_l \theta_n + d_k \phi_l \theta_n + a_i d_k \phi_l \theta_n + \phi_l \lambda_m \theta_n + a_i \phi_l \lambda_m \theta_n + d_k \phi_l \lambda_m \theta_n + a_i d_k \phi_l \theta_n \lambda_m + Error(2)$$

where,

$y_{ijklmn}$ = observation for the $i^{th}$ TRIAL within the $j^{th}$ BLOCK in the $k^{th}$ CULTIVAR with the $l^{th}$ SEEDING DENSITY within the $m^{th}$ COHORT at the $n^{th}$ THINNING TIME.

$\mu$= overall mean.

$a_i$= random effect due to the $i^{th}$ level of factor TRIAL (i= 1, 2, 3).

$b_{j(i)}$ = random effect due to the $j^{th}$ of factor BLOCK (m=1, 2, 3, 4), (0, $\sigma_b^2$).

$d_k$= random effect due to the $k^{th}$ level of factor CULTIVAR (j= 1, 2).

$\phi_l$= fixed effect due to the $l^{th}$ level of factor SEEDING DENSITY (k= 1, 2, 3, 4).

$a_i d_k$= random interaction effect due to the $i^{th}$ level of factor TRIAL and the $k^{th}$ level of factor CULTIVAR.

$a_i \phi_l$= random interaction effect due to the $i^{th}$ level of factor TRIAL and $l^{th}$ level of factor SEEDING DENSITY.

$d_k \phi_l$= random interaction effect due to the $k^{th}$ level of factor CULTIVAR and $l^{th}$ level of factor SEEDING DENSITY.

$a_i d_k \phi_l$= random interaction effect due to the $i^{th}$ level of factor TRIAL and the $k^{th}$ level of factor CULTIVAR in $l^{th}$ level of factor SEEDING DENSITY.

Error (1) = whole-plot error effect assumed identically and independently distributed (i.i.d.) N (0, $\sigma_{e1}^2$).

$\lambda_m$= fixed effect due to the $m^{th}$ level of factor COHORT (m= 1, 2).

$\theta_n$= fixed effect due to the $n^{th}$ level of factor THINNING TIME (n= 1, 2, 3, 4).

$a_i \lambda_m$= random interaction due to the $i^{th}$ level of factor TRIAL and the $m^{th}$ level of factor COHORT.

$d_k \lambda_m$= random interaction due to the $k^{th}$ level of factor CULTIVAR and $m^{th}$ level of factor COHORT.

$\phi_l \lambda_m$= fixed interaction due to the $l^{th}$ level of factor SEEDING DENSITY and $m^{th}$ level of factor COHORT.

$a_i \theta_n$= random interaction due to the $i^{th}$ level of factor Trial and $n^{th}$ level of factor THINNING TIME.

$d_k \theta_n$= random interaction due to the $k^{th}$ level of factor CULTIVAR and $n^{th}$ level of factor THINNING TIME.

$\phi_l \theta_n$= fixed interaction due to the $l^{th}$ level of factor SEEDING DENSITY and $n^{th}$ level of factor THINNING TIME.

$\lambda_m \theta_n$= fixed interaction due to the $m^{th}$ level of factor COHORT and $n^{th}$ level of factor THINNING TIME.

$a_i \phi_l \lambda_m$= random interaction effect due to the $i^{th}$ level of factor TRIAL and $l^{th}$ level of factor SEEDING DENSITY and the $m^{th}$ level of factor COHORT.

$a_i \phi_l \theta_n$= random interaction effect due to the $i^{th}$ level of factor TRIAL and $l^{th}$ level of factor SEEDING DENSITY and $n^{th}$ level of factor THINNING TIME.

$a_i d_k \lambda_m$= random interaction due to the $i^{th}$ level of factor TRIAL and $k^{th}$ level of factor CULTIVAR and the $m^{th}$ level of factor COHORT.

$d_k \phi_l \lambda_m$= random interaction effect due to the $k^{th}$ level of factor CULTIVAR and $l^{th}$ level of factor SEEDING DENSITY and the $m^{th}$ level of factor COHORT.

$a_i d_k \theta_n$= random interaction due to the $i^{th}$ level of factor TRIAL and $k^{th}$ level of factor CULTIVAR and the $n^{th}$ level of factor THINNING TIME.

$a_i \lambda_m \theta_n$= random interaction due to the $i^{th}$ level of factor TRIAL and the $m^{th}$ level of factor COHORT and the $n^{th}$ level of factor THINNING TIME.

$d_k \lambda_m \theta_n$= random interaction due to the $k^{th}$ level of factor CULTIVAR and $m^{th}$ level of factor COHORT and the $n^{th}$ level of factor THINNING TIME.

$d_k \phi_l \theta_n$= random interaction effect due to the $k^{th}$ level of factor CULTIVAR and $l^{th}$ level of factor SEEDING DENSITY and the $n^{th}$ level of factor THINNING TIME.

$\phi_l\lambda_m\theta_n$= fixed interaction due to the $l^{th}$ level of factor SEEDING DENSITY and $m^{th}$ level of factor COHORT and the $n^{th}$ level of factor THINNING TIME.

$a_id_k\phi_l\lambda_m$= random interaction effect due to the $i^{th}$ level of factor TRIAL and the $k^{th}$ level of factor CULTIVAR in $l^{th}$ level of factor SEEDING DENSITY and the $m^{th}$ level of factor COHORT.

$a_id_k\lambda_m\theta_n$= random interaction due to the $i^{th}$ level of factor TRIAL and $k^{th}$ level of factor CULTIVAR and the $m^{th}$ level of factor COHORT and the $n^{th}$ level of factor THINNING TIME.

$a_id_k\phi_l\theta_n$= random interaction effect due to the $i^{th}$ level of factor TRIAL and the $k^{th}$ level of factor CULTIVAR in $l^{th}$ level of factor SEEDING DENSITY and the $n^{th}$ level of factor THINNING TIME.

$a_i\phi_l\lambda_m\theta_n$= random interaction effect due to the $i^{th}$ level of factor TRIAL and $l^{th}$ level of factor SEEDING DENSITY and the $m^{th}$ level of factor COHORT and the $n^{th}$ level of factor THINNING TIME.

$d_k\phi_l\lambda_m\theta_n$= random interaction effect due to the $k^{th}$ level of factor CULTIVAR and $l^{th}$ level of factor SEEDING DENSITY and the $m^{th}$ level of factor COHORT and the $n^{th}$ level of factor THINNING TIME.

$a_id_k\phi_l\lambda_m\theta_n$= random interaction effect due to the $i^{th}$ level of factor TRIAL and the $k^{th}$ level of factor CULTIVAR in $l^{th}$ level of factor SEEDING DENSITY and the $m^{th}$ level of factor COHORT and the $n^{th}$ level of factor THINNING TIME.

Error (2) = is the sub-plot error effect or residual, assumed i.i.d. N (0, $\sigma_{e2}^2$).

Errors 1, and 2 are assumed to be independent of one another.

These models were analyzed using the MIXED procedure of SAS (SAS Institute Inc., 2009). When covariance parameter estimates appear to be negative or zero, we used the -2Log Likelihood test to compare successive reduced forms of the original models (Littell et al., 2002). Mean separation procedure was accomplished by using the macro *%pdmix800* (SAS Institute Inc., 2009).

The matching SAS coding was as follows,

```
Proc mixed data=thesis method=type3;
class trial cultivar seeddensity thintime cohort block;
model variable = seeddensity|thintime|cohort;
random trial var block(trial)
/* 2way interaction terms*/
trial*cultivar trial*seeddensity trial*thintime cultivar*seeddensity cultivar*thintime trial*cohort
cultivar*cohort
/* 3way interaction terms*/
trial*cultivar*seeddensity trial*cultivar*thintime trial*cultivar*cohort trial*seeddensity*thintime
cultivar*seeddensity*thintime trial*seeddensity*cohort cultivar*seeddensity*cohort
trial*thintime*cohort
cultivar*thintime*cohort cultivar*seeddensity*block(trial)
/* 4way interaction terms*/
trial*seeddensity*cultivar*thintime  trial*seeddensity*cultivar*cohort trial*cultivar*thintime*cohort
trial*seeddensity*thintime*cohort cultivar*seeddensity*thintime*cohort
/* 5way interaction term*/
trial*seeddensity*cultivar*thintime*cohort;
run;
```

Table 3. Each trial had 32 main plots that were 6.5 m x 6 m (8 rows). Main plot treatments were cultivar (AG3803 and AG3205) and seeding density (15, 30, 45, and 60 plants $m^{-2}$), and were replicated four times.

| variety X seeding density | | |
|---|---|---|
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |

| Treatment # | Variety | Seeding Density (plants $m^{-2}$) |
|---|---|---|
| 1 | AG3205 | 15 |
| 2 | AG3803 | 15 |
| 3 | AG3205 | 30 |
| 4 | AG3803 | 30 |
| 5 | AG3205 | 45 |
| 6 | AG3803 | 45 |
| 7 | AG3205 | 60 |
| 8 | AG3803 | 60 |

| Rep |
|---|
| 1 |
| 2 |
| 3 |
| 4 |

**Soybean Sampling and Analysis**

To provide evidence of interplant competition, for each cohort and thinning time, all studied variables were obtained as the difference between measurements taken from plant stands thinned to a population of 5.3 plants $m^{-2}$ (competition removed, (-)) and plants that remained in the initial plant densities (according to seeding density treatments (+)) all season. Figure 1a, b, and c help visualize how we managed the plots to assess interplant competition.

Each of the main plots including one of the combinations of cultivar and seeding density levels were 8 soybean rows wide with walk alleys (76 cm wide) at both ends. The first, fourth, fifth, and eighth rows served as border rows between subplots. The eight subplots including one of the combinations of cohort and thinning time levels were established in the remaining four rows comprising and area of 1.5 m long by 1.5 m wide and started 1 m away from the walk alley on each end of the main plots. Plant cohort size treatments were established in singular, adjacent rows within subplots. The remaining area (1.5 m long by 1.5 m wide) in the center of the main plots served as the reference areas where large and small cohort plants remained with (+) interplant competition.

Non-destructive growth parameters and yield data related to plant cohorts were gathered from twelve plants (6 large and 6 small) that remained in subplots after cohort competition was relieved, and six plants (3 large and 3 small) that continued growth in competition (+) following each respective timing. Large and small plants that remained in the competition subplots beyond the respective thinning timings, were numbered by placing an aluminum tag (GEMPLER'S®) around the base of the main stem. Non-destructive measurements included; plant heights taken to the tip of the apical meristem to the nearest half centimeter, the number of branch nodes including the node with the most recently opened trifoliate, and the widths of that trifoliates leaflets measured to the nearest half centimeter. Except for 12

Figure 1a.  Each main plot consists of 1 cultivar (AG3205, AG3803) and one seeding density (15, 30, 45, or 60 plants m$^{-2}$).  Sub-plot factors include plant cohort size (small, large), and plant growth stage of thinning time (V3, V6, R2, or R4) (Fehr and Caviness, 1977).  At each thinning time, 6 small and 6 large evenly spaced plants were selected to remain, while interplant competition was relieved (-).  The yellow, orange, blue, and gray regions are designated as areas where relief took place at a respective thin time.  In addition, at the same time, 3 similar small and large cohorts were selected to remain in the competition level (+) of the initial seeding density.  These regions are designated as the green area shown.
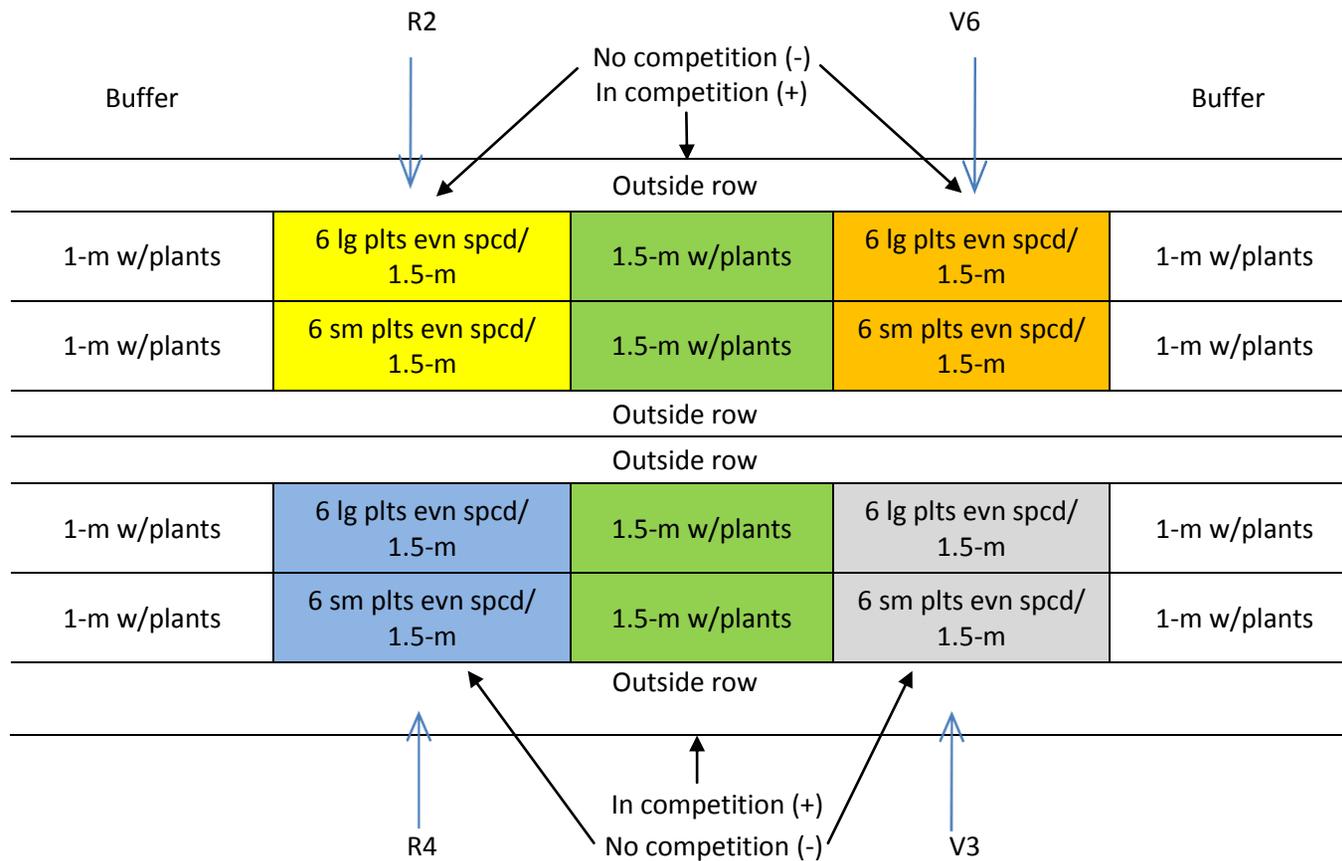
Figure 1b. A main plot prior to any treatment.  The yellow, orange, blue and gray regions represent thinning times (rows 2,3,6,7), where competition will be relieved (-).  Rows adjacent to those, are border rows (white)(rows 1,4,5,8), and will be thinned in addition to the colored regions at a respective thin time to prevent any border effect. The center green region (rows 2,3,6,7) represents an area where plants were left in competition (+),  these cohorts will be tagged for identity.  The regions adjacent to these will not be thinned.  The black dots represent different sized cohorts in each region.

Figure 1c. A main plot after competition has been relieved and cohorts have been tagged.  The yellow, orange, blue, and gray regions (rows 2,3,6,7) have been thinned to six evenly spaced plants and the adjacent (white) regions (rows 1,4,5,8) have been thinned to prevent a border effect. The green region (no removal) has similar sized cohorts selected to remain in level of competition of the initial seeding density and have been tagged (green dots).  There were three tagged cohorts for that were compared to six untagged cohorts in neighbor plots.  Therefore, three of the tagged cohorts in row 2, where representatives of cohorts in the yellow region, while the other 3 tagged cohorts represented the orange region.

| Row # | | | | Row # |
|---|---|---|---|---|
| 1 | | | | 1 |
| 2 | | | | 2 |
| 3 | | | | 3 |
| 4 | | | | 4 |
| 5 | | | | 5 |
| 6 | | | | 6 |
| 7 | | | | 7 |
| 8 | | | | 8 |

evenly spaced plants that remained growing after competition removal (-), all other plants were removed from the subplots by hand clipping primary plant stems at the soil surface.  Those plants were counted and used to calculate established plant stands.

Plant heights to the uppermost pod were recorded in the field, and then all plants were harvested at R8.  Plants were harvested by hand clipping primary plant stems at the soil surface and dried in a forced-air dryer for 72 hr at 60°C to get all plant and seed material to equal moisture content.  Dry weights of the whole plant were recorded to the nearest $1\ 1000^{-1}$ of a gram.  Plant stem diameters were measured with a digital caliper in mm, and the total number of productive pods $plant^{-1}$ were counted.  Whole plants were threshed in a single plant belt thresher (Almaco, Nevada, Iowa).  The seed was collected and cleaned with sieves to remove pods, stem debris, and dirt.  Total seed weight was taken to the nearest $1\ 1000^{-1}$ of a gram. Seed samples were further cleaned with sieves to remove split seeds and weights of whole seeds were recorded.  Whole seeds were counted with a computerized seed counter (Agriculex, Guelph, Ontario, Canada) to calculate mass $seed^{-1}$.

**Results and Discussion**

Environmental conditions varied among the 2009 and 2010 growing seasons at the University of Illinois Crop Science Research and Education Center in Urbana, Illinois. The most notable difference was July and August rainfall in 2009 which was 37 and 39 mm above the twenty year average (Table 4). Comparatively, July and August rainfall in 2010 was 28 and 58 mm, respectively, below the twenty year average. Temperatures, versus rainfall, were more similar between the 2009 and 2010 growing seasons. July and August temperatures were 2.4 and 1.5° C, respectively, cooler than the twenty year averages in 2009, and 1.5 and 2.2° C, respectively, warmer than the twenty year averages in 2010 (Table 4). Although 2009 brought higher than normal July and August rainfall and cooler than normal temperatures, soybean yields were similar to the twenty year averages at 3094 kg ha$^{-1}$ (USDA NASS, 2011). Environmental conditions in 2010 were also favorable for normal soybean growth and development and the highest average yields to date were reported for the state of Illinois at 3463 kg ha$^{-1}$ (USDA NASS, 2011).

**<u>Plant Height</u>**

A higher order interaction between cohort size, seeding density, and thinning time effect was considered significant ($p < 0.00$) for the differences of plant heights between plants with and without interplant competition (Table 5). The average plant heights ranged from 80.5 to 84.5 cm across all planting densities when competition was not relieved (Table 6). However, at the R4 thinning time, large cohorts were 3.6, 10.5, 17.0, and 25.0 cm taller than small cohorts in the 15, 30, 45, and 60 plants m$^{-2}$ densities, respectively (Table 6). Therefore, as planting density and plant development increased, the variability that contributed to the average plant height increased.

Table 4. Monthly precipitation and average temperatures, from May to September, for 2009 and 2010, and the twenty year averages for Champaign, Illinois (ICN, 2011).

| Month | Year | | |
|---|---|---|---|
| | 2009 | 2010 | 20 yr ave. |
| | ————Precipitation (mm)———— | | |
| May | 129 | 78 | 127 |
| June | 108 | 198 | 99 |
| July | 155 | 90 | 118 |
| August | 137 | 39 | 98 |
| September | 15 | 76 | 75 |
| | ————Temperature (°C)———— | | |
| May | 17.3 | 18.3 | 17.1 |
| June | 22.8 | 23.8 | 22.3 |
| July | 21.3 | 25.2 | 23.7 |
| August | 21.4 | 25.1 | 22.9 |
| September | 19.2 | 19.7 | 19.1 |

Table 5. Analysis of variance results for data collected on, two soybean cultivars, plant growth and yield components by cohort, seeding density, and thinning time fixed effects and their interactions for the three trials conducted at Urbana, IL.   Cultivar and trial were considered random effects

| | Height | Dry weight | Seed weight | Pod number | Seed mass | Harvest index |
|---|---|---|---|---|---|---|
| | cm | ————g plant$^{-1}$———— | | no. plant$^{-1}$ | mg seed$^{-1}$ | % |
| **Effect** | | | | | | |
| Cohort (C) | NS | NS | NS | NS | NS | NS |
| Seed density (S) | NS | * | * | * | NS | NS |
| Thin time (T) | NS | ** | ** | * | * | NS |
| C x S | NS | ** | ** | ** | NS | NS |
| C x T | * | ** | * | ** | NS | NS |
| S x T | ** | ** | ** | ** | NS | ** |
| C x S x T | ** | NS | NS | p = 0.0569 | NS | p = 0.0931 |

*Significant at p = 0.05
**Significant at p = 0.01
†NS = not significant at p = 0.05.

Table 6.  Average values of soybean heights (cm) at R8.  Cohorts that remained in the competition level of the initial seeding density (+), include both small and large plants combined (N = 288).  Large and small cohorts with interplant competition relieved (-) are presented separately (N = 144).

| Cohort Size | Competition level | Seeding Density | NR | V3 | V6 | R2 | R4 |
|---|---|---|---|---|---|---|---|
| | ———(+/-)——— | —Plants m$^{-2}$— | | | —Height (cm)— | | |
| | | 15 | | | | | |
| Both | + | | 82.5 | | | | |
| Large | - | | | 81.0 | 81.0 | 80.0 | 83.5 |
| Small | - | | | 76.5 | 74.5 | 75.5 | 80.0 |
| | | 30 | | | | | |
| Both | + | | 84.5 | | | | |
| Large | - | | | 81.5 | 79.0 | 78.5 | 87.5 |
| Small | - | | | 77.5 | 70.5 | 67.0 | 77.0 |
| | | 45 | | | | | |
| Both | + | | 84.0 | | | | |
| Large | - | | | 83.0 | 78.5 | 77.5 | 88.0 |
| Small | - | | | 75.0 | 66.0 | 62.5 | 71.0 |
| | | 60 | | | | | |
| Both | + | | 80.5 | | | | |
| Large | - | | | 81.0 | 76.5 | 76.5 | 86.5 |
| Small | - | | | 71.5 | 60.0 | 55.5 | 61.5 |

Soybean growth stage at thinning time

Table 7.  Difference of plant height, at R8, between plants with competition relieved and plants that remained in competition.  These data were collected at four levels of seeding density (15, 30, 45, and 60 plants m$^{-2}$), and at four levels of thinning time (V3, V6, R2, and R4).

| Cohort | Seeding Density | Thinning time | | | |
|---|---|---|---|---|---|
| | | V3 | V6 | R2 | R4 |
| | ——Plants m$^{-2}$—— | ——————————Δ Height (cm)————————— | | | |
| Small | | | | | |
| | 15 | -2.8bA | -4.7abA | -5.5aA | -2.0aA |
| | 30 | -4.4bA | -4.0aA | -15.8bcB | -3.2abA |
| | 45 | -3.4bA | -10.0bAB | -11.7abB | -9.2bAB |
| | 60 | 6.4aA | -4.7abB | -18.5cC | -15.4cC |
| Large | | | | | |
| | 15 | -2.9aA | -4.3aA | -3.7aA | -1.4aA |
| | 30 | -4.6abB | -9.2abB | -9.4abB | -1.6aA |
| | 45 | -8.4abA | -12.1bB | -12.4bB | -4.5aA |
| | 60 | -9.1bAB | -13.3bB | -13.2bB | -5.8aA |

[a] Differences within columns with the same lowercase letters and differences within rows with the same uppercase letters are not statistically different according to the LSD  test at α = 0.05.

When interplant competition was relieved, plant heights were nearly always reduced ranging from -1.4 to -18.5 cm (Table 7). The only exception was small cohorts that were relieved of interplant competition in the highest density at V3. They were 6.4 cm taller than cohorts left in competition (Table 7). While plant height was nearly always reduced between levels of competition, the magnitude of differences were influenced by increasing plant development and increasing plant density. At 15 plants m$^{-2}$, differences in heights were similar ranging from -1.4 to -5.5 cm regardless of thinning time and cohort size. However, at 60 plants m$^{-2}$, differences in small cohort plant heights ranged from a positive 6.4 cm at V3 to -18.5 cm at R2 with no further difference by R4. Conversely, differences in heights between levels of competition of large cohorts were more moderate ranging from -5.8 to -13.3 cm at 60 plants m$^{-2}$. Moreover, the trend was different for large cohorts where smaller, but similar, differences were observed at V3 (-9.1 cm) and R4 (-5.8 cm). Height differences at R4 were smaller than at V6 (13.3 cm) and R2 (13.2 cm) (Table 7). Additionally, differences in plant heights for small cohorts were influenced more by increased plant densities at the later thinning times. Small plants removed from competition at R4 were 2 cm shorter than plants not relieved of competition in the 15 plants m$^{-2}$ seeding density, and the difference increased to 15.4 cm shorter at 60 plants m$^{-2}$. Conversely, differences in heights among large cohorts were not influenced by plant density at the R4 thinning time (Table 7).

According to these results, competition relief prior to and including R4 reduced plant height even at the lowest density, and earliest thinning time (Table 7). These results support previous findings that an increase in plants per unit area will increase plant height (Board, 2000; De Bruin and Pedersen, 2008; Green-Tracewicz et al., 2011). In addition, based on the observation of stem elongation, it appears competition for light began as early as V3, in seeding densities as low as 15 plants m$^{-2}$. These results are similar to those found by Conley et al.

(2008), where they found that plant removal from V3 to R3.5, reduced plant height linearly, and also Egli (1988) who found competition between soybean plants could be observed with as few as 1.5 plants m$^{-2}$. Although differences in plant height were noticed, the magnitude of change, for both large and small cohorts, between competition levels at all thinning times was not different at the lowest seeding density (Table 7). This indicates that the level of interplant competition for both small and large cohorts, at a density of 15 plants m$^{-2}$, remains uniform throughout the growing season. However, while the overall magnitude of differences was the same for large and small cohorts at the lowest density, the effect of increasing density and delaying thinning times was different between cohorts. Over all seeding densities, large cohorts were subject to greater height differential between levels of competition when relieved at V6 and R2 versus V3 or R4. This response was likely due to lower levels of competition at V3, and a reduced amount of time for differences to occur after R4. Conversely, small cohorts were subject to height differences when competition was relieved during reproductive growth at higher initial seeding densities.

**Dry Weight**

Lower order interactions between seeding density and thinning time, seeding density and cohort size, and thinning time and cohort size effects were considered significant (p < 0.00) for the differences of plant dry weights between plants with and without interplant competition (Table 5). Accumulated soybean dry weights expressed as tonnes ha$^{-1}$ for all seeding densities and thinning times are presented in Table 8. The highest recorded dry weight was 9.1 tonnes ha$^{-1}$ at 60 plant m$^{-2}$ when interplant competition was not relieved (Table 8). At reduced initial seeding densities of 45, 30, and 15 plants m$^{-2}$, total dry matter production was reduced by 10, 11, and 14%, respectively. This demonstrated that at the whole field level, plant densities

Table 8. Average soybean dry weights (tones ha$^{-1}$) at R8. Cohorts that remained in the competition level of the initial seeding density (+), include both small and large plants combined (N = 288). Cohorts with interplant competition relieved (-) are presented separately (N = 144).

| Cohort Size | Competition level | Seeding Density | Soybean growth stage at thinning time | | | | |
|---|---|---|---|---|---|---|---|
| | | | NR | V3 | V6 | R2 | R4 |
| | ———(+/-)——— | ——Plants m$^{-2}$—— | ———Dry weight (tonnes ha$^{-1}$)——— | | | | |
| | | 15 | | | | | |
| Both | + | | 7.87 | | | | |
| Large | - | | | 5.78 | 5.49 | 5.12 | 4.44 |
| Small | - | | | 4.72 | 4.06 | 3.72 | 3.33 |
| | | 30 | | | | | |
| Both | + | | 8.11 | | | | |
| Large | - | | | 5.05 | 4.57 | 3.78 | 3.01 |
| Small | - | | | 3.89 | 2.75 | 2.08 | 1.57 |
| | | 45 | | | | | |
| Both | + | | 8.22 | | | | |
| Large | - | | | 4.85 | 3.88 | 3.04 | 2.12 |
| Small | - | | | 3.05 | 2.01 | 1.39 | 0.92 |
| | | 60 | | | | | |
| Both | + | | 9.11 | | | | |
| Large | - | | | 4.53 | 3.53 | 2.65 | 1.74 |
| Small | - | | | 2.62 | 1.70 | 0.97 | 0.65 |

Table 9. Differences in dry weights plant[-1], at R8, between plants with competition relieved and plants that remained in competition at four levels of seeding density (15, 30, 45, and 60 plants m[-2]), and at four levels of thinning time (V3, V6, R2, and R4).

| Cohort Size | Seeding Density | Soybean growth stage at thinning time | | | |
|---|---|---|---|---|---|
| | | V3 | V6 | R2 | R4 |
| | ——Plants m[-2]—— | ——————————Δ Dry weight (g) plt[-1] —————————— | | | |
| Both | | | | | |
| | 15 | 41.75bA | 29.41cB | 23.97aB | 16.22aC |
| | 30 | 53.30aA | 40.64aB | 23.23aC | 11.45abD |
| | 45 | 53.65aA | 34.66bB | 20.67abC | 6.46bcD |
| | 60 | 50.95aA | 32.99bcB | 16.62bC | 5.67cD |
| Large | † | 55.90aA | 40.58aB | 28.89aC | 12.83aD |
| Small | † | 43.93bA | 28.27bB | 13.35bC | 7.07aC |

| Cohort Size | Soybean growth stage at thinning time | Seeding density (plants m[-2]) | | | |
|---|---|---|---|---|---|
| | | 15 | 30 | 45 | 60 |
| | | ——————————Δ Dry weight (g) plt[-1] —————————— | | | |
| Large | ‡ | 29.53aB | 37.21aA | 36.87aA | 34.57aA |
| Small | ‡ | 26.14aA | 27.10bA | 20.84bB | 18.54bB |

[a] Differences within columns with the same lowercase letters and differences within rows with the same uppercase letters are not statistically different according to the LSD test at α = 0.05.
† Denotes all seeding densities
‡ Denotes all soybean growth stages at competition relief

established with only 25% of the initial highest seeding density produced 86% as much total biomass as the highest initial seeding density.

Soybean plants grown in all densities were able to increase the most additional dry matter plant$^{-1}$ when competition was relieved at V3 (Table 9). As competition relief was delayed, plants in each density produced less amounts of additional dry matter over plants left in competition with the exception of the lowest seeding density which had similar dry matter at V6 and R2 (Figure A3). Therefore, plants grown in 15, 30, 45, and 60 plants m$^{-2}$ densities produced 150, 360, 730, and 800% more additional dry matter plant$^{-1}$ following competition relief at V3 versus R4, respectively. Furthermore, at V3, soybean dry weights in 30, 45, and 60 plants m$^{-2}$ seeding densities were not different from each other. However, cohorts in these densities increased dry matter plant$^{-1}$ by 11.6, 12, and 9.2 g plant$^{-1}$, respectively, or by at least 22% over the lowest seeding density. Conversely, when competition relief was delayed to the reproductive stages, cohorts in the two lower seeding densities increased additional dry weight plant$^{-1}$ over cohorts in the highest seeding density. Moreover, following the R4 thinning time, the two lowest seeding densities increased additional dry matter plant$^{-1}$ by > 100%, or 5 g, over cohorts grown in 60 plants m$^{-2}$ seeding density (Table 9).

Furthermore, over all seeding densities, large cohorts accumulated more dry weight plant$^{-1}$ versus small cohorts at V3, V6, and R2 by 27%, 44%, and 115%, respectively (Table 9) (Figure A5). However, when competition relief was delayed to R4, large and small cohorts accumulated similar amounts of additional dry matter plant$^{-1}$ over plants left in competition all season. Over all growth stages, large and small cohorts, accumulated more dry weight plant$^{-1}$ over plants in competition following competition relief at all thinning times (Table 9). However, large cohorts accumulated more additional dry weight plant$^{-1}$ than small cohorts by 37, 77, and 86 % in 30, 45, and 60 plants m$^{-2}$ seeding densities, respectively. In the lowest initial seeding

density, additional dry matter plant$^{-1}$ accumulation was not different for large and small cohorts (Table 9) (Figure A4).

Soybean plants accumulated additional whole plant dry matter when competition was relieved even as late as the R4 growth stage. However, it is apparent the greatest opportunity for soybean plants to accumulate the most additional biomass in relation to plants left in competition occurred at the earliest competition relief timing (V3) (Table 9). This indicates the plant's ability to compensate, or increase dry weight on a per plant basis, is reduced as plant development progresses through the growing season. These results are similar to previous research reports which have suggested this is likely due to a decrease in the number of days, or a limited amount of time, that plants have to recover at later relief timings (Board, 1985).

However, both large and small cohorts exist in most soybean environments, and this research shows the ability of these cohorts to accumulate additional biomass in response to seeding densities and growth stages are not always similar. The dry weights plant$^{-1}$ of large and small cohorts in this experiment are shown in Table 9. The most interesting contrast is that small cohorts did not increase dry weight plant$^{-1}$ differently at R2 than at R4. This suggests that small cohorts may lose the ability to recover dry weight earlier in the growing season than large cohorts. Different sized cohorts also responded differently due to changing seeding densities. Large cohorts increased more dry weight plant$^{-1}$ over plants in competition at higher densities, whereas small cohorts increased more dry weight plant$^{-1}$ over plants in competition at the lower densities. This was likely a result of increased plant stand uniformity at the lower densities which suppressed the large cohorts' ability to express compensation. Furthermore, a uniform plant stand may have resulted in more robust small cohorts allowing them to express compensation. The opposite would be true for the higher densities.

**Pod Number**

      The higher order interaction between cohort size, seeding density, and thinning time effects were considered significant ($p \leq 0.06$) for pod number plant$^{-1}$ differences between plants with and without interplant competition (Table 5).  The actual pod numbers extrapolated to pods m$^{-2}$ for all seeding densities and thinning times are presented in Table 10.  The highest recorded pod number m$^{-2}$ was 1609 pods at 60 plants m$^{-2}$ when interplant competition was not relieved (Table 10).  With lower seeding densities of 45, 30, and 15 plants m$^{-2}$, pod numbers were reduced by 4, 6, and 12%, respectively.  Conversely, the highest recorded pod number plant$^{-1}$ was 177, and was achieved by large cohorts that were relieved of competition at V3 in the lowest seeding density (Table 10).

      While pod number was always increased between levels of competition, the magnitude of differences were influenced by increasing plant development and increasing seeding density for both sized cohorts.  For small cohorts, at the earliest thinning time, the difference between the highest and lowest number of additional pods produced plant$^{-1}$ was 20%.  At R4 the difference had increased to 90%.  Large cohorts expressed similar differences, only smaller in magnitude, as the difference between the highest and lowest number of additional pods produced at V3 and R4 were 37 and 62%, respectively.  Furthermore, at the lowest initial seeding density, differences in pod number plant$^{-1}$ between competition levels were more similar as large and small cohorts produced 38 and 27% as many pods plant$^{-1}$, respectively, following competition relief at R4 versus V3.  Conversely, at 60 plants m$^{-2}$, large and small cohorts produced 9 and 3% as many pods plant$^{-1}$, respectively, following relief at R4 versus V3 (Table 11).

Table 10.  Average number of soybean pods (m$^{-2}$) at R8.  Cohorts that remained in the competition level of the initial seeding density (+), include both small and large plants combined (N = 288).  Cohorts with interplant competition relieved (-) are presented separately (N = 144).

| Cohort Size | Competition level | Seeding Density | NR | V3 | V6 | R2 | R4 |
|---|---|---|---|---|---|---|---|
| | (+/-) | Plants m$^{-2}$ | | | Pods m$^{-2}$ | | |
| | | 15 | | | | | |
| Both | + | | 1411 | | | | |
| Large | - | | | 940 | 895 | 822 | 692 |
| Small | - | | | 774 | 676 | 612 | 511 |
| | | 30 | | | | | |
| Both | + | | 1510 | | | | |
| Large | - | | | 840 | 763 | 612 | 448 |
| Small | - | | | 657 | 476 | 346 | 242 |
| | | 45 | | | | | |
| Both | + | | 1541 | | | | |
| Large | - | | | 812 | 656 | 482 | 308 |
| Small | - | | | 515 | 356 | 241 | 140 |
| | | 60 | | | | | |
| Both | + | | 1609 | | | | |
| Large | - | | | 748 | 604 | 414 | 247 |
| Small | - | | | 459 | 305 | 173 | 100 |

"Soybean growth stage at thinning time" spans columns NR, V3, V6, R2, R4.

Table 11.  Difference in pod number plant$^{-1}$, at R8, between plants with competition relieved and plants that remained in competition at four levels of seeding density (15, 30, 45, and 60 plants m$^{-2}$), and at four levels of thinning time (V3, V6, R2, and R4).

| Cohort | Seeding Density | Thinning time | | | |
|---|---|---|---|---|---|
| | | V3 | V6 | R2 | R4 |
| | —Plants m$^{-2}$— | ——————————Δ Pod no. plant$^{-1}$——————————— | | | |
| Small | | | | | |
| | 15 | 68bA | 51abB | 35aC | 19aD |
| | 30 | 85aA | 63aB | 23bC | 11abC |
| | 45 | 74abA | 47bB | 21bC | 2bD |
| | 60 | 72bA | 44bB | 15bC | 2bD |
| Large | | | | | |
| | 15 | 69cA | 52bB | 44abB | 26aC |
| | 30 | 96bA | 79aB | 52aC | 15abD |
| | 45 | 110aA | 75aB | 47abC | 12bD |
| | 60 | 104abA | 76aB | 39bC | 10bD |

[a] Differences within columns with the same lowercase letters and differences within rows with the same uppercase letters are not statistically different according to the LSD test at α = 0.05.

Increased pod production within a soybean plant community has been reported as a primary component of yield compensation, or yield stability, in soybeans (Board, 2000; Carpenter and Board, 1997a). The greatest opportunity for soybeans to produce additional pods plant$^{-1}$ following competition relief is during early vegetative growth (V3) (Table 11). Competition relief after V3 still increased pod number plant$^{-1}$; however, the magnitude of increase was reduced as relief was delayed. This was especially evident in higher densities, where large and small cohorts in 60 plants m$^{-2}$ density, at R4, only produced 9 and 3% of additional pods plant$^{-1}$, respectively, of similar cohorts when competition was relieved in early vegetative growth (Table 11). Soybean in higher densities increased pod number plant$^{-1}$ over cohorts in the lowest initial density following the V3 thinning time. Conversely, soybean in the lower densities produced more additional pods plant$^{-1}$, following competition relief, than higher densities when relief was delayed to reproductive growth. This is likely the result of increased plant stand uniformity at lower densities which allowed for more consistent pod increases as competition relief was delayed. At higher densities, soybean were subject to more interplant competition which suppressed the ability to compensate following relief later in the season.

**Seed Mass**

The main effect of thinning time was significant ($p \leq 0.04$) for the difference in seed mass between plants with and without interplant competition (Table 5). Actual seed mass data across all seeding densities and thinning times is presented in Table 12. The average seed mass ranged from 149.46 to 152.21 mg seed$^{-1}$ across all planting densities when competition was not relieved. Although seed mass was similar among all densities with no relief, an average of both sized cohorts following competition relief reveals seed mass was most affected at later thinning times, especially in higher densities (Table 12).

Table 12.  Average soybean seed mass (mg seed$^{-1}$) at R8.  Cohorts that remained in the competition level of the initial seeding density (+), include both small and large plants combined (N = 288).  Cohorts with interplant competition relieved (-) are presented separately (N = 144).

| Cohort Size | Competition level | Seeding Density | Soybean growth stage at thinning time | | | | |
|---|---|---|---|---|---|---|---|
| | | | NR | V3 | V6 | R2 | R4 |
| | ———(+/-)——— | –Plants m$^{-2}$– | ————Seed mass (mg seed$^{-1}$)———— | | | | |
| | | **15** | | | | | |
| Both | + | | 149.46 | | | | |
| Large | - | | | 147.85 | 146.77 | 151.20 | 159.61 |
| Small | - | | | 142.72 | 145.04 | 149.79 | 160.30 |
| | | **30** | | | | | |
| Both | + | | 151.01 | | | | |
| Large | - | | | 143.63 | 146.14 | 155.00 | 168.27 |
| Small | - | | | 142.27 | 139.55 | 146.16 | 163.20 |
| | | **45** | | | | | |
| Both | + | | 152.21 | | | | |
| Large | - | | | 144.59 | 143.59 | 156.51 | 173.58 |
| Small | - | | | 140.80 | 139.27 | 139.65 | 163.00 |
| | | **60** | | | | | |
| Both | + | | 151.09 | | | | |
| Large | - | | | 145.63 | 144.93 | 155.57 | 174.92 |
| Small | - | | | 139.35 | 136.43 | 136.83 | 152.69 |

Table 13.  Difference in seed mass (mg seed$^{-1}$), at R8, between plants with competition relieved and plants that remained in competition.  These data were collected at four levels of seeding density (15, 30, 45, and 60 plants m$^{-2}$), and at four levels of thinning time (V3, V6, R2, and R4).

| Cohort | Seeding Density | Thinning time | | | |
|---|---|---|---|---|---|
| | | V3 | V6 | R2 | R4 |
| | | ———————————— Δ Seed Mass (mg sd$^{-1}$)———————————— | | | |
| † | ‡ | -6.98b | -7.03b | -3.40b | 13.01a |

[a] Differences within rows with the same lowercase letters are not statistically different according to the LSD test at $\alpha = 0.05$.
† Denotes both cohort sizes
‡ Denotes all seeding densities

In this experiment, seed mass was uniform and differences between competition levels were insensitive to initial seeding densities or cohort size (Table 13). These findings support Board (2000) who also found seed mass was not affected by seeding density. Furthermore, competition relief during vegetative and early reproductive growth resulted in seed mass that was less than when plants remained in competition all season long (Table 13) (Figure A8). These values ranged from -7.03 to -3.4 mg seed$^{-1}$, and were not different from each other. The only detected difference in seed mass was following competition relief at R4, when seed mass was increased by 13.01 mg seed$^{-1}$ (9%) over cohorts that remained in competition. Similar results were found by Conley et al. (2008) when they found seed mass was increased by 14.2% when stands were reduced at R3.5. This response is likely due to the increase in space that results from competition relief. An increase in space would allow each plant more access to light and therefore more carbohydrate production per plant. R4 is likely too late in the growing season for substantial increases in pod number per plant or seed number per pod. However, individual soybean seeds are receptacles for assimilate and would provide the plant with an available sink as seed fill is not initiated until R5.

**Seed Yield**

Lower order interactions between seeding density and thinning time, seeding density and cohort size, and thinning time and cohort size effects were significant (p < 0.00) for differences in plant seed yield between plants with and without interplant competition (Table 5). Soybean seed yield extrapolated to kg ha$^{-1}$ for all seeding densities and relief timings are presented in Table 14. The highest observed seed yield was 4890 kg ha$^{-1}$ at 60 plants m$^{-2}$ when interplant competition was not relieved (Table 14). As seeding densities were reduced to 45, 30, and 15 plants m$^{-2}$ seed yields were only reduced by 9, 10, and 12%, respectively. Therefore, 25% of the plants were capable of producing 88% of the maximum yield. At the lowest seeding

Table 14. Average values of soybean seed yield (kg ha$^{-1}$) at R8. Cohorts that remained in the competition level of the initial seeding density (+), include both small and large plants combined (N = 288). Cohorts with interplant competition relieved (-) are presented separately (N = 144).

| Cohort Size | Competition level | Seeding Density | Soybean growth stage at thinning time | | | | |
|---|---|---|---|---|---|---|---|
| | | | NR | V3 | V6 | R2 | R4 |
| | ——(+/-)—— | –Plants m$^{-2}$– | ————Seed yield (kg ha$^{-1}$)———— | | | | |
| | | 15 | | | | | |
| Both | + | | 4301.9 | | | | |
| Large | - | | | 3106.2 | 2963.8 | 2798.7 | 2413.87 |
| Small | - | | | 2571.9 | 2223.9 | 2117.1 | 1846.2 |
| | | 30 | | | | | |
| Both | + | | 4420.7 | | | | |
| Large | - | | | 2705.19 | 2486.5 | 2080.3 | 1623.4 |
| Small | - | | | 2152.9 | 1539.9 | 1170.4 | 854.7 |
| | | 45 | | | | | |
| Both | + | | 4424.1 | | | | |
| Large | - | | | 2573.5 | 2055.4 | 1709.5 | 1128.7 |
| Small | - | | | 1685.5 | 1139.7 | 746.9 | 485.1 |
| | | 60 | | | | | |
| Both | + | | 4890.4 | | | | |
| Large | - | | | 2425.3 | 1926.4 | 1455.3 | 911.3 |
| Small | - | | | 1429.8 | 946.1 | 541.1 | 332.4 |

Table 15. Difference of seed weight plant[-1] between plants with competition relieved and plants that remained in competition at four levels of seeding density (15, 30, 45, and 60 plants m[-2]), and at four levels of thinning time (V3, V6, R2, and R4).

| Cohort Size | Seeding Density | Soybean growth stage at thinning time | | | |
|---|---|---|---|---|---|
| | | V3 | V6 | R2 | R4 |
| | ——Plants m[-2]—— | ——————————Δ Seed weight (g) plt[-1] ——————————— | | | |
| Both | | | | | |
| | 15 | 22.45bA | 15.89bB | 13.47aBC | 8.99aC |
| | 30 | 29.02aA | 22.50aB | 13.06aC | 6.08abD |
| | 45 | 29.03aA | 18.73bB | 11.74abC | 3.42bcD |
| | 60 | 27.75aA | 18.38bB | 9.24bC | 2.75cD |
| Large | † | 29.7aA | 21.85aB | 15.99aC | 6.70aD |
| Small | † | 24.41bA | 15.90bB | 7.77bC | 3.93aC |

| Cohort Size | Soybean growth stage at thinning time | Seeding rate (plants m[-2]) | | | |
|---|---|---|---|---|---|
| | | 15 | 30 | 45 | 60 |
| | | ——————————Δ Seed weight (g) plt[-1] ——————————— | | | |
| Large | ‡ | 15.64aB | 20.12aA | 19.61aA | 18.87aA |
| Small | ‡ | 14.76aA | 15.21bA | 11.85bB | 10.19bB |

[a] Differences within columns with the same lowercase letters and differences within rows with the same uppercase letters are not statistically different according to the LSD test at α = 0.05.
† Denotes all seeding densities
‡ Denotes all soybean growth stages at competition relief

density, and when competition was relieved at V3, the remaining 35% of the initial stand still produced 66% of the yield of the initial stand without competition relief and 58% of the yield of the experiments maximum yield. At the same seeding density, when competition was not relieved until R4, the remaining stand produced 50% of the yield of the initial stand. Comparatively, when soybean was seeded at 60 plants m$^{-2}$ and competition was relieved at V3 and R4, the remaining 9% of the initial stand produced 40 and 13% of the yield of the initial stand, respectively (Table 14).

Soybean plants grown in all densities were able to increase the most seed yield plant$^{-1}$ when competition was relieved at V3 (Table 15). As competition relief was delayed, plants in each density produced less amounts of seed yield over plants left in competition with the exception of the lowest seeding density which had similar seed yield at V6 and R2, and at R2 and R4 (Table 15) (Figure A9). This translates to soybean in the 15, 30, 45, and 60 plants m$^{-2}$ density produced 250, 480, 850, and 1000% more seed yield plant$^{-1}$ following competition relief at V3 versus R4. Furthermore, at V3, additional seed yield plant$^{-1}$ in 30, 45, and 60 plants m$^{-2}$ densities were not different from each other, but were 6.6, 6.6, and 5.3 g plant$^{-1}$, respectively, or more than 23%, greater than additional seed yield produced in the lowest density. Conversely, soybean in 15 and 30 plants m$^{-2}$ densities increased yield plant$^{-1}$ over cohorts in the highest seeding density by 4.2 (45%) and 3.8 (41%) g plant$^{-1}$, respectively, at R2, and by 6.2(227%) and 3.3 (120%) g plant$^{-1}$, respectively, at R4 (Table 15).

Large cohorts increased more seed yield plant$^{-1}$ versus small cohorts at V3, V6, and R2 by 22, 37, and 105%, respectively (Table 15) (Figure A11). However, when competition relief was delayed to R4, large and small cohorts produced similar amounts of additional seed yield plant$^{-1}$ over plants left in competition. Both large and small cohorts produced more seed yield plant$^{-1}$ after competition relief than plants left in competition (Table 15). However, large

cohorts produced more additional seed yield plant$^{-1}$ than small cohorts by 32, 65, and 85% in each of the three higher seeding densities. In the lowest initial seeding density large and small cohorts were not different (Table 15) (Figure A10).

Regardless of seeding density, soybean plants were able to increase seed yield plant$^{-1}$ when interplant competition was relieved even as late as R4. Although, it is apparent the greatest opportunity for soybean to increase seed yield after competition relief occurred at the earliest thinning time (V3) (Table 15). This indicates that soybean plant's ability to compensate seed yield on a per plant basis is reduced as plant development progresses through the growing season. These results support previous reports by others (Conley et al., 2008; Hintz and Fehr, 1990; Pickle and Caviness, 1984). Moreover, these seed yield compensation results are similar to the results reported above regarding the additional assimilation in dry weight plant$^{-1}$, and again is likely the result of a decrease in the number of days, or a limited amount of time, that plants have to recover at later thinning times (Board, 1985). Furthermore, soybean at higher densities received a larger benefit from relief during vegetative growth, where soybean in the lower densities increased seed yield per plant after competition relief more when delayed to reproductive growth. Perhaps, this again supports the idea there is a benefit for increased plant stand uniformity at lower densities (Elmore, 1998), which in this research allowed for more consistent yield increases as competition relief was delayed. At higher seeding densities, the variability in soybean plant sizes suggests there were higher levels of interplant competition, which suppressed the ability of plants to compensate after later competition relief timings.

This research shows that the ability of large and small cohorts to increase seed yield per plant in response to seeding densities and competition relief are not always similar. The most interesting contrast is that small cohorts did not increase seed yield plant$^{-1}$ differently at R2 than R4. This suggests that small cohorts may lose the ability to recover seed yield earlier in the

growing season than large cohorts. According to these results, large and small cohorts responded differently to changing seeding densities. Large cohorts increased more seed yield plant$^{-1}$ over plants in competition at higher densities, whereas small cohorts increased more seed yield plant$^{-1}$ over plants in competition at lower densities. This is likely a result of increased plant stand uniformity at the lower densities which suppressed the large cohorts' ability to express compensation. Furthermore, a uniform plant stand may have resulted in more robust small cohorts allowing them to express compensation. The opposite would be true for soybean in higher densities.

**Harvest Index**

The higher order interaction between cohort size, seeding density, and thinning time effect was considered significant (p ≤ 0.09) for harvest index (HI) differences between plants with and without interplant competition (Table 5). Harvest Index is a measure of crop yield in that it expresses the weight of the harvested product as a percentage of the whole plant weight of the crop. In this experiment, the average HI remained relatively constant; as HI only ranged from 52 to 55% across all planting densities when competition was not relieved (Table 16). These results agree with Board (2000) and Green-Tracewicz (2011) who also found HI non responsive to plant density, and also with Spaeth et al. (1984) who found HI to be stable even after periods of stress throughout plant development.

Differences in HI for large cohorts ranged from a negative 1.25% to a positive 3.04% across all seeding densities and thinning times and no statistical differences were found (Table 17). Conversely, statistical differences were found in HI for small cohorts as seeding densities increased and thinning times were delayed. At 15 plants m$^{-2}$, HI ranged from 0.68 to 3.22% among all thinning times and were not different. However, at 60 plants m$^{-2}$, and as soybean

Table 16. Average soybean harvest index (%) at R8.  Cohorts that remained in the competition level of the initial seeding density (+), include both small and large plants combined (N = 288).  Cohorts with interplant competition relieved (-) are presented separately (N = 144).

| Cohort Size | Competition level | Seeding Density | Soybean growth stage at thinning time | | | | |
|---|---|---|---|---|---|---|---|
| | | | NR | V3 | V6 | R2 | R4 |
| | ——(+/-)—— | ——Plants m$^{-2}$—— | ————Harvest Index (%)———— | | | | |
| | | 15 | | | | | |
| Both | + | | 55 | | | | |
| Large | - | | | 54 | 55 | 55 | 55 |
| Small | - | | | 55 | 56 | 57 | 56 |
| | | 30 | | | | | |
| Both | + | | 54 | | | | |
| Large | - | | | 54 | 56 | 56 | 55 |
| Small | - | | | 56 | 58 | 56 | 53 |
| | | 45 | | | | | |
| Both | + | | 53 | | | | |
| Large | - | | | 55 | 54 | 57 | 54 |
| Small | - | | | 56 | 56 | 53 | 49 |
| | | 60 | | | | | |
| Both | + | | 52 | | | | |
| Large | - | | | 55 | 56 | 56 | 52 |
| Small | - | | | 55 | 55 | 53 | 41 |

Table 17.  Difference in harvest index (%) between plants with competition relieved and plants that remained in competition.  These data were collected at four levels of seeding density (15, 30, 45, and 60 plants m$^{-2}$), and at four levels of competition relief time (V3, V6, R2, and R4).

| Cohort | Seeding Density | V3 | V6 | R2 | R4 |
|---|---|---|---|---|---|
| | | | Thinning time | | |
| | —Plants m$^{-2}$— | | —————Δ Harvest Index (%)————— | | |
| Small | | | | | |
| | 15 | 0.68bA | 3.22aA | 2.08aA | 0.90aA |
| | 30 | 2.63bAB | 5.61aA | 1.22aAB | -1.40aB |
| | 45 | 3.10abA | 3.32aA | 3.2aA | -2.42aA |
| | 60 | 7.80aA | 3.74aAB | 0.39aB | -10.00bC |
| Large | | | | | |
| | 60 | -1.25aA | -0.02aA | 0.02aA | 0.46aA |
| | 120 | -0.10aA | 1.54aA | 1.09aA | 0.56aA |
| | 180 | 1.12aA | -1.07aA | 0.82aA | -0.55aA |
| | 240 | 1.38aA | 3.04aA | 1.34aA | -0.79aA |

[a] Differences within columns with the same lowercase letters and differences within rows with the same uppercase letters are not statistically different according to the LSD test at α = 0.05.

progressed from V3 to R4, HI ranged from a positive 7.8% to a negative 10%, respectively (Table 17). Therefore, at V3, small cohorts that were seeded at 60 plants m$^{-2}$ increased HI over soybean in the lowest density by 7.12 percentage points. At V6 and R2 there were no differences in small cohort's ability to increase HI regardless of seeding density. However, at R4, soybean in the lowest initial seeding density were the only cohorts able to increase HI, while, soybean HI in the 30 and 45 plants m$^{-2}$ densities were not different. The greatest difference at R4 was between soybean in the 15 and 60 plants m$^{-2}$ densities, where soybean in the lowest density increased HI by 0.90%, while cohorts in the higher density decreased HI by 10% following competition relief (Table 17).

**Summary and Conclusion**

These data demonstrate interplant competition can begin early in the growing season and the effects of interplant competition increases as plant development increases. Although the increase following competition relief was not always significant, different sized cohorts responded differently to competition in various density environments and multiple stages of growth. The literature reviewed indicates that competition within a crop community can begin as early as V1 (Knezevic et al., 2003), and based solely on height, Conley et al. (2008) found that competition between soybean plants can begin by V3. In addition, Egli (1988) found interplant competition can begin in densities as low as 1.5 plants $m^{-2}$, while Duncan (1986) suggests that appreciable competition between cohorts begins at 2 plant $m^{-2}$. The decrease in plant height following competition relief, the increase in dry weight, seed yield, and pod number plant$^{-1}$, all at V3 suggests that competition between plants, in our experiment, began during early vegetative growth, especially in higher densities.

Plant height was nearly always reduced following competition relief for both sized cohorts, in all seeding densities, and at each thinning time. Large cohorts were more affected by relief at V6 and R2, while small cohorts showed more differentiation when relief occurred during reproductive growth and at higher seeding densities. Results for dry weight and seed yield plant$^{-1}$ differences, of large and small cohorts, were similar to each other as small cohorts did not increase either component differently by relief at R2 than at R4, which is opposed to large cohorts. Also, large cohorts increased additional dry weight and seed yield plant$^{-1}$ following competition relief more at higher densities, whereas small cohorts seemed to benefit more at lower densities. Pod number plant$^{-1}$, for both sized cohorts and at higher densities, was increased more during vegetative growth. Conversely, at lower densities, cohorts increased more additional pods per plant following competition relief during reproductive growth. Seed

mass was found to be insensitive to seeding density and cohort size. However competition relief lowered seed mass at all thinning times, except at R4 where seed mass was increased by 13.01 mg seed$^{-1}$. The difference in HI between cohorts relieved of competition and cohorts that remained in competition was similar regardless of planting density and thinning time for large cohorts. However, competition relief for small cohorts did alter HI, and the largest difference was in the highest seeding density where cohorts relieved of competition at V3 increased HI by 7.8% versus competition relief at R4 where HI was reduced by 10%.

The results of this research provides a better understanding of plant-to-plant relationships, and how different sized cohorts respond to changes in competition in different seeding environments at different developmental growth stages. These results also provide evidence that plants of different sizes mostly respond similarly to interplant competition; however, regarding the magnitude of change, and time in which cohorts could change, were different. Therefore, to some degree, this shows even the smallest cohorts contributes to overall yield in normal density environments, and furthermore, until the crop reaches full bloom they provide a potential for producing compensatory yield in cases where adverse events cause a stand loss. If soybeans were seeded at densities where competition does not exist (1.5-2 plants m$^{-2}$ (Duncan, 1986; Egli, 1988)) the whole crop community would likely not reach full yield potential because the community would rely entirely on an optimum environment that rarely exists. However, as interplant competition intensifies, so does plant size variability. My results showed that differences in plant sizes were smaller early in development, and increased as crop development progressed and as interplant competition for above and below ground resources intensified. However, it is not likely that any one soybean community will include only large or small cohorts. As I hypothesized, large cohorts performed better than small cohorts in higher densities, and recovered at higher levels when competition was relieved later in the season,

whereas small cohorts lost the ability to recover earlier in the reproductive developmental stages of growth. What were considered small cohorts had value in lower densities; however, at higher densities one could conclude that their intrinsic value was less due to their lack of additional growth following competition relief. Nonetheless, they produced some seed yield at nearly equivalent HI ratios suggesting their seed yield to dry matter assimilatory efforts were nearly as efficient. My results indicate that maximizing plant stand uniformity, to optimize interplant competition, should be a goal of soybean producers in an effort to maximize profits but interplant competition should not be eliminated.

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**Appendix**

**Plant Height**

Table A1. Type 3 tests of fixed effects for differences in plant height.

| Effect | Type 3 Tests of Fixed Effects | | | |
|---|---|---|---|---|
| | —Num DF— | —Den DF— | —F Value— | —Pr > F— |
| S | 3 | 6 | 8.82 | 0.0128 |
| T | 3 | 3 | 7.32 | 0.0681 |
| S*T | 9 | 701 | 4.34 | <.0001 |
| C | 1 | 8 | 0.13 | 0.7282 |
| S*C | 3 | 701 | 0.91 | 0.4339 |
| T*C | 3 | 8 | 4.52 | 0.0391 |
| S*T*C | 9 | 701 | 3.60 | 0.0002 |

[a] S = seeding density
[b] T = thinning timing
[c] C = cohort size
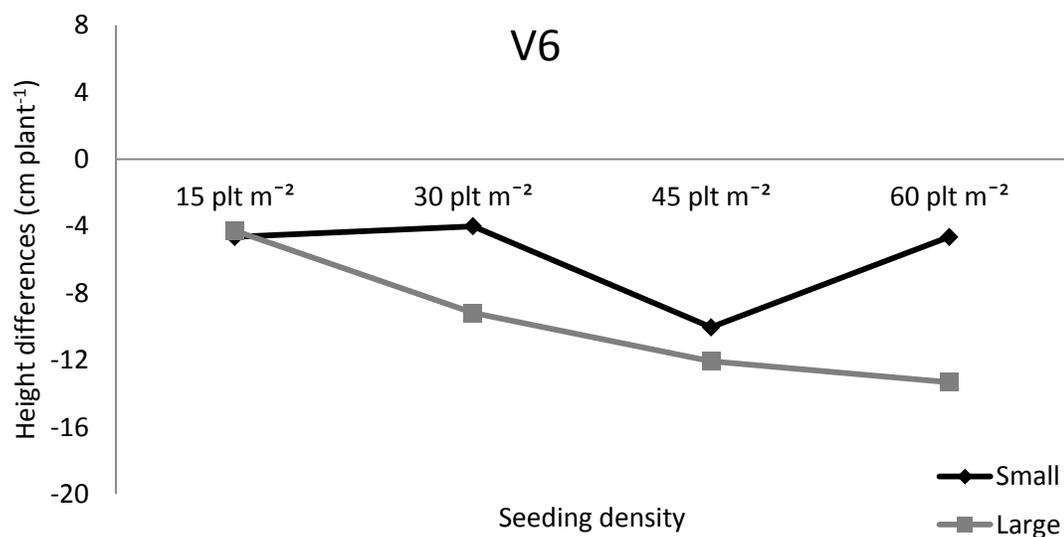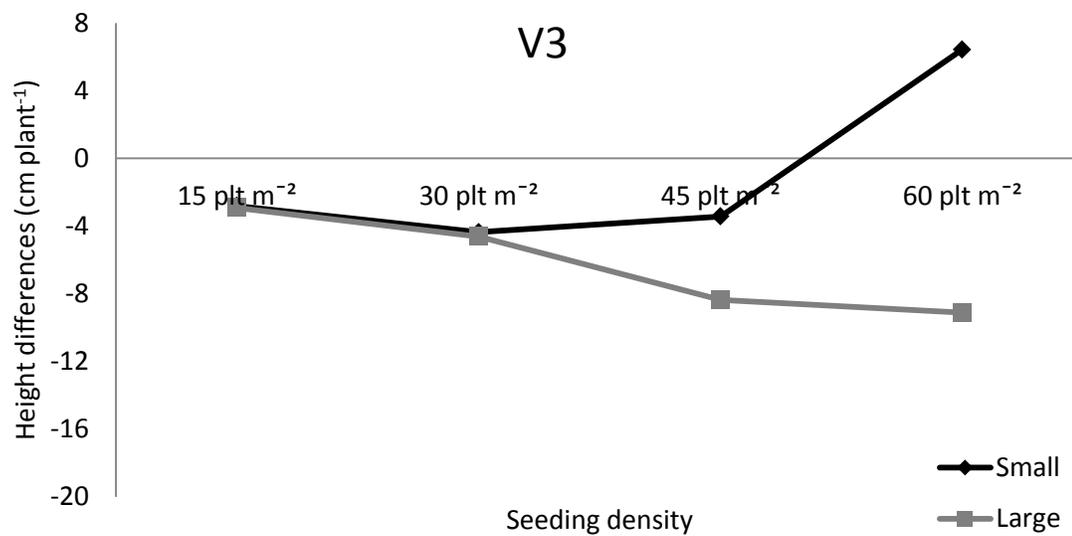
Figure A1. Differences in soybean plant height of large and small cohorts with interplant competition relieved (-) to a density of 5.3 plants m$^{-2}$, at V3 and V6, and cohorts that remained with the level of interplant competition of the initial seeding density (+) (15, 30, 45, and 60 plants m$^{-2}$) all season.
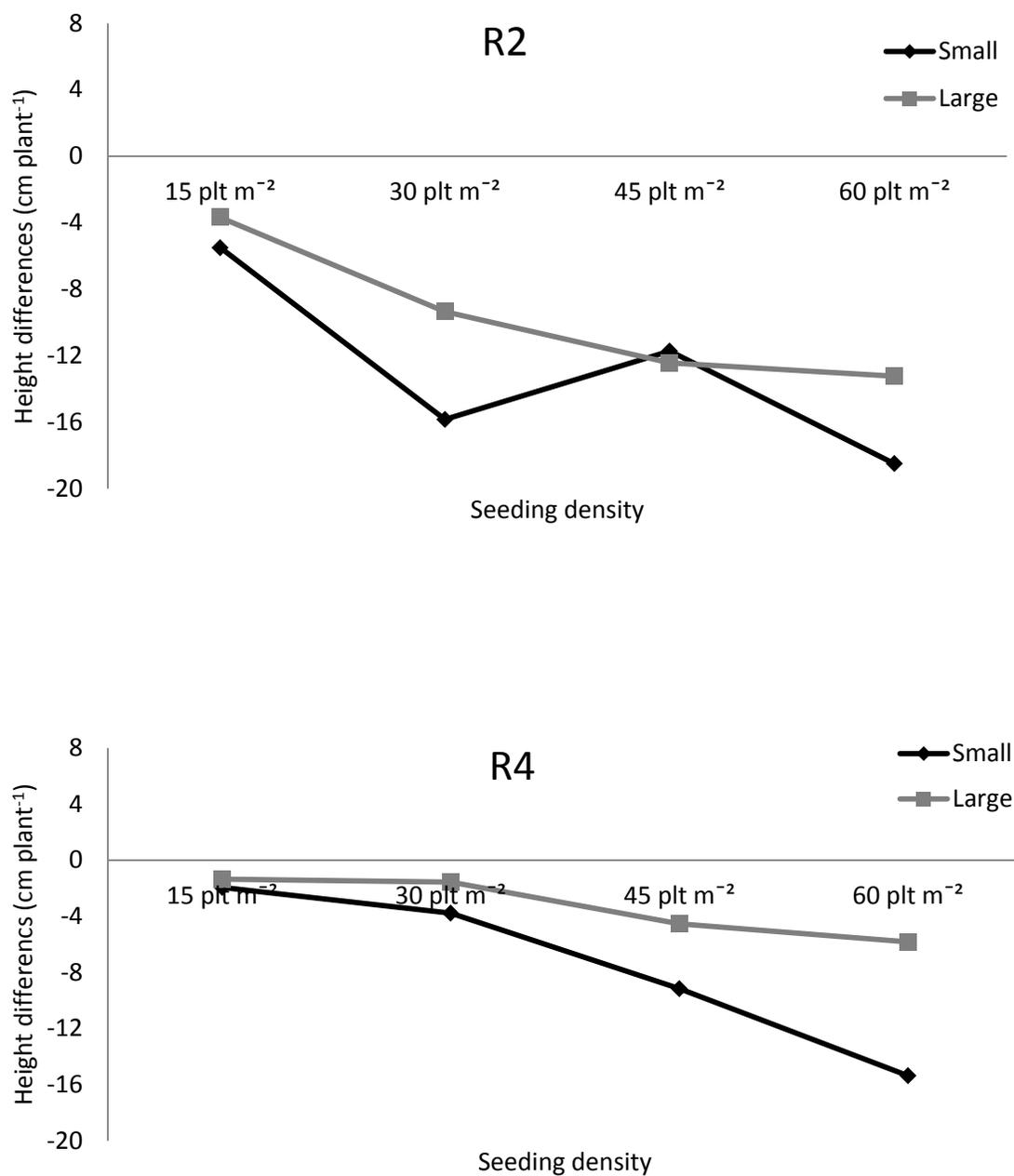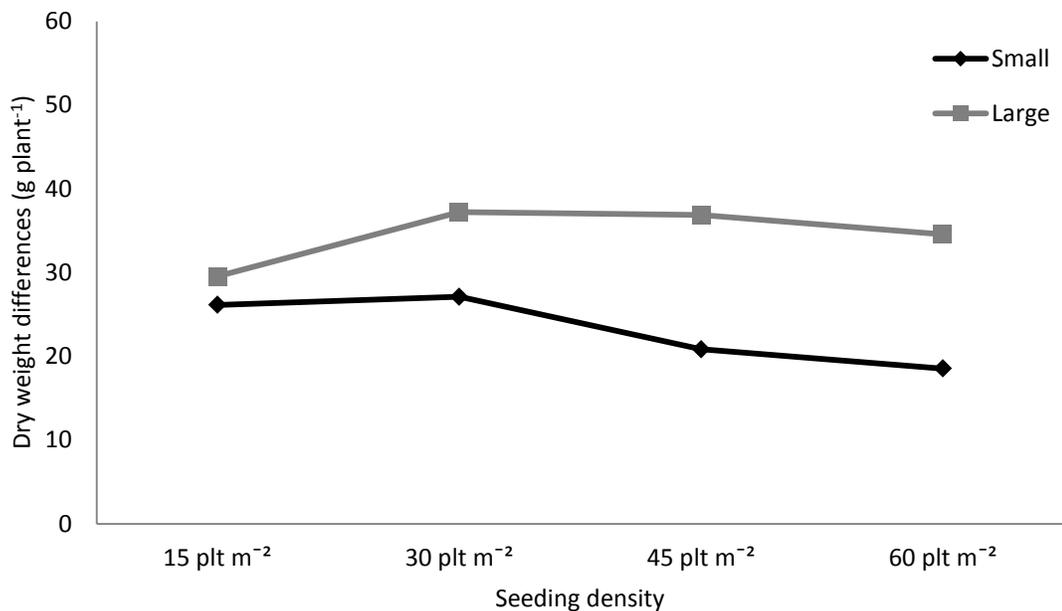
Figure A2. Differences in soybean plant height of large and small cohorts with interplant competition relieved (-) to a density of 5.3 plants m$^{-2}$, at R2 and R4, and cohorts that remained with the level of interplant competition of the initial seeding density (+) (15, 30, 45, and 60 plants m$^{-2}$) all season.
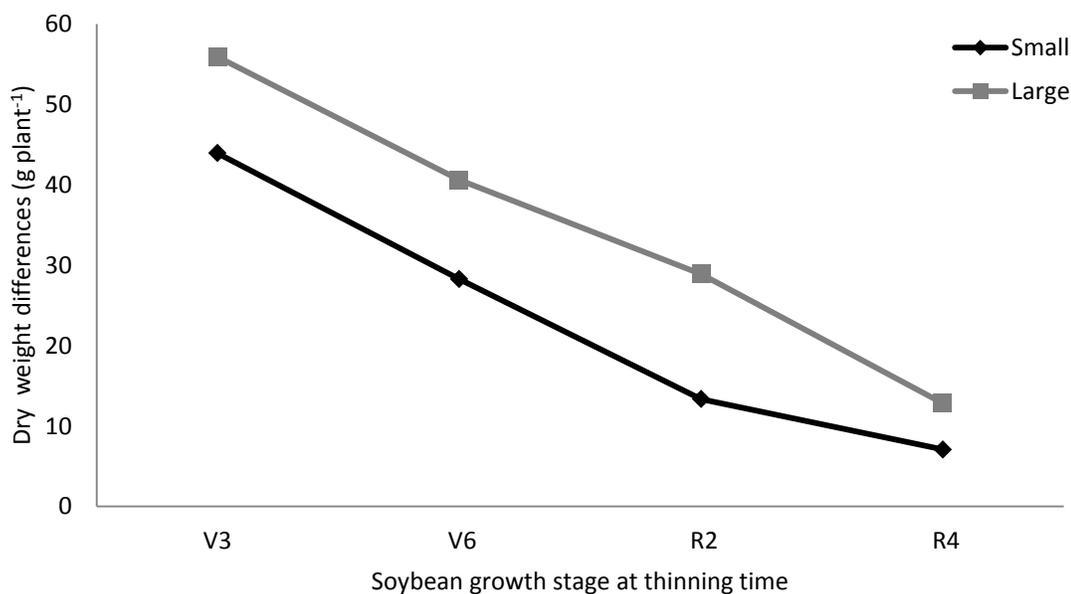
**<u>Dry Weight Plant<sup>-1</sup></u>**

Table A2. Type 3 tests of fixed effects for differences in dry weight plant$^{-1}$.

| Effect | Type 3 Tests of Fixed Effects | | | |
|---|---|---|---|---|
| | Num DF | Den DF | F Value | Pr > F |
| S | 3 | 6 | 5.38 | 0.0389 |
| T | 3 | 3 | 60.01 | 0.0035 |
| S*T | 9 | 707 | 6.62 | <.0001 |
| C | 1 | 2 | 6.4 | 0.1272 |
| S*C | 3 | 707 | 11.06 | <.0001 |
| T*C | 3 | 707 | 5.08 | 0.0017 |
| S*T*C | 9 | 707 | 1.15 | 0.3224 |

[a] S = seeding density
[b] T = thinning timing
[c] C = cohort size
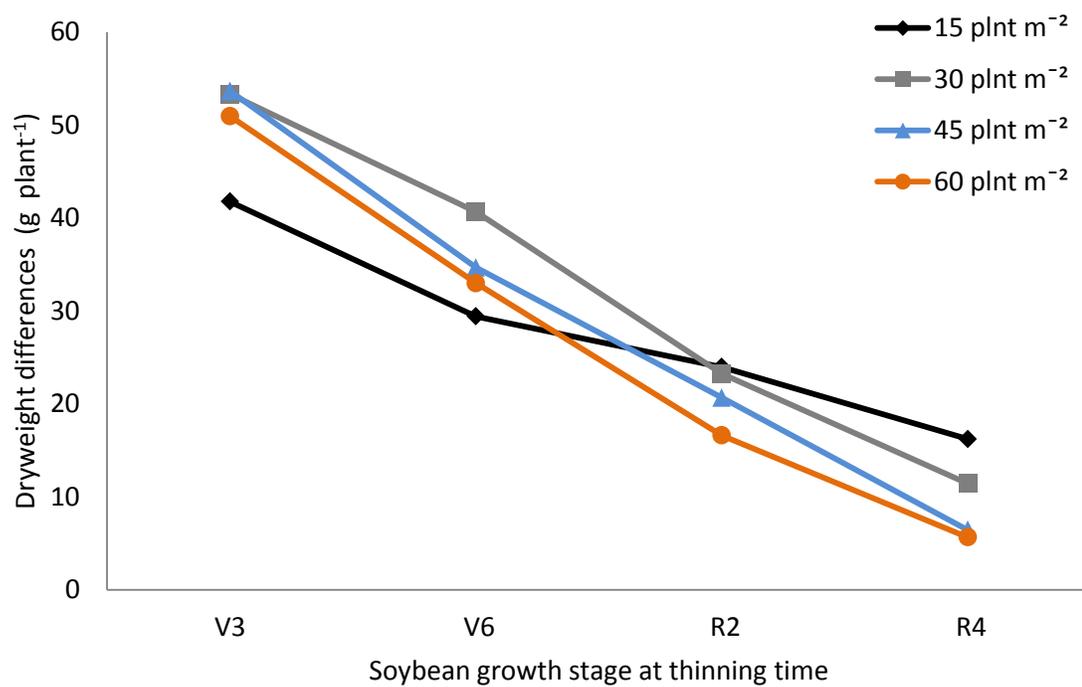
Figure A3. Differences in dry weight (g) plant[-1] between cohorts with interplant competition relieved (-) to a density of 5.3 plants m[-2] at V3, V6, R2, or R4 and cohorts that remained with the level of interplant competition of the initial seeding density (+) (15, 30, 45, and 60 plants m[-2]) all season.
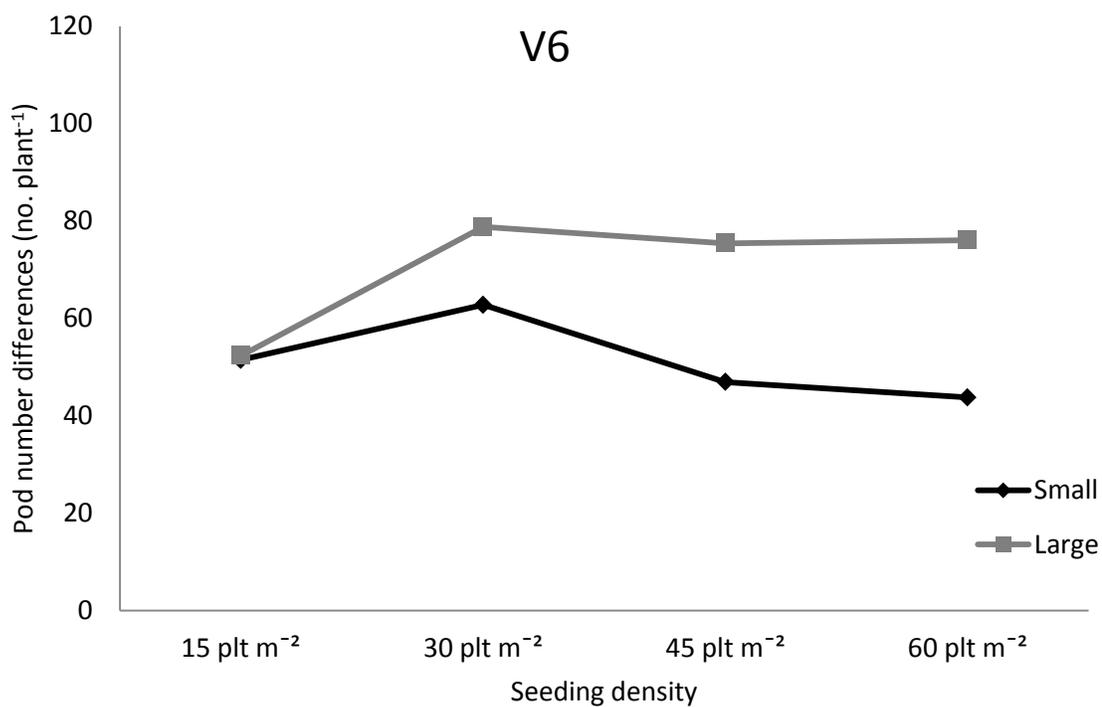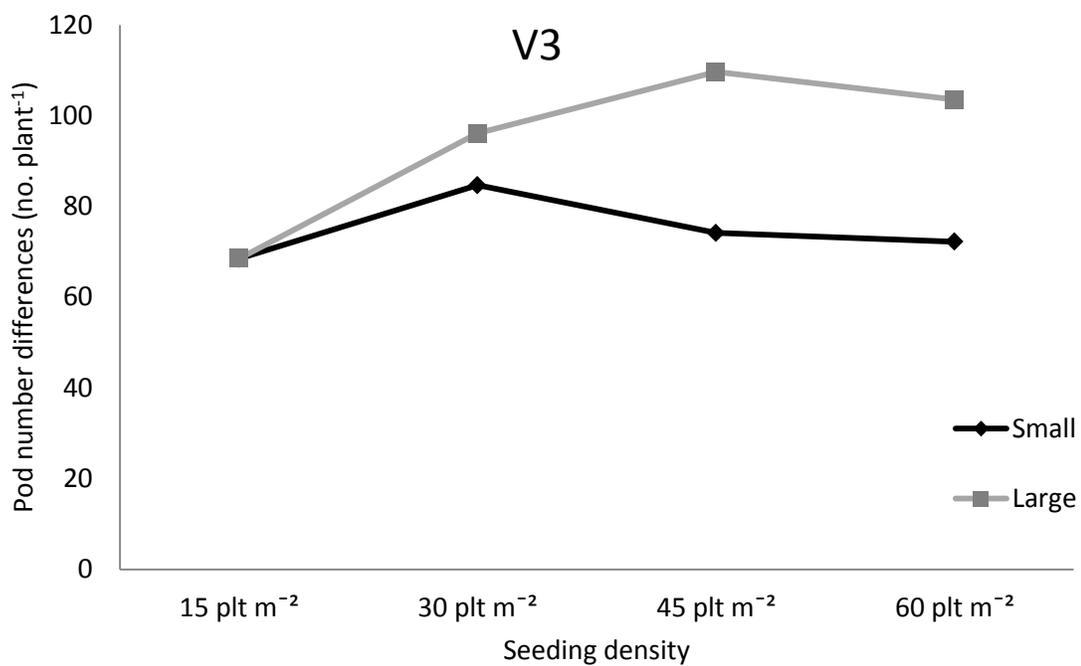
Figure A4. Differences in dry weight (g) plant[-1] of large and small cohorts with interplant competition relieved (-) to a density of 5.3 plants m[-2] and cohorts that remained with the level of interplant competition of the initial seeding density (+) (15, 30, 45, and 60 plants m[-2]) all season.



Figure A5. Differences in dry weight (g) plant[-1] of large and small cohorts with interplant competition relieved (-) to a density of 5.3 plants m[-2] at V3, V6, R2, or R4 and cohorts that remained with the level of interplant competition of the initial seeding density (+) (15, 30, 45, and 60 plants m[-2]) all season.
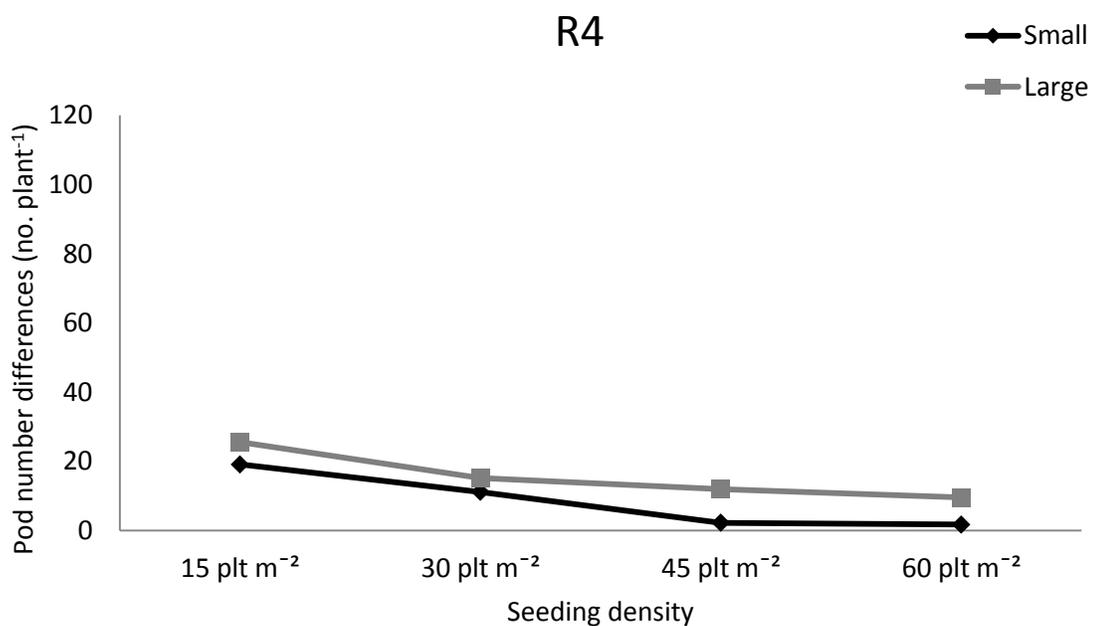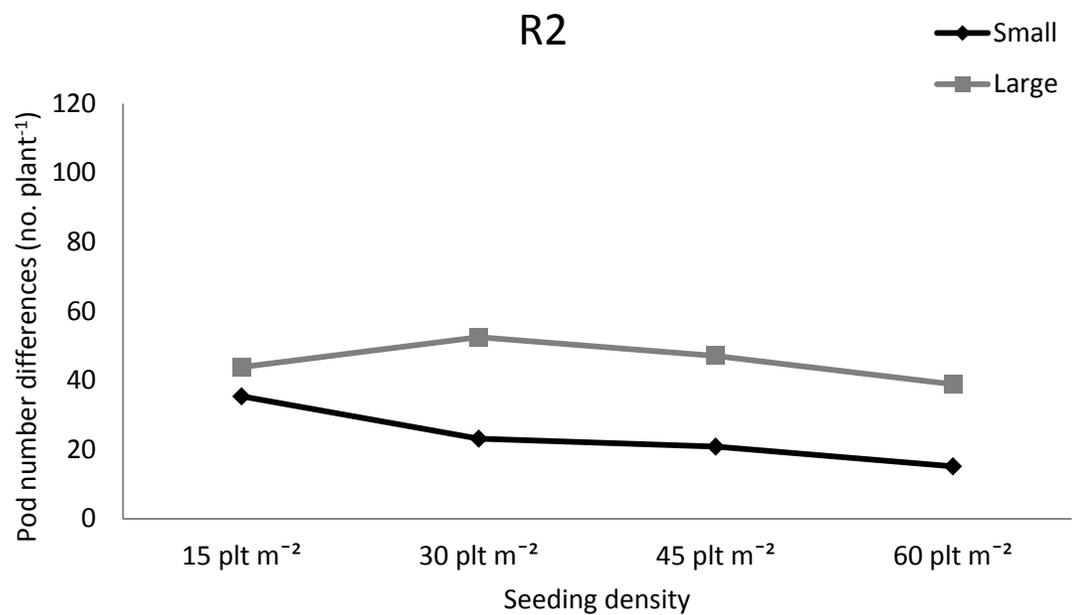
## Pod Number Plant[-1]

Table A3. Type 3 tests of fixed effects for pod number plant[-1] differences.

| Effect | Type 3 Tests of Fixed Effects | | | |
|--------|---------|---------|---------|---------|
|        | —Num DF— | —Den DF— | —F Value— | —Pr > F— |
| S      | 3 | 6 | 3.98 | 0.0707 |
| T      | 3 | 3 | 69.75 | 0.0028 |
| S*T    | 9 | 707 | 8.12 | <.0001 |
| C      | 1 | 2 | 4.64 | 0.1641 |
| S*C    | 3 | 707 | 10.69 | <.0001 |
| T*C    | 3 | 707 | 5.18 | 0.0015 |
| S*T*C  | 9 | 707 | 1.85 | 0.0569 |

[a] S = seeding density
[b] T = thinning timing
[c] C = cohort size

Figure A6. Differences in pod number plant$^{-1}$ of large and small cohorts with interplant competition relieved (-) to a density of 5.3 plants m$^{-2}$, at V3 and V6, and cohorts that remained with the level of interplant competition of the initial seeding density (+) (15, 30, 45, and 60 plants m$^{-2}$) all season.

Figure A7. Differences in pod number plant$^{-1}$ of large and small cohorts with interplant competition relieved (-) to a density of 5.3 plants m$^{-2}$, at R2 and R4, and cohorts that remained with the level of interplant competition of the initial seeding density (+) (15, 30, 45, and 60 plants m$^{-2}$) all season.

**Seed Mass**

Table A4. Type 3 tests of fixed effects for seed mass differences.

| Effect | Type 3 Tests of Fixed Effects | | | |
|---|---|---|---|---|
| | —Num DF— | —Den DF— | —F Value— | —Pr > F— |
| S | 3 | 6 | 0.27 | 0.8420 |
| T | 3 | 3 | 10.88 | 0.0404 |
| S*T | 9 | 9 | 1.18 | 0.4029 |
| C | 1 | 3 | 1.54 | 0.3024 |
| S*C | 3 | 6 | 1.41 | 0.3288 |
| T*C | 3 | 3 | 2.32 | 0.2536 |
| S*T*C | 9 | 645 | 1.38 | 0.1946 |

[a] S = seeding density
[b] T = thinning timing
[c] C = cohort size
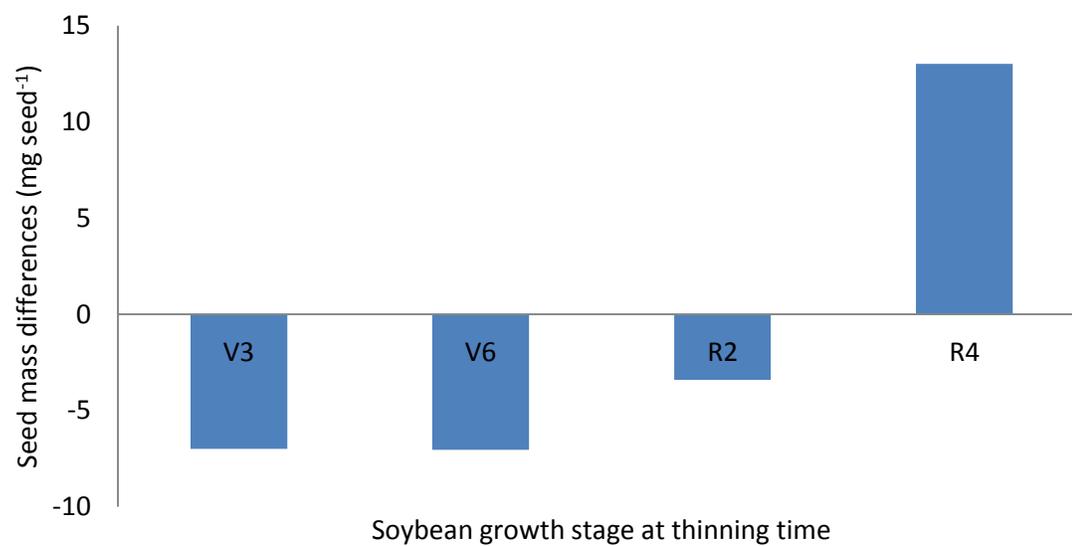
Figure A8. Differences in seed mass between plants with and without competition at each thinning time (V3, V6, R2, and R4).

## Seed Yield Plant$^{-1}$

Table A5. Type 3 tests of fixed effects for differences in seed yield plant$^{-1}$.

| Effect | Type 3 Tests of Fixed Effects | | | |
|---|---|---|---|---|
| | —Num DF— | —Den DF— | —F Value— | —Pr > F— |
| S | 3 | 6 | 4.32 | 0.0606 |
| T | 3 | 3 | 30.20 | 0.0096 |
| S*T | 9 | 706 | 6.61 | <.0001 |
| C | 1 | 1 | 8.71 | 0.2080 |
| S*C | 3 | 706 | 11.28 | <.0001 |
| T*C | 3 | 706 | 4.59 | 0.0034 |
| S*T*C | 9 | 706 | 1.07 | 0.3846 |

[a] S = seeding density
[b] T = thinning timing
[c] C = cohort size
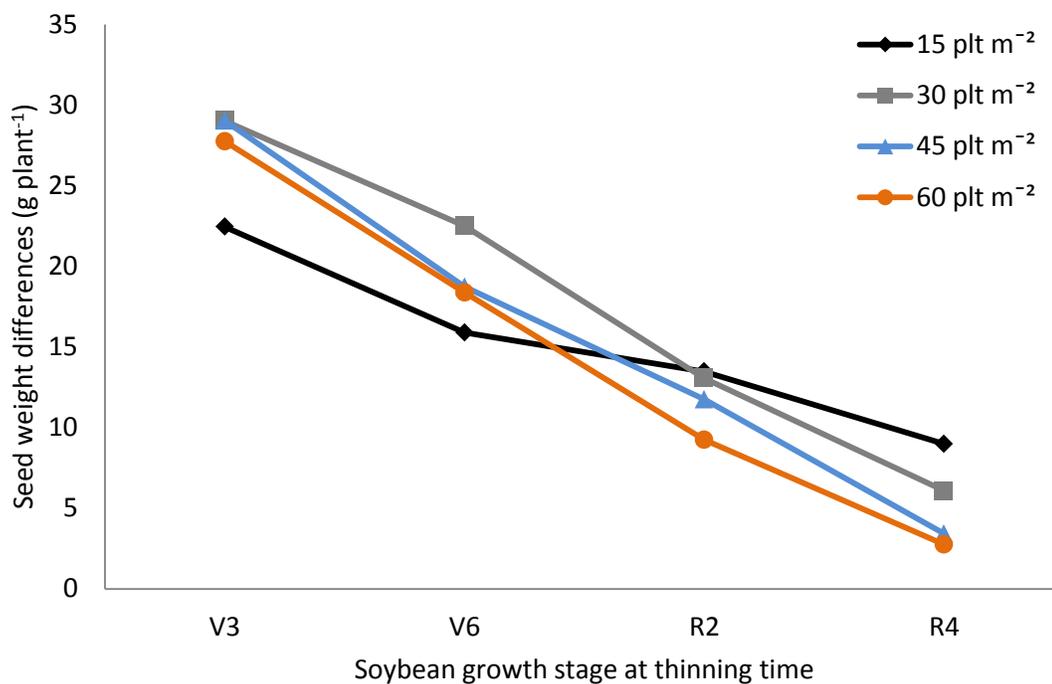
Figure A9. Differences in seed (g) weight plant$^{-1}$ between cohorts with interplant competition relieved (-) to 5.3 plants m$^{-2}$ at V3, V6, R2, or R4 and cohorts that remained with the level of interplant competition of the initial seeding density (+)(15, 30, 45, and 60 plants m$^{-2}$) all season.
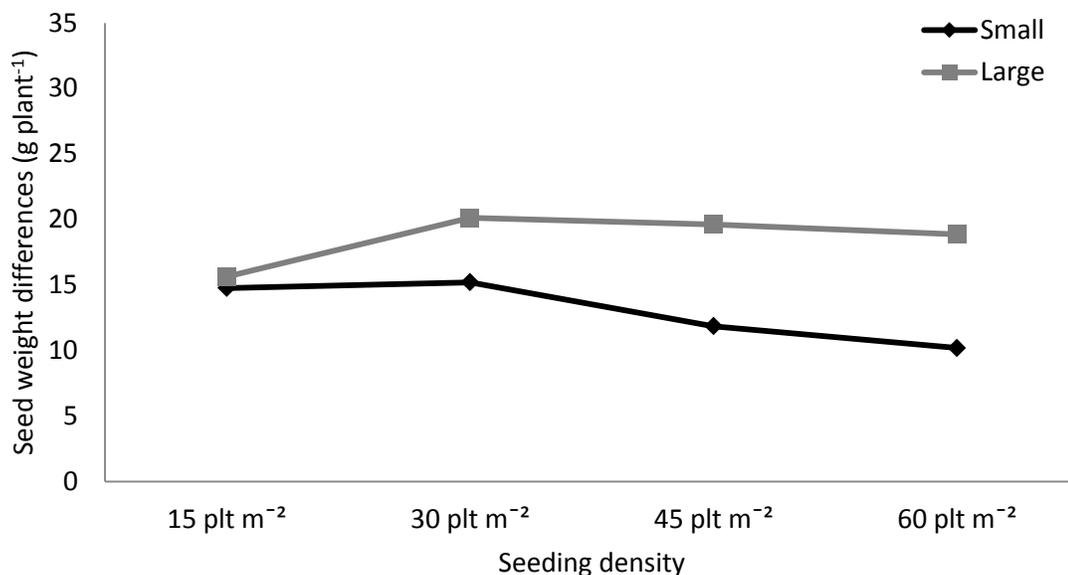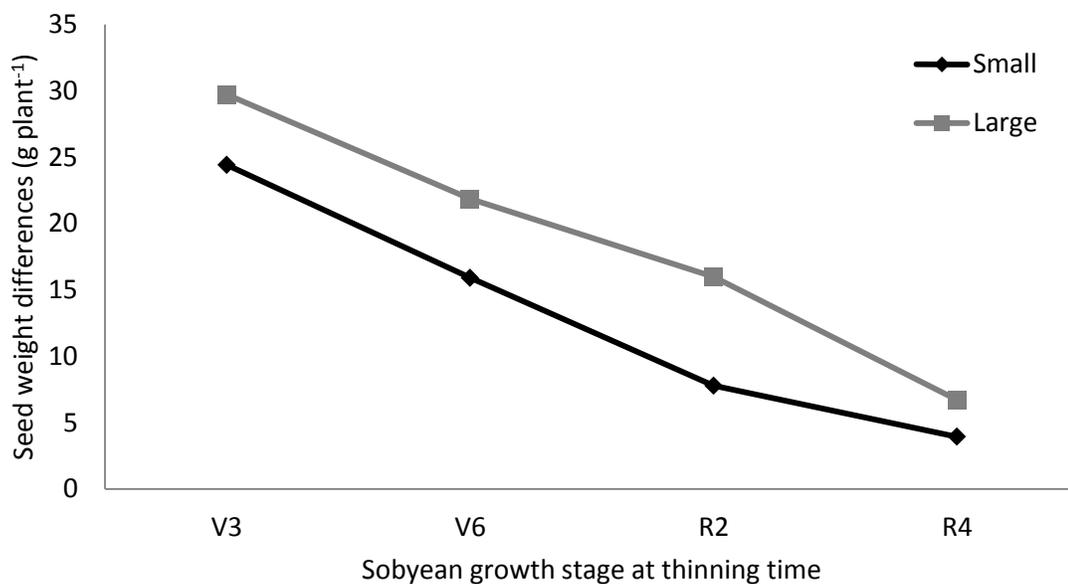
Figure A10. Differences in seed weight (g) plant$^{-1}$ of large and small cohorts with interplant competition relieved (-) to a density of 5.3 plants m$^{-2}$ and cohorts that remained with the level of interplant competition of the initial seeding density (15, 30, 45, and 60 plants m$^{-2}$) all season.



Figure A11. Differences in seed weight (g) plant$^{-1}$ of large and small cohorts with interplant competition relieved (-) to a density of 5.3 plants m$^{-2}$ at V3, V6, R2, or R4 and cohorts that remained with the level of interplant competition of the initial seeding density (+) (15, 30, 45, and 60plants m$^{-2}$) all season.

## Harvest Index

Table A6. Type 3 tests of fixed effects for harvest index differences.

| Effect | Type 3 Tests of Fixed Effects | | | |
|--------|--------|--------|--------|--------|
| | —Num DF— | —Den DF— | —F Value— | —Pr > F— |
| S | 3 | 3 | 0.07 | 0.9704 |
| T | 3 | 3 | 0.93 | 0.5236 |
| S*T | 9 | 696 | 3.94 | <.0001 |
| C | 1 | 2 | 0.54 | 0.5391 |
| S*C | 3 | 696 | 1.40 | 0.2409 |
| T*C | 3 | 6 | 2.33 | 0.1737 |
| S*T*C | 9 | 696 | 1.67 | 0.0931 |

[a] S = seeding density
[b] T = thinning timing
[c] C = cohort size

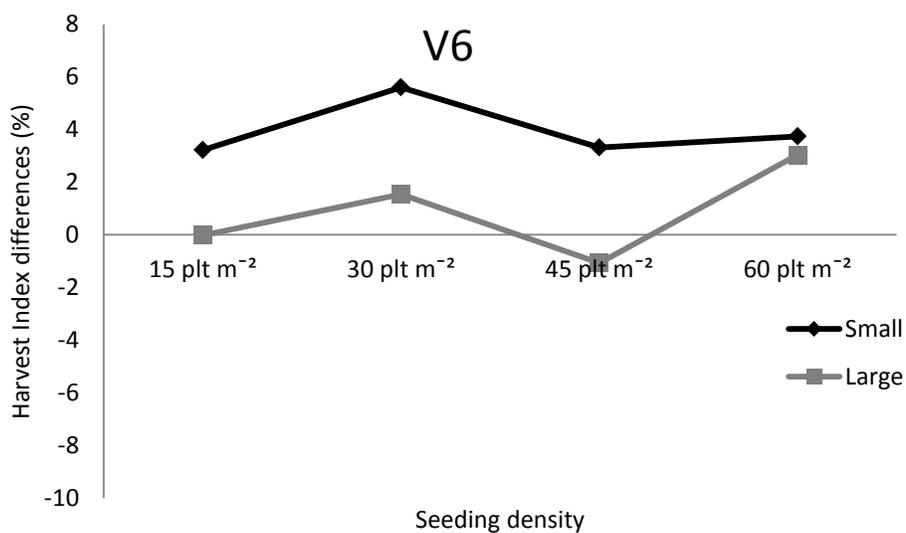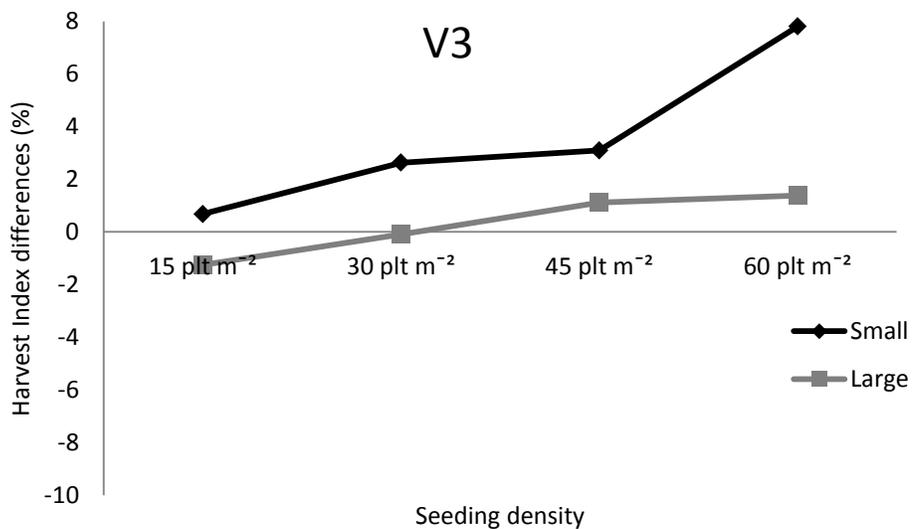Figure A12. Differences in soybean harvest index of large and small cohorts with interplant competition relieved (-) to a density of 5.3 plants $m^{-2}$, at V3 and V6, and cohorts that remained with the level of interplant competition of the initial seeding density (+) (15, 30, 45, and 60 plants $m^{-2}$) all season.

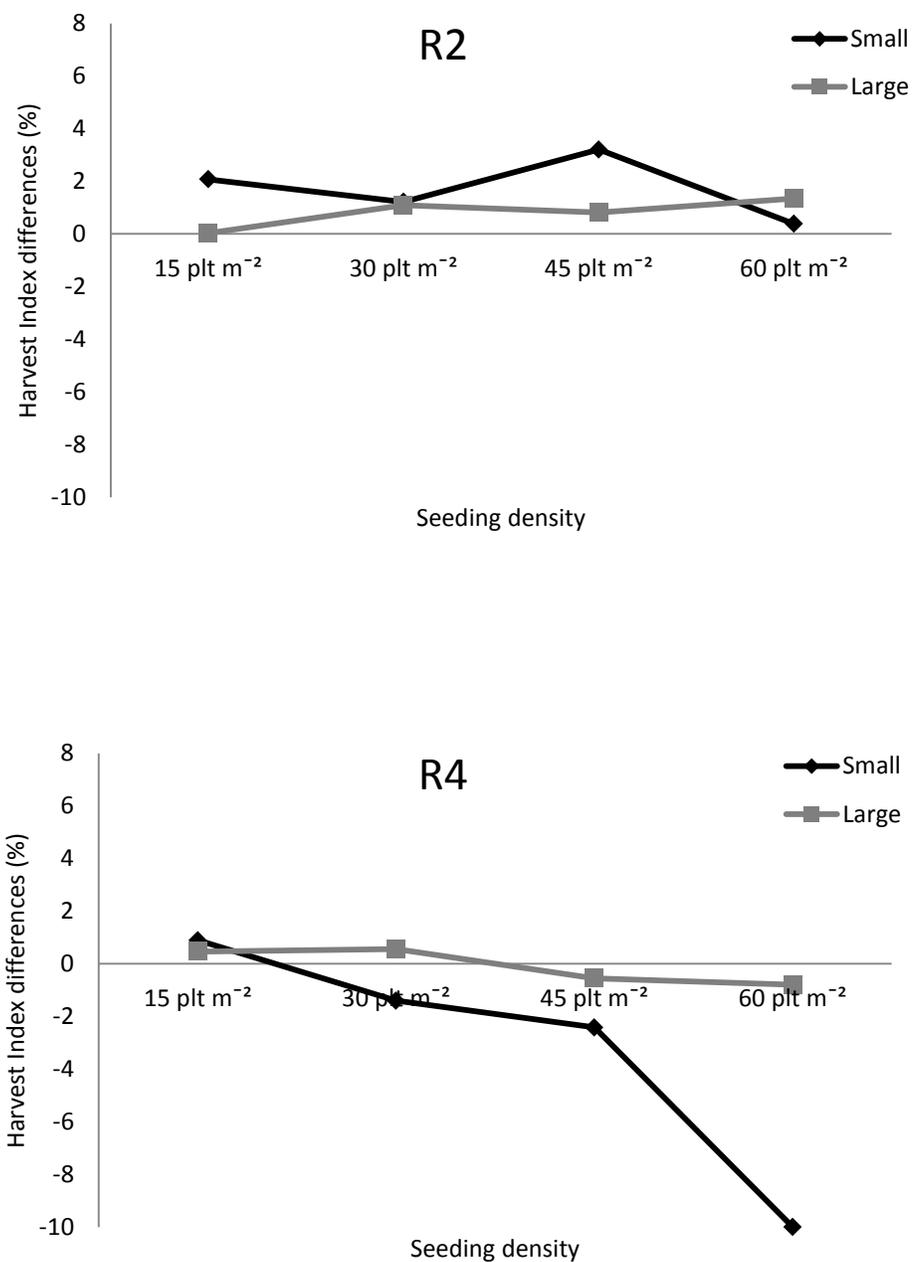Figure A13. Differences in soybean harvest index of large and small cohorts with interplant competition relieved (-) to a density of 5.3 plants m$^{-2}$, at R2 and R4, and cohorts that remained with the level of interplant competition of the initial seeding density (+) (15, 30, 45, and 60 plants m$^{-2}$) all season.