Management Effects on Lowest Pod Placement and Yield Formation in Soybean

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Chapter 1

Overview of Management Impacts on Yield and Height Characteristics in Soybean

Soybean [*Glycine max* (L.) Merr.] is an important global commodity crop for direct human consumption, livestock feed, biofuels and many other products. Currently the United States is the top soybean producer in the world followed by Brazil and then Argentina. In recent years approximately 75 million acres of land in the United States have been allocated to soybean, producing approximately 3 billion bushels each year. Soybean acreage has not largely increased in the past few decades, however; production has increased by almost a billion bushels in that time (USDA-National Agricultural Statistics Service, 2009).

Density Effects

Yield

Population density, which is determined in part by seeding rates, has long been known to be an important yield component in soybean as well as many other crops. The effects of population density on yield have been extensively studied, and it is generally concluded that planting higher soybean density leads to increased yield with declining gain as population density further increased where for some cultivars can be as low as 20 plants m^{-2} (Miura et al., 1987; Rigsby and Board, 2003; Cober et al., 2005; Edwards and Purcell, 2005; Epler and Staggenborg, 2008). It is also not uncommon to find higher than necessary seeding rates, where additional input costs from higher seeding rates will not be justified by the resulting yield (Egli, 1988).

Reduced yield due to higher soybean density has also been reported. Lodging was the primary contributor to the resulting yield reduction (Weber et al., 1966; Hicks et al., 1969; Felton, 1976; Boquet, 1990; Adams and Weaver, 1998; Ball et al., 2000).

Increased lodging has been most commonly reported to be associated with an increase in average plant height in higher plant populations (Weber et al., 1966; Boquet, 1990; Cober et al., 2005; Epler and Staggenborg, 2008;). Alternatively, others reported increased lodging due to higher densities without any effects on plant height (Leuschen and Hicks, 1977; Cober et al., 2005). Leuschen and Hicks (1977) suggested that stem diameter might better determine the risk of lodging due to increased population than height, and they also reported that some cultivars were more prone to lodging than others, due to genetic determination of stem diameter. Hicks et al. (1969) attributed increased risk of lodging to both decreased stem diameter and increased plant height. However, increased height and decreased stem diameter may not be the only factors affecting lodging, since Ethredge et al. (1989) suggested that increased branching may also the risk of lodging.

Yield Components

The components used to determine crop yield are seeds per unit area and individual seed size. Studies investigating population density effects on these components in soybean have reported that increasing population caused individual plants to decrease their pod set (Lehman and Lambert, 1960; Weber et al., 1966; Hicks et al., 1969; Pandey and Torrie, 1973; Felton, 1976; Lueschen and Hicks, 1977; Kasperbauer, 1987; Ethredge et al., 1989; Epler and Staggenborg, 2008;); however, it was also reported that the number of seeds m^{-2} was relatively unaffected by population density (Pandey and Torrie, 1973; Carpenter and Board, 1997). Both of these studies found that there were fewer seeds per plant in higher densities; however, yields were

not reduced because there was an increased number of plants present (Ethredge et al., 1989). According to these studies, increased yield due to higher population density would most likely result from an increase in seeds m^{-2}.

Spaeth and Sinclair (1984) found that average individual seed mass was negatively correlated with seed number per plant. Other studies, however, found that there was no consistent trend in seed weight due to increasing population density from as low as 25,000 plants ha^{-1} to as much as 1,330,000 plants ha^{-1} (Wilcox, 1974; Carpenter and Board, 1997; Cober et al., 2005;). Research by Frederick et al. (1998) reported that soybean seed yield is closely correlated with seed number and reported little relationship between overall yield and individual seed mass. Earlier studies conducted by Egli et al. (1978) and Pandey and Torrie (1973) also reported that seed size in soybean tends to be relatively unimportant in determining overall yield.

Yield Distribution

It has long been known that soybean has the ability to compensate for low population densities by increasing its branching, where highest densities produce the least number of branches (Lehman and Lambert, 1960; Weber et al., 1966; Pandey and Torrie, 1973; Lueschen and Hicks, 1977; Kasperbauer, 1987; Miura et al., 1987; Boquet, 1990; Carpenter and Board, 1997; Epler and Staggenborg, 2008). Rigsby and Board (2003) also reported that the total amount of vegetative dry matter partitioned into branches was significantly higher for a low population of 90,000 plants ha^{-1} compared to a higher population of 250,000 plants ha^{-1}. It has also been reported that in a population of 210,000 plants ha^{-1}, that as much as 30 to 40% of the total yield was

located on branches, while at 1,280,000 plants ha^{-1} only 5 to 16% of the total yield was found on branches (Herbert and Litchfield 1982). Carpenter and Board (1997) reported a highly significant correlation between yield per plant and branch pods per plant, suggesting branching is a key component in attaining highest yields. In contrast with branch yield, Boquet (1990) reported main stem yield per plant increases within higher densities.

Lowest Pod Height

Pods that are located closest to the base of the plant can be difficult to harvest depending on the height of the pods and the harvest equipment available. Cutterbar heights for harvesting soybeans have been reported to typically be about 10 cm above the ground (Grabau and Pfeiffer, 1990a), so pods that form below this threshold are likely to be left in the field after harvest. Grabau and Pfeiffer (1990a) also reported that with an average cutterbar height of 10.7 cm and average LPH (lowest pod height) of 19.7 cm, stubble losses still averaged around 1.4% due to wide plant to plant variation in this trait. This suggests that reduction in LPH could potentially lead to substantial losses.

Several studies have recommended increased population density as a management tool to raise LPH (Hicks et al., 1969; Wilcox, 1974; Felton 1976; Lueschen and Hicks, 1977; Beaver and Johnson, 1981a; Grabau and Pfeiffer, 1990b; Edwards and Purcell, 2005; Epler and Staggenborg, 2008). Hicks et al. (1969) attributed the findings of increased LPH with higher densities to be due to increased plant height. Several studies found that average plant height increased with increasing

soybean density (Weber et al., 1966; Hicks et al., 1969; Wilcox, 1974; Beaver and Johnson, 1981; Boquet, 1990; Cober et al., 2005; Epler and Staggenborg, 2008). It was reported, however, by Grabau and Pfeiffer (1990b) that higher planting densities raised LPH without any effect on plant height. None of these studies confirm whether increased LPH is produced from taller plants directly or whether LPH and plant height are independent responses due to increased population density.

Population density has also been found to control characteristics such as node number. The number of main stem nodes for individual soybean plants has been reported to decrease as population increased (Pandey and Torrie, 1973; Ball et al., 2001). This may also have an impact on where low pods form.

Plant Spacing Effects

Yield

Another management practice affecting soybean productivity that has received a great deal attention is the use of narrow row widths, which affects intra-row plant spacing. The effect of narrow row width on soybean is the creation of more equidistant plant spacing, where inter-row and intra-row plant spacing become more equal. This reduction in row width causes reduced or delayed competition for light, nutrients, and water, and can lead to higher yield in soybean (Weber et al., 1966; Duncan, 1986; Miura et al., 1987; Ethredge et al., 1989). Most row width studies have concluded that narrower rows tend to yield higher than wide rows (Lehman and Lambert, 1960; Weber et al., 1966; Burmood and Fehr, 1973; Costa et al., 1980; Ethredge et al., 1989; Boquet, 1990; Adams and Weaver, 1998; Frederick et al., 1998; Ball et al., 2000; Bowers et al.,

2000; Pedersen, 2008;). It has also been reported that there was a more positive yield response to increasing population within narrow rows rather than wide rows since inter-plant competition is reduced in narrow rows (Duncan, 1986; Boquet, 1990). Boquet (1990) also found that the yield advantage of 50 cm rows versus 100 cm rows was more pronounced with delayed planting. Additionally, the yield advantage for equidistant rows in comparison with 76 cm rows was reported by Egli (1994) to be dependent on the cultivar being grown, and that some cultivars are more responsive to narrow rows than others.

In contrast, it has been found by some recent studies that narrow rows provide no yield advantage over wide rows (Pedersen and Lauer, 2003; Epler and Staggenborg, 2008). A study conducted by Beaver and Johnson (1981) found a significant yield increase due to 50 cm rows over 80 cm rows, but no difference in yield between 50 cm and 20 cm rows. They suggested this was because, at all the planting dates tested, the 50 and 20 cm row plots had reached full canopy closure at or before R3 stage of maturity (Fehr and Caviness 1977), well before the onset of seed fill, where full canopy closure (90 to 95% cover) is necessary to achieve optimum yield (Rigsby and Board, 2003). The increased amount of early season light interception was reported by Board and Harville (1992) to also be a factor contributing to higher seed yield when comparing 50 and 100 cm rows.

Plant Spacing and Lodging

Pedersen and Lauer (2003) found increased lodging within 19 cm rows resulting in no yield advantage over 25 cm rows. Studies have also observed that as row width

decreased, plant height increased, indicating why increased lodging might be found (Boquet 1990; Pedersen and Lauer 2003). Additionally, it was reported by Beaver and Johnson (1981) that the differences in plant height due to row width were dependant on the cultivar being grown.

Yield Components

Studies investigating row width effects on yield components have found that highest seed number per unit area were obtained in narrow rows (Weber et al., 1966; Ethredge et al., 1989). Additionally Ethredge et al. (1989) reported smaller seeds in 25 cm compared to 76 cm rows, however; Norsworthy and Shipe (2005) reported that there were no differences between individual seed weights for soybean grown in narrow (19 cm) versus wide (97cm) rows. Higher yields obtained from narrow rows are attributable to an increase in seeds m^{-2} since soybean yields are more highly correlated with seeds per m^2 than individual seed size (Egli, 1993; Norsworthy and Shipe, 2005).

Yield Distribution

It has been reported in several studies that decreased row width caused an increase in the number of branches per plant (Weber et al., 1966; Adams and Weaver, 1998; Ball et al., 2000; Norsworthy and Shipe, 2005). Frederick et al. (1998) additionally reported that total seeds per m^2 was more closely correlated to branch seeds per m^2 than main stem seeds per m^2 for both wide (76 cm) and narrow (19 cm) row width. This correlation may suggest that the increased yield seen for narrow rows

is due to increased branch seeds since a greater number of seeds per m^2 have been seen for narrow rows.

Lowest Pod Height

Beaver and Johnson (1981) found when comparing 20 and 76-cm row widths at seeding rates of 350,000 and 500,000 seeds ha^{-1}, that narrow rows had a significantly higher lowest pod height. This suggests that narrow rows may tend to simulate the effects of increased population on LPH. Pedersen and Lauer (2003) reported that plants were taller in narrower rows for all row width comparisons of 76, 38 and 19 cm rows, which according to Hicks et al. (1969) and Beaver and Johnson (1981), it might be concluded that increased plant height may have also raised LPH. These findings, however, do not confirm whether increased plant height is the primary driver of increased LPH, just that the two seem to arise from similar environmental conditions.

Maturity Effects

Maturity and Population

The relative maturity of cultivars also plays an important role in soybean growth, development and overall yield. Cultivars with earlier maturation will have shorter vegetative periods and earlier reproductive stages causing the production of fewer nodes and shorter plants (Gan et al., 2002). With short season varieties, it is important to increase population density, compared with growing late season varieties, in order to maximize yield (Ball et al., 2000). It was recently shown by Edwards and Purcell (2005) that in order to maximize yield, lower seeding rates were required for

late maturity cultivars. Edwards and Purcell (2005) also reported that lodging was most problematic for the highest population density in later maturity cultivars. It was reported by Thomas and Raper (1976) that short season varieties tend to have less branching, which might help explain why higher densities are necessary to maximize yields in these varieties. Similar effects were seen in an investigation of delayed planting date by Boquet (1990). Their findings suggested that with delayed planting of earlier maturity soybeans, that population density should be increased in order to maximize yield. Late planting, the use of short season varieties, or a combination of the two will shorten the period of vegetative growth and may limit the amount of leaf area produced by onset of seed fill explaining why higher densities are often necessary. Leaf area index (LAI), which is the proportion of leaf area to ground area, has also been shown to be important in determining yield. It has been reported that a LAI of 4.0 or more is required in soybean to fully close the canopy by the beginning of R5 (Fehr and Caviness, 1977) in order to maximize yield potential (Rigsby and Board, 2003). Proper leaf area is important in maximizing photosynthesis potential and allowing sufficient grain fill to occur in soybean. Increased seeding rates in short season varieties have been shown to allow for faster canopy coverage and a higher proportion of light interception which should increase total biomass (Ball et al. 2000). In agreement with Ball et al. (2000), other studies have found that that photosynthesis on an area basis is proportional to grain yield (Wells et al., 1982) and maximizing biomass is key for producing greatest yield response (Egli et al., 1987).

Hicks et al. (1969) reported that higher soybean densities maximized LAI and high yields were observed along with it. In a study conducted by Weber et al. (1966),

however, it was observed that population densities which increased the accumulation of LAI and plant dry weight did not impact yield. More recently it was reported by Rigsby and Board (2003) that yield response to total vegetative dry matter (TVDM) accumulation was important in determining yield when total TVDM was below 500 g m^{-2} by the beginning of seed fill. However, they found no increase in yield once TVDM became greater than 500g m^{-2} at R5 stage of maturity. This threshold of 500g m^{-2} was also observed in a study conducted by Egli et al. (1987).

Plant Spacing and Maturity

Studies have reported that earlier maturity cultivars tend to show greater yield response due to the use of narrow row widths than later maturity cultivars (Costa et al., 1980). Decreased row width for short season varieties may help to remedy the shorter vegetative growth period by increasing the ability to attain sufficient canopy closure by the beginning of seed fill (Board et al., 1992; Frederick et al., 1998; Ball et at., 2000). Boquet (1990) also reported that with delayed planting, yield was found to be higher in narrow rows. It may be more important, according to these studies, that short season varieties are planted in narrow rows than long season varieties, since they have a shorter vegetative growth period and will have less time to sufficiently reach full canopy coverage before the onset of seed fill.

Maturity and Lowest Pod Height

Maturity length is another characteristic that has shown importance in determining LPH. Previous research has shown there is a general trend that LPH is increased with later relative maturity (Beaver and Johnson, 1981; Grabau and Pfeiffer, 1990a; Edwards and Purcell, 2005). It was also reported by Martin and Wilcox (1973) that there was a correlation between flowering time and LPH, where delayed flowering resulted in increased LPH. This is in agreement with the studies reporting increased LPH with later relative maturity since these cultivars would generally have a later flowering time.

Effects of Light Quality

Physiology and Morphology

Another topic, one that has received very little research attention in comparison with population density and row width for soybean, and perhaps underlies the effects of both of those management strategies, is light quality. The detection of light quality is one of the many ways plants are able to identify their surroundings in a particular environment to help guide their growth pattern. These light perception mechanisms detect the presence or absence of specific colors of visible, far-red, or ultraviolet light. The density of neighboring plants is one thing that can be detected through light quality, where red/far-red (R/FR) light ratios will be reduced when there are more neighboring plants. Direct sunlight contains approximately equal amounts of red and far-red light, but when the light passes through the canopy much of the red portion of light is absorbed by the leaves of plants while the far-red light is reflected or transmitted. This means that when there are more plants present, there will be a greater

proportion of far-red light beneath the canopy than red light, resulting in a lower R/FR light ratio (Taiz and Zeiger, 2006). Row width is another management driven factor that has been seen to affect R/FR light ratio. It was reported by Kasperbauer (1987) that a higher ratio of R/FR light was found with 100 cm rows compared to 20 cm rows throughout the entire day.

The ratio of R/FR light is perceived by a photoreceptor called phytochrome, which can mediate many different physiological or morphological responses. Some of the responses mediated by phytochrome include germination, stem growth, leaf formation, internode length and flowering (Taiz and Zeiger, 2006); however, red and far-red light are not the only important types of light perceived by plants. It is well known that blue light, which is recognized by two classes of photoreceptors, cryptochrome and phototropin, affects responses such as hypocotyl elongation, chloroplast movement, stomatal opening and closing, phototropism, and many others (Taiz and Zeiger, 2006). A study conducted by Kasperbauer and Hunt (1987) found that southern pea (*Vigna unguiculata*) grown over white soil surface coloration produced shorter stems than those grown over black soil surface coloration. They also noted that there were similar R/FR ratios in reflected light between surfaces, while plants grown over the white surface were found to receive considerably more reflected blue light. Hunt et al. (1989) reported that soybean plants had shorter and thicker stems when they were grown over white insulation panels compared to black or red insulation panels, and they similarly found that there was 42% reflection of the incident blue light from the white panels compared to 5% for both the red and black panels. It was found in a more recent study that increasing the blue light fraction from 0% to 2% decreased

soybean stem length by 7%, where 6% blue light fraction decreased stem length by 44% when soybean were measured approximately three weeks after planting (Dougher and Bugbee, 2001).

Yield Effects

Light quality has also been suggested by previous studies to be important in determining yield. It was found that when soybean was planted at low population densities, plants received higher R/FR ratios, which also coincided with more branch development (Kasperbauer, 1987; Board, 2000). In high populations, the reverse was found (Carpenter and Board, 1997), so perhaps R/FR ratios are important in controlling branch development. Additionally, it has been shown that during the time of flowering, supplemental red light increased the number of pods set compared to far-red supplemental light (Myers et al., 1987), thus demonstrating that higher R/FR light ratios may be contributing to higher pod set and potentially greater yield on a per plant basis.

Tillage

There is a potential difference in the amount of light reflected depending on the type of tillage performed. For example, in no-till, there would potentially be more reflective dead plant material left on the surface of the soil. It was reported in a recent study that yield was 6% higher for soybeans grown in no-till as compared to conventional tillage (Pedersen and Lauer, 2003). One study reported that at a depth of 23 and 46 cm, no-surface-tillage as opposed to disk tillage had higher water content on many of the measurement dates (Frederick et al., 1998). This study also found that

soybean had increased branching and a larger number of branch seeds in no-till treatments; however, they also reported lower overall yields for no-till treatments. The previous studies do not however, indicate whether increased branching or yield was due to the effects light quality, aided ability in soil moisture retention, or a combination of the two.

Stand Reduction

Light Interception

In soybean production, there is always the potential for reduced stand numbers to occur due to unpredictable biotic and abiotic stresses. Soybeans are able to compensate quite well for reduced stands since they are able to make use of more available resources and increase branching (Andrade and Abbate, 2005). This is likely not due to increased photosynthesis in the remaining leaves even though stand reduction exposed the lower portion of the canopy to more sunlight (Weil and Ohlrogge, 1976). Instead this is because prolonged shading of the bottom leaves tends to reduce their light saturation point over time and lower their overall photosynthetic potential (Burnside and Bohning, 1957).

Yield

In relation to yield loss due to stand reduction, it has been shown that, similar to other crops, the later the damage occurs during development, the greater the potential yield loss (Teigen and Vorst, 1975; Conley et al., 2008). Conley et al. (2008) reported that soybean plants can adequately compensate for stand loss occurring at or before R1

stage of development, as long as the final plant population is at least 247,000 plants ha^{-1}. Previous studies conducted by Teigen and Vorst (1975) supported these findings; however, they suggested a final population of only 145,000 plants ha^{-1} was necessary when stand reduction occurred at V7 (Fehr and Caviness, 1977). Their results showed that yield was significantly reduced at R3 stand reduction, which they explained to be due to the fact that R3 plants would already be past full bloom into the beginning pod stage and several flowers were likely already aborted, rendering less capacity for increased pod set. Additionally, it was reported by Burmood and Fehr (1973) that the ability to compensate for stand reduction was not significantly different between 50 cm and 100 cm row widths; however, all thinning treatments occurred before the R3.

Yield Components

Teigen and Vorst (1975) found as much as 50% increase in pods per plant for stand reduction at V7, while only 20% for R3. This study also found no significant effects of stand reduction on the number of seeds per pod or weight per seed. Thus, an increase in pod set was the primary driver found to increase yield per plant. Other studies reported that increased pod set due to stand reduction was found to occur as late as R2 (Burmood and Fehr, 1973) and R3 (Weil and Ohlrogge, 1976).

Weil and Ohlrogge (1976) also reported that stand reduction occurring after R3 resulted in yield compensation occurring primarily from increased individual seed size. Similarly, Conley et al. (2008) reported that stand reduction at R3.5 showed increased individual seed size as more plants were removed. They also reported that remaining plants were still unable to fully compensate for lost yield from reduced stands. Weil

and Ohlrogge (1976) observed that soybean stands that were thinned at the R4 stage of maturity had delayed leaf senescence compared to the control, potentially indicating a lengthening of the seed filling period and allowing the production of larger seeds.

Studies conducted by Carpenter and Board (1997) reported that the majority of branch dry matter accumulation occurred between R1 and R3 stages of development and also that cultivars more capable of branching will likely show less effect on yield due to stand reduction occurring before R3.

Plant Characteristics

Plant height was also found to be affected by stand reduction, where Teigen and Vorst (1975) reported shorter plants as stand reduction was increased. More recently, it was reported that as stand reduction rate increased, there was a linear decrease in plant height (Conley et al., 2008). Other studies have also simply reported that there were shorter plants in thinned plots compared to the control (Burmood and Fehr, 1973). It was also observed that with later thinning there was reduced risk of lodging in addition to reduced plant height (Burmood and Fehr, 1973; Teigen and Vorst, 1975).

Chapter 2

Management Effects on Lowest Pod Height, Plant Height, and Nodal Characteristics in Soybean

Chapter Summary:

In recent years, increased harvest loss for soybean [*Glycine max* (L.) Merr.] due to low forming pods has been noted in southern Minnesota. These harvesting losses come from the inability of the cutterbar on harvesting equipment to be operated close enough to the soil surface to gather low formed pods. In order to better understand the effects of management strategy on height and nodal characteristics and their relation to lowest pod height, studies were conducted in the southern Minnesota region in 2008 and 2009 to investigate plant density, relative maturity, row width, mulch color, and stand reduction. Increasing population density from 19 to 43 plants m^{-2} increased the height of the lowest pod from 12.2 to 15.8 cm. The relative maturity of soybean varieties also affected the height of the lowest pod, increasing it from 10.9 to 18.8 cm going from a late MG 0 and a late MG II variety. Changes in row width revealed there was no significant effect on the height of the lowest pod. Red colored mulch produced a significantly higher lowest pod height at 14.7 cm compared to no mulch which had a height of 13.0 cm. Stand reduction studies revealed that lowest pod height could be reduced from 15.9 to 11.5 cm when population was reduced from 43 to 19 plants m^{-2} as late as R3. Only population density was found to affect LPH and internode length simultaneously, so the impacts seen on LPH do not appear to be primarily working through differences in internode length.

Introduction:

Proper management techniques are important in promoting the development of desirable plant characteristics in soybean [*Glycine max* (L.) Merr.], which can directly

affect harvest efficiency and overall crop yield. Increased harvesting losses for soybean due to low forming pods have occurred in recent years for the southern Minnesota region. These harvesting losses come from the inability of the cutterbar on harvesting equipment to be operated close enough to the soil surface to gather the lowest forming pods. Cutterbar heights for harvesting soybean are reported by Grabau and Pfeiffer (1990a) to typically average around 10 cm above the soil surface, so pods that form at or below this threshold are especially susceptible to being left in the field at the time of harvest. Grabau and Pfeiffer (1990a) also reported that with an average cutterbar height of 10.7 cm and an average LPH (lowest pod height) of 19.7 cm, stubble losses still averaged around 1.4% of total yield. This indicates that even with a LPH average well above average cutterbar heights, harvesting losses due to low pods still occur and reduction in average LPH could lead to greater losses.

Several previous studies have reported that increasing plant density is one of the primary management tools found to increase LPH (Hicks et al., 1969; Felton, 1976; Lueschen and Hicks, 1977; Dominguez and Hume, 1978; Beaver and Johnson, 1981; Edwards and Purcell, 2005; Epler and Staggenborg, 2008). Within higher plant densities, several studies have also noted increased plant height (Weber et al., 1966; Hicks et al., 1969; Beaver and Johnson, 1981; Boquet, 1990; Cober et al., 2005; Epler and Staggenborg, 2008) which Hicks et al. (1969) believed to be one of the drivers increasing LPH.

The seed cost for soybean is also expected to increase, following the trend seen for corn. This increase in seed cost may cause producers to use lower seeding rates to reduce costs, which may increase the amount of low set pods that are below the reach

of harvesting equipment. Martin and Wilcox (1973) reported losses of approximately 4% of the total gross yield for every 2.5 cm increase in cutterbar height above the soil surface. It is reasonable to assume that decreased LPH at 2.5 cm intervals could simulate the detrimental yield effects of raising cutterbar height that were reported by Martin and Wilcox (1973). Studies have also found that population density affects the number of nodes plant^{-1}, which tends to decrease with increasing population (Pandey and Torrie, 1973; Ball et al., 2001) and may also have some impact on LPH.

Changing population density alters the interplant spacing within the field and may be why the effects on LPH are seen; however, interplant spacing is not only affected by population density but also through the use of alternate row widths. Beaver and Johnson (1981) found 20 cm rows to have a significantly greater LPH compared to 25 cm rows for population density comparisons at 350,000 and 500,000 plants ha^{-1}. They did not, however, find a significant difference between those row widths at a population density of 650,000 plants ha^{-1}, which may be an indication that as population is increased the effects of row width are reduced. According to Kasperbauer (1987), decreasing row width creates more equidistant plant spacing, which they found resulted in decreased R/FR (red/far-red) light ratio, an effect that is also caused by increasing population density (Taiz and Zeiger, 2006). This R/FR light ratio is an important environmental characteristic perceived by phytochrome receptors within plants and affects certain physiological responses in soybean such as plant height and internode length (Kasperbauer, 1987; Kasperbauer, 1988).

Another characteristic that has been shown to be important in determining LPH is relative maturity. Previous research indicates that for cultivars with later relative

maturity there is generally increased LPH (Dominguez and Hume, 1978; Grabau and Pfeiffer, 1990a; Edwards and Purcell, 2005). Martin and Wilcox (1973) reported a correlation between flowering time and LPH, where delayed flowering resulted in increased LPH. This supports the studies finding that LPH increased with relative maturity, since cultivars of later maturity generally have delayed flowering.

Recent studies have shown that in recent years the Midwest, eastern, and southeastern states, there is a greater adoption of conservation tillage practices than being implemented for glyphosate resistant soybean cultivars than previous years (Givens et al., 2009). This has several implications for effects on yield and plant characteristics in soybean and could include LPH. Not only have studies reported that reduced tillage helps to better retain soil water content (Ojeniyi, 1986; Frederick et al., 1998), but also that reduced tillage maintains a lower and more consistent soil temperature (Johnson and Lowery, 1985). Kasperbauer and Hunt (1987) reported that there was a greater amount of light reflected off of white soil surfaces than black soil surfaces, which could potentially simulate light reflection comparisons for no-till and conventional tillage. The white and black soil surfaces produced a similar R/FR light ratio; however, there was a considerably greater amount of blue light reflected off the white surface. Other studies have shown that when grown over a white soil surface, plants produced shorter and thicker stems than those grown over a black soil surface for both southern pea [*Vigna unguiculata* (L.) Walp.] and soybean (Hunt et al., 1989).

Conley et al. (2008) selectively removed soybean plants at several times with varying severity levels throughout the growing season. They reported that there was a linear decrease in plant height as the proportion of the original stand removed was

increased. Within the highest proportion of plants removed (75%), plant heights with the V3 and R3.5 thinning treatment were similar while R1 thinning treatment was approximately 6 cm shorter. This may indicate that some important plant dynamics are occurring due to changes around R1 but no later than R3. Studies have also shown that soybean is able to respond to stand reduction by increasing pod set as late in the season as R3 stage of maturity (Teigen and Vorst, 1975; Weil and Ohlrogge, 1976). Plants have already passed R2 (full flowering) by the time of R3 and many flowers may have already been aborted. Before many of the flowers are aborted flexibility remains in the number of pods that are set. It may be the case that this coincides with LPH determination.

The objectives of this study are to (i) evaluate the effects of population density and soybean maturity on LPH; (ii) evaluate the effects of inter and intra-row plant spacing on LPH; (iii) examine the effects of R/FR light ratio as a possible mechanism in LPH determination; (iv) evaluate the effects of colored mulches on LPH; and (v) investigate the timing of LPH determination.

Materials and Methods:

Experiments were conducted at University of Minnesota locations near St. Paul [44°59' N, 93°10'W; Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive mesic Typic Hapludolls)], and Waseca [44º4' N, 93°30' W; Nicollet clay loam (fine-loamy, mixed, mesic Aquic Hapludoll)] in 2008 and 2009. Four different studies were conducted to evaluate the objectives: Maturity, Plant Arrangement, Mulch, and Timing of Thinning. All treatments within maturity (Table

1), Plant Arrangement (Table 2), mulch, and timing of thinning studies were arranged in a randomized complete block design with 4 replications of each treatment. Individual plots measured 1.5 by 4.6 m. Machine planted plots were planted on 8 May 2008 and 6 May 2009 in St. Paul and 15 May 2008 and 14 May 2009 in Waseca. Hand planted, equidistant plots (where equidistant is defined as the planting arrangement such that inter-row plant spacing is exactly equal to row width) within the Plant Arrangement study were planted on 8-9 May 2008 and 8 May 2009 in St. Paul and 15-16 May 2008 and 14 May 2009 in Waseca. Row plots were seeded at a rate of 150% of the target population with the exception of the 25 cm row treatments where plots were seeded at 125% of the target population. The planter used was an Almaco heavy cone-type drill (Nevada, IA). Equidistant plots were hand seeded at a rate of 300% of the target population. Both machine and hand planted plots were hand thinned to their respective populations to provide uniform stands between approximately V1 and V2 stages of growth (Fehr and Caviness, 1977) by removing the entire plant and discarding it from the plot.

Maturity

The Maturity study incorporated 9 treatments, consisting of 3 population densities (19, 31, and 43 plants m^{-2}) for 3 cultivars of varying maturity (early AG0803 MG 0.8, adapted AG2108 MG 2.1, and late AG2802 MG 2.8) (Table 1).

Plant Arrangement

The Plant Arrangement study had 12 treatments using only the adapted maturity cultivar AG2108 (MG 2.1), 4 types of row width treatments (equidistant, 25, 51, and 76 cm) and 3 population densities (19, 31 and 43 plants m^{-2}) (Table 2). Equidistant plots had narrower rows than any of the other row width treatment for all densities tested and were considered as a single row width treatment in comparison with the other row width treatments for data analysis.

Mulch

Mulch types used were Excelsior Erosion Control Natural Blanket with Rapid-Go™ Netting (Forestry Suppliers, Inc., Jackson, MS) for straw mulch to simulate no-till, SRM® Red Plastic mulch (Ken-Bar, Peabody, MA) to investigate R/FR effects, and bare soil as the control. The mulch experiment used cultivar AG2108 planted in 51 cm row widths for populations of 19 plants m^{-2} and 43 plants m^{-2} for each of the 3 types of mulches totaling 6 treatments. Straw and red mulches were cut to 0.46 by 3 m and applied to row spaces within 4 days of thinning, where they remained until harvest.

Reflectance spectra were measured for each of the mulches, including soil (Waukegan Silt Loam) obtained from the St. Paul field location, using an Apogee model SPEC-UV/PAR Spectroradiometer (Apogee Instruments, Inc., Logan, UT). Measurements were also taken for photosynthetically active radiation (PAR) using an AccuPAR LP-80 (Decagon Devices Inc., Pullman, WA) and R/FR light ratio using a SKYE SKR 110 R/FR meter (Skye Instruments Ltd., Llandrindod Wells, UK) for red and soil mulch plots in 2010. Plot setup was the similar to 2008 and 2009 years,

however; the straw mulch treatment was excluded and only a density of 43 plants m^{-2} was used. There were two replications for each of the two treatments in 2010. The light measurements were taken with both the PAR and R/FR sensors oriented in an upward, horizontal, and downward position approximately 10cm above the ground surface for each or the 4 row spaces within a plot on approximately a bi-weekly basis until after canopy closure.

Timing of Thinning

Timing of thinning plots used cultivar AG2108 and 51 cm row widths. All plots were initially thinned between V1 and V2 to 43 plants m^{-2} and were then thinned from 43 plants m^{-2} to 19 plants m^{-2} upon reaching stages V1, R3, R5 (Fehr and Caviness, 1977) or no thinning (control). Stand reduction for the V1 treatment was accomplished by removing whole plants by hand and discarding them from the plot. Stand reductions at R3 and R5 were conducted by severing the stem with a pruner within a 1 cm of the soil surface and then removing those plants from the plots, ensuring not to damage any of the remaining plants.

Weed and Pest Management

Weeds were controlled by glyphosate [N-(phosphonomethyl)glycine] applications of 0.84 kg a.e. ha^{-1} and hand weeding on an as needed basis in both 2008 and 2009. During the 2008 growing season soybean aphids (*Aphis glycines* Matsumura) were controlled using the pyrethroid insecticide lambda-cyhalothrin (Warrior, Syngenta Crop Protection, Greensboro, NC) for both St. Paul and Waseca,

which was applied at a rate of 0.028 kg a.i. ha^{-1}. A combination of soybean aphid and two-spotted spider mite infestation (*Tetranychus urticae*) in 2009 was controlled with bifenthrin insecticide/miticide Sniper® (Loveland Products, Inc, Greeley, CO) at Waseca and Tundra™ (Agriliance, LLC, St. Paul, MN) at St. Paul, both applied at a rate of 0.113 kg a.i. ha^{-1}.

Height and Nodal Measurement

All plots were harvested by hand shortly after reaching R8 stage of maturity for determining plant height characteristics. A 0.5 m^2 area was randomly chosen from non-border rows from the interior of the plot for all row plots and harvested. For equidistant plots, 25 plants from a 5 X 5 square of plants were collected for analysis, again chosen randomly from non-border rows from the interior of the plot. Plants were cut where the stem met the surface of the soil and straight across the stem diameter to ensure accurate height and nodal measurements. Plants were then collected, bagged, and carefully transported to the lab where measurement of the samples was conducted. Measurements were then taken for LPH, node 6, 10, and 14 height, plant height, and nodes $plant^{-1}$ for each plant. Lowest pod height was measured as the vertical height from the ground to the attachment point of the lowest pod to its main stem or branch node. Nodal height measurements were measured as the vertical height of nodes 6, 10, and 14 from the soil surface, where the unifoliolate was the 0 node. Total plant height was measured as the height from the soil surface to the tip of the main stem. Total node number was determined by counting the number of nodes above the unifoliolate node. For each plot LPH, node 6, 10, and 14 heights; plant height; and nodes $plant^{-1}$ were

calculated by taking averages for all plants sampled within that plot. Average internode length was calculated by dividing average plant height by average nodes plant^{-1}.

Statistical Analysis

All statistical analyses for each of the plot averages for nodal and height characteristics were conducted using PROC MIXED (SAS Institute, 2002) in SAS 9.1.2. Year and replication were considered random effects and all other variables fixed. Significance was reported on a basis of $P<0.05$ and mean separations were conducted using Fisher's Protected LSD (Steel and Torrie, 1980).

Results and Discussion:

Rainfall patterns in 2008 and 2009 produced drier than normal conditions but did not vary considerably between years for St. Paul. Waseca, however, was especially dry during the middle of the 2009 growing season (1 Apr. to 30 Sep.), accumulating almost 150 mm less rainfall than in 2008 (data not shown). Irrigation was available in St. Paul and was supplied as needed. Approximately 25 mm of water was applied 3 times in 2008 and 2009. Temperatures were cooler than normal for both years at Waseca and in 2009 at St. Paul but warmer than usual for St. Paul in 2008 (data not shown).

On average between locations, St. Paul had a 2-3 cm higher LPH than Waseca for each cultivar (data not shown). This could be attributable to the 7-8 day later planting date at Waseca than St. Paul that occurred for both years since Beaver and Johnson (1981b) reported that LPH decreased with later planting date.

Maturity study:

Maturity experimentation revealed maturity (cultivar) and population density each affected LPH (Table 3). Population density was found to cause a significant increase in LPH between low (19 plants m^{-2}), mid (31 plants m^{-2}) and high (43 plants m^{-2}) populations (Table 4). The maturity effect on LPH showed no difference between the early and adapted cultivars AG0803 and AG2108. Both cultivars, however, were significantly lower than late maturity cultivar, AG2802 (Table 4). Unlike the findings reported by Edwards and Purcell (2005), there was no interaction between the cultivars used in this study and population (Table 3).

Population density had a significant effect on nodes $plant^{-1}$ (Table 3) where nodes $plant^{-1}$ was highest for the low population density (Table 4). This is in agreement with previous studies that have found decreased nodes $plant^{-1}$ as soybean density increased (Pandey and Torrie, 1973; Ball et al., 2001), and suggests that the number nodes $plant^{-1}$ might have some impact on LPH since population also affected LPH.

Population density was also found to significantly affect average internode length (Table 3), where internode lengths were found to increase in length with increasing population density (Table 4). The effect of density on internode length appeared to be less prominent in the upper nodes. Average internode length and the height of node 6 were not, however, found to be affected by maturity. These results suggest that if internode length is affecting LPH, it is not the only mechanism at work since relative maturity affected LPH without any effect on internode length.

The results of the Maturity study agree with previous studies that the use of increased population density (Hicks et al. 1969; Felton 1976; Lueschen and Hicks 1977; Beaver and Johnson, 1981a; Grabau and Pfeiffer 1990b; Edwards and Purcell 2005; Epler and Staggenborg 2008), as well as the use of cultivars with later relative maturity (Beaver and Johnson, 1981b; Grabau and Pfeiffer, 1990a; Edwards and Purcell, 2005) are effective management tools to increase LPH. The data here suggest that population density effects on LPH may be due to differences in internode length, especially on the lower portions of the plant, since increased height of node 6 and LPH were found to occur simultaneously. Relative maturity may not be affecting LPH through changes in internode length since the lowest pods do not appear to be set based on the height of a particular node across a range of maturities. The highest population density in combination with the latest relative maturity cultivar produced the highest LPH, suggesting that the use of both factors might be the most effective management strategy to increase LPH. Population density and maturity could have additive effects on LPH since both appear to work through separate mechanisms.

Plant Arrangement study:

As with the Maturity study, population significantly affected LPH (Table 3). Row width did not have an effect on LPH (Table 3). The alteration of either population density or row width both affect individual plant spacing; however, the results here suggest that the effects on LPH are attributable only to an increase in density and not directly due to changes in either inter-row or intra-row spacing alone.

A significant effect on nodes plant^{-1} was found due to both population and row width (Table 3). High population density, as was seen in the Maturity study, had fewer nodes plant^{-1} than both mid and low populations, and the 76-cm rows were also found to have fewer nodes plant^{-1} than all other row width treatments (Table 4). Even though high population density and wide rows were found to similarly produce the fewest nodes plant^{-1} only population affected LPH, again suggesting nodes plant^{-1} may not play an important role in determining where the lowest pods form. Although nodes plant^{-1} was seen to be affected within this study by both of the main effects, there was not found to be an effect on average internode length (Table 3). This is likely because the effects on internode length were most obvious in the lowest nodes only (Table 4). Although the height of node 6 was greatest in 76 cm rows, LPH remained unchanged. It appears that where lowest pods form may not be dependant on the height of a particular node.

Mulch study:

Population density within this study was not found to affect LPH. Only plant height and the height of node 10 were affected (Table 3). Numerically, low and high population density produced a similar response in LPH as the maturity and Plant Arrangement studies even though not significant (Table 4). The production of shorter plants within the high population density and the numerically higher LPH suggest that, in contrast with Hicks et al. (1969), increased plant height may not promote increased LPH.

Mulch was found to have a significant effect on LPH (Table 3), red colored mulch produced a higher LPH than both the straw mulch and the control (Table 4). Mulch treatment was not found to affect any other height or nodal characteristics. It appears that within the red mulch treatment low pods formed on slightly higher nodes than in the straw mulch or control treatments since nodal heights were not affected.

Measurement of reflectance spectra of mulches, including bare soil, revealed that red mulch had the highest reflectance in the red portion of the visible light spectrum (greater than about 600 nm), the straw mulch had the highest reflectance throughout the entire spectrum (400 to 800 nm), and the soil had the lowest reflectance in the red light portion but reflectance was slightly higher than the red mulch reflectance for the remaining portion of the visible light spectrum (about 400 to 600 nm) (Figure. 1). Blue light is known to cause a number of responses in plants and may have counteracted the effects that occurred due to increased red light reflectance for the straw mulch. The red colored mulch reflected primarily only red light, which in the absence of blue light reflection may have produced the higher LPH.

Further investigation of the differences between red and control mulch treatments were conducted in 2010 until canopy closure and revealed that just prior to canopy closure (2 July, at R2 stage of maturity) there was a much lower R/FR light ratio found for red mulch upward and horizontal measurements (Figure 2). The effects on LPH were likely not due to differences in PAR since treatments appeared to result in similar PAR for all of the measurements (Figure 3).

The mulch effects on LPH within this study agree with the findings in the maturity and Plant Arrangement studies in that where low pods form may not be

dependant on the height of any particular node. Measurements of soil temperature and moisture were not conducted within this study, so it is unknown whether differences did exist and whether or not those differences might have been responsible for the effects seen on LPH.

Timing of Thinning study:

Timing of thinning was found to have a significant effect on LPH (Table 3). The V1 thinning treatment produced a lower LPH compared to the unthinned control (Table 4), which agrees with the low and high population density comparisons discussed in the maturity and Plant Arrangement studies, since the V1 treatment would simulate an initial low population density. The R3 thinning was also found to have a lower LPH compared to the control (Table 4) and indicates that even with stand reduction as late as R3 that the plants were able to compensate for reduced populations by placing additional pods low within the canopy. The R5 thinning treatment was not found to differ from the control for LPH, suggesting that it was too late in development to produce additional low pods. This indicates that LPH determination may occur between R3 and R5 stages of development.

Plant height was also affected by timing of thinning (Table 3), where R3 thinning resulted in lower plant height than all other treatments including the control (Table 4). This may be an indication that altered carbon allocation to increased branch biomass and less stem elongation occurred within the plots thinned during R3. Similar findings were reported by Conley et al. (2008) who found R1 thinning to produce shortest plants. Soybean are able to compensate for reduced stands by increased

branching as late as R3 (Weil and Ohlrogge, 1976), accumulating the majority of branching dry matter from R1 to R3 (Carpenter and Board, 1997), which may have been why such a low plant height was seen for R1 and R3 stand reduction.

A significant treatment effect was also seen concerning nodes plant^{-1} (Table 3), where V1 stand reduction was found to have more nodes than R5 stand reduction and the control; however, V1 stand reduction was not found to significantly differ from R3 stand reduction (Table 4). This suggests that unlike LPH, nodes plant^{-1} were affected on a gradual basis throughout development.

Average internode length was also significantly affected by thinning treatment (Table 3). The results showed a similar trend to that of LPH where thinning at V1 and R3 produced shorter average internode lengths than the control, and thinning at R5 did not result in internode lengths different from the control. However, these differences were most prevalent for nodes higher on the plant since there were no significant differences between node 6 heights due to thinning and thus average internode length did not likely reflect upon LPH determination. So, in agreement with the maturity, Plant Arrangement, and mulch studies the differences in LPH did not appear to occur in conjunction with changes in the height of the lowest nodes. This indicates that node height and internode length likely do not play a role in LPH determination. The effects of thinning on LPH follow a similar trend to the differences seen between the low and high populations observed in the maturity and Plant Arrangement studies as long as thinning occurs no later than the R3 stage of development.

Conclusions:

Studies here determined that increased population and the use of later relative maturity cultivars are reasonable management strategies to increase LPH in southeastern Minnesota. Population density was the only main effect found to affect both the height of the lowest nodes and LPH simultaneously. Relative maturity, row width, mulch and timing of thinning all affected either LPH or the height of node 6 without a concurrent response in the other, suggesting that there is not a direct relation between LPH and the height of the lowest nodes. Alternatively, the impacts seen on LPH appear to be primarily working through differences in the likelihood of pods being set at a particular node, which might be attributable to differences in light quality beneath the canopy.

Tables:

Table 1. Plant density and spacing after thinning for the Maturity study in St. Paul and Waseca 2008, 2009. Row width for all plots was 51 cm.

Variety	plants m^{-2}	Plant spacing (cm)
AG2108 (MG 2.1)	19 (low)	10.8
	31 (mid)	6.4
	43 (high)	4.6
AG0803 (MG 0.8)	19	10.8
	31	6.4
	43	4.6
AG2802 (MG 2.8)	19	10.8
	31	6.4
	43	4.6

MG is the relative maturity or maturity group for each cultivar. Low, mid, and high denote low, mid, and high population densities within this study.

Table 2. Plant density and spacing after thinning for the Plant Arrangement study in St. Paul and Waseca 2008, 2009. Only variety AG2108 was used.

Row width (cm)	plants m^{-2}	Plant spacing (cm)
25	19 (low)	21.3
25	31 (mid)	12.7
25	43 (high)	9.1
51	19	10.8
51	31	6.4
51	43	4.6
76	19	7.1
76	31	4.3
76	43	3
Equidistant (23.1)	19	23.1
Equidistant (18.0)	31	18
Equidistant (15.2)	43	15.2

Equidistant is defined as the row width such that inter-row and intra-row plant spacing is equal. Low, mid, and high denote low, mid, and high population densities within this study.

Table 3. Analysis of variance for average LPH (lowest pod height), node 6, 10, and 14 heights, plant height, nodes plant^{-1} and average internode length for the maturity, Plant Arrangement, mulch and timing of thinning studies.

Study	Fixed source of variation	df	LPH	Node 6	Node 10	Node 14	Plant height	Nodes plant^{-1}	Average internode length
			---	---	---	*P* >F	---	---	---
Maturity	L (location)	1	NS	NS	NS	NS	NS	NS	NS
	P (population)	2	**	***	*	*	NS	*	*
	C (cultivar)	2	*	NS	*	NS	*	NS	NS
	L x P	2	NS	NS	NS	NS	NS	NS	NS
	L x C	2	NS	NS	NS	*	*	NS	NS
	P x C	4	NS	**	*	NS	NS	NS	NS
	L x C x P	4	NS	NS	NS	NS	NS	NS	NS
Plant Arrangement	L	1	NS	NS	NS	NS	NS	NS	NS
	P	2	*	**	*	NS	NS	*	NS
	R (row width)	3	NS	*	NS	NS	NS	**	NS
	L x P	2	NS	NS	NS	NS	NS	NS	NS
	L x R	3	NS	NS	NS	NS	NS	NS	NS
	P x R	6	NS	NS	**	NS	NS	NS	NS
	L x P x R	6	NS	NS	NS	NS	NS	NS	NS
Mulch	L	1	NS	NS	NS	NS	NS	NS	NS
	P	1	NS	NS	*	NS	*	NS	NS
	M (mulch)	2	*	NS	NS	NS	NS	NS	NS
	L x P	1	NS	NS	NS	NS	NS	NS	NS
	L x M	2	NS	NS	NS	NS	NS	NS	NS
	P x M	1	NS	NS	NS	NS	NS	NS	NS
	L x P x M	2	NS	NS	NS	NS	NS	NS	NS
Timing of thinning	L	1	NS	NS	NS	NS	NS	NS	NS
	T (thin time)	3	*	NS	*	NS	***	*	*
	L x T	3	NS	NS	NS	NS	NS	NS	NS

Significance levels * = < 0.05, ** = < 0.01, *** = < 0.001.
NS = Not significant.

Table 4. The means for LPH (lowest pod height), node 6, 10, and 14 heights, plant height, nodes plant^{-1} and average internode length for the maturity, Plant Arrangement, mulch and Timing of Thinning study.

	LPH (cm)	Node 6 (cm)	Node 10 (cm)	Node 14 (cm)	Plant height (cm)	Nodes plant^{-1}	Average internode length (cm)
Maturity study	---	---	---	---	---	---	---
Low (population)	12.2c	21.3c	46.3c	74.0b	85.5a	15.5a	5.50c
Mid (population)	14.2b	25.8b	54.9b	81.4a	85.1a	14.3b	5.97b
High (population)	15.8a	29.2a	60.4a	83.6a	84.9a	13.5b	6.32a
AG0803 (MG 0.8)	10.9b	25.9a	56.9a	82.8a	84.0b	13.9a	6.07a
AG2108 (MG 2.1)	12.4b	24.3a	49.6b	73.1b	75.7b	13.6a	5.60a
AG2802 (MG 2.8)	18.8a	26.0a	55.1a	83.0a	95.8a	15.7a	6.13a
Plant Arrangement study	---	---	---	---	---	---	---
Low (population)	11.5b	20.9c	44.0c	71.0a	77.8a	14.6a	5.29a
Mid (population)	13.0ab	24.2b	50.5b	74.5a	75.3a	13.8a	5.52a
High (population)	14.4a	26.6a	54.8a	75.9a	74.9a	12.7b	5.87a
Equid (row width)	13.3a	23.0bc	49.6a	73.6a	78.3a	13.7b	5.64a
25 cm (row width)	12.9a	21.6c	47.1a	73.0a	76.6a	14.1a	5.45a
51 cm (row width)	13.2a	25.0ab	50.6a	74.8a	74.6a	13.7b	5.59a
76 cm (row width)	12.6a	26.0a	52.0a	73.9a	74.6a	13.3c	5.58a
Mulch study	---	---	---	---	---	---	---
Low (population)	11.8a	20.3a	44.4b	70.6a	75.9a	14.6a	5.22a
High (population)	15.6a	26.1a	54.5a	77.3a	73.1b	12.5a	5.86a
Control (mulch)	13.0b	22.9a	49.2a	73.5a	73.4a	13.6a	5.48a
Red (mulch)	14.7a	23.4a	49.2a	74.2a	74.9a	13.5a	5.54a
Straw (mulch)	13.4b	23.2a	49.9a	74.1a	75.2a	13.5a	5.96a
Timing of thinning study	---	---	---	---	---	---	---
Control	15.9a	26.5a	55.0a	76.2a	74.6a	12.8b	5.85a
V1 (thinning)	11.6b	21.8a	45.8b	70.3a	75.6a	14.2a	5.24b
R3 (thinning)	11.5b	25.1a	51.9a	69.2a	69.4b	13.3ab	5.24b
R5 (thinning)	15.1a	26.0a	55.1a	77.1a	74.5a	12.9b	5.75a

+Mean separations conducted according to Fisher's Protected LSD test ($P \leq 0.05$). Means with same letter within each box are not significantly different.

Figures:

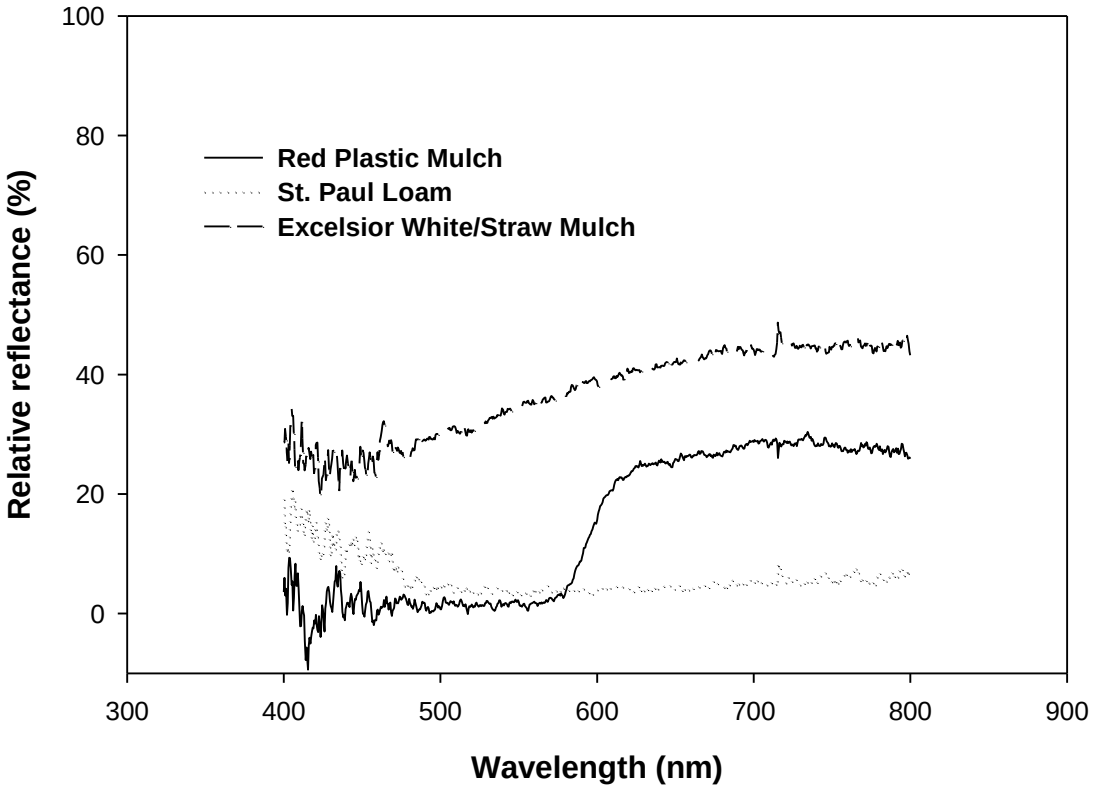

Figure 1. Light reflectance (% transmission) of Mulch study samples SRM® Red Plastic (red mulch), soil sampled from St. Paul (Waukegan silt loam), and Excelsior Erosion Control Natural Blanket with Rapid-Go™ Netting (straw mulch).

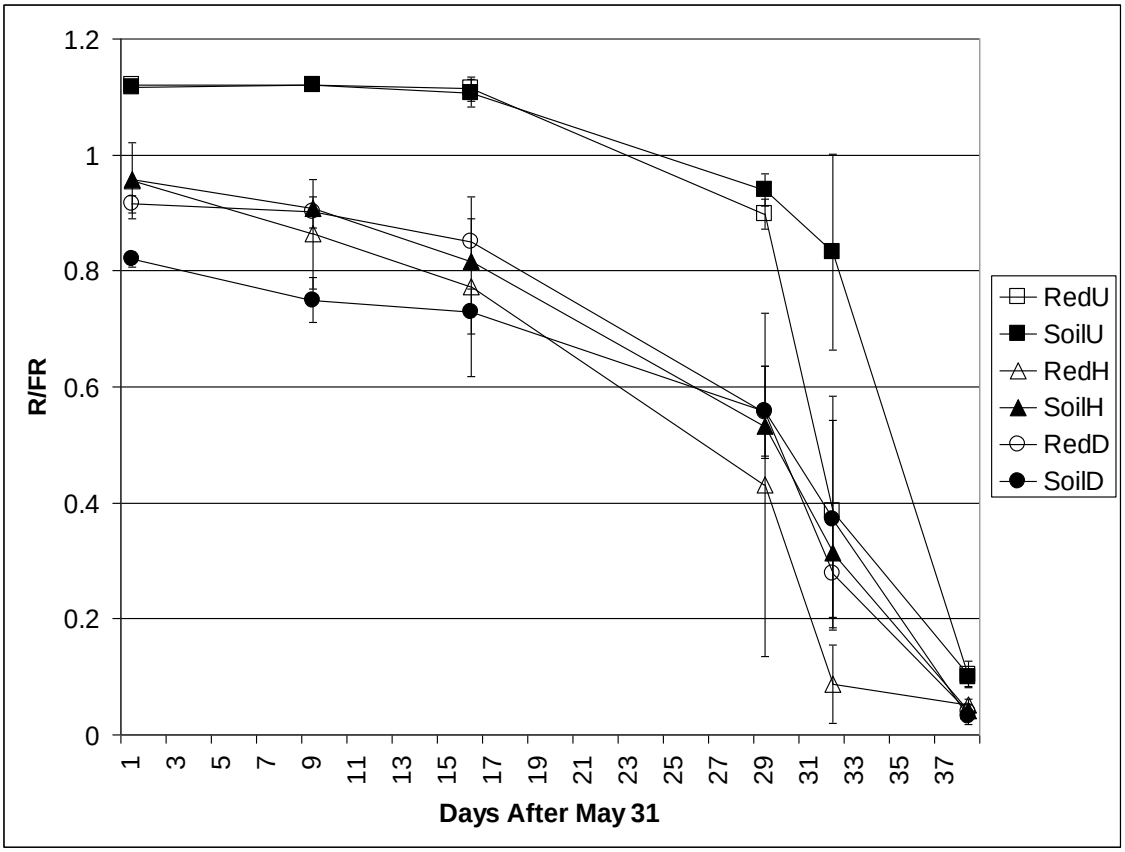

Figure 2. Red to far-red (R/FR) light ratio measurement during the season of 2010 at St. Paul for both red and soil mulch treatments in an upward (U), horizontal (H), and downward (D) sensor position approximately 10 cm above the soil surface. Corresponding plant height/stage measurements were, 5 cm/late VC, 7 cm/late V1, 13 cm/early V3, 30 cm/late R1, 36 cm/R2, and 44 cm/late R2.
+Error bars display ± standard errors.

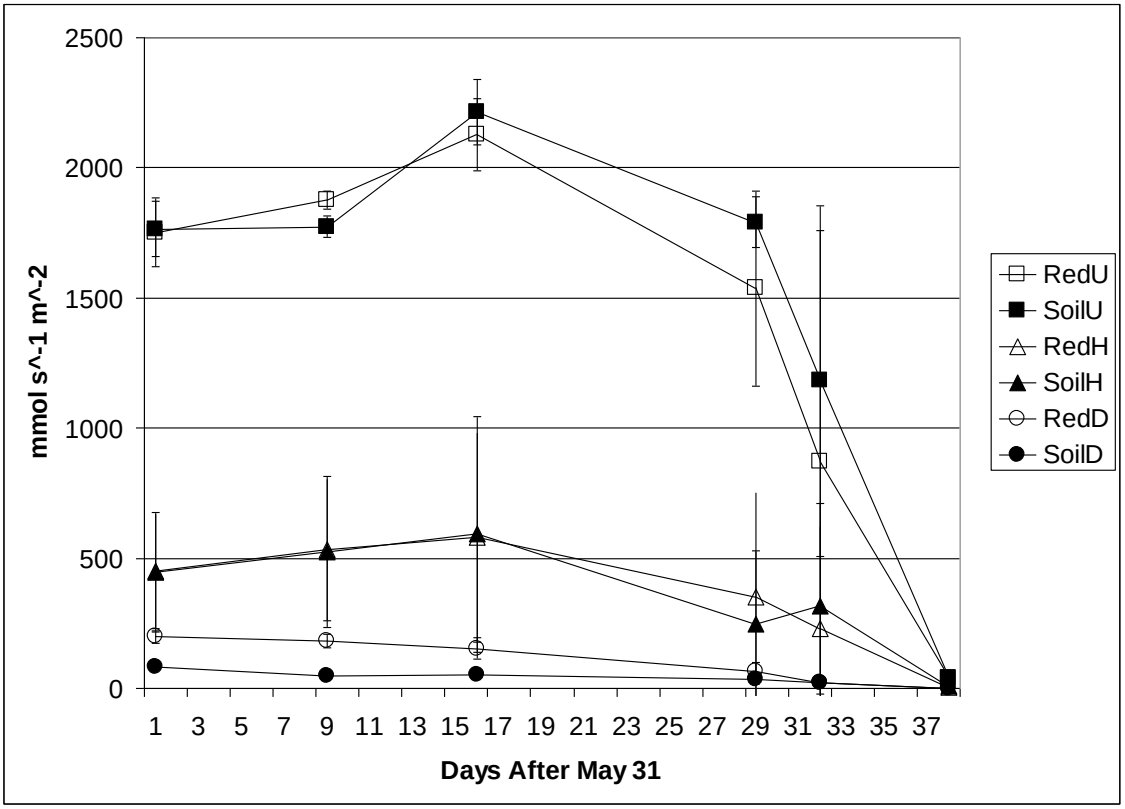

Figure 3. Photosynthetically active radiation (PAR) measurement in μmol s^{-1} m^{-2} during the season of 2010 at St. Paul for both red and soil mulch treatments in an upward (U), horizontal (H), and downward (D) sensor position approximately 10 cm above the soil surface. Corresponding plant height/stage measurements were, 5 cm/late VC, 7 cm/late V1, 13 cm/early V3, 30 cm/late R1, 36 cm/R2, and 44 cm/late R2.
+Error bars display ± standard errors.

Chapter 3

Management Effects on Yield, and Yield Distribution within the Soybean Canopy

Chapter Summary:

Proper management techniques are important for promoting the development of desirable plant characteristics in soybean [*Glycine max* (L.) Merr.] and can affect things such as yield distribution within the canopy. Current management practices in the southern Minnesota region are moving toward lower seeding rates, narrower rows, and reduced tillage. To better evaluate yield and its distribution due to these potential alterations in management strategy, four studies were conducted to determine the effects of population density, relative maturity, row width, mulch color, and stand reduction on soybean yield components and distribution in the southern Minnesota region during 2008 and 2009. Increasing population density from 19 to 43 plants m^{-2} was found to decrease branch yield from 250 to 99 g m^{-2} and increase yield for main stem nodes 0-10 from 118 to 189 g m^{-2}. Lengthening relative maturity from 0.8 to 2.8 resulted in node 0-6 yield dropping from 64.2 to 18.9 g m^{-2} without any other effects noted. Row width and mulch treatment did not show any significant effect on overall yield or yield distribution. Reducing stands from 43 to 19 plants m^{-2} resulted in an individual seed size for nodes 11-14 of 185 mg $seed^{-1}$ for R5 thinning, 175 mg $seed^{-1}$ for R3 thinning and 160 mg $seed^{-1}$ for the unthinned control. Stand reduction at R3 resulted in increased pod set and increased individual seed size on the uppermost portions of the canopy while stand reduction at R5 resulted in only the production of larger seeds. Results here show that soybeans were able to produce yields similar to the unthinned control with stand reduction occurring as late in the season as R3 with a final

plant population of 19 plants m^{-2} due to both an increase in pod set and increased individual seed size.

Introduction:

Management strategy is important in promoting maximal yield in soybean [*Glycine max* (L.) Merr.] and is directly affected by yield distribution on the plant and yield components. One characteristic that might be particularly interesting is yield distribution within the canopy and its relation to harvest efficiency and maximizing overall yield.

Increasing population density in soybean has been generally shown to increase yield, with less yield gain from seeding above sufficient densities (Miura et al., 1987; Rigsby and Board, 2003; Cober et al., 2005; Edwards and Purcell, 2005; Epler and Staggenborg, 2008). Several studies have also confirmed that soybean distributes relatively more yield to branches at low population densities and more yield to the main stem in high population densities (Lehman and Lambert, 1960; Weber et al., 1966; Pandey and Torrie, 1973;Kasperbauer, 1987; Miura et al., 1987; Boquet, 1990; Epler and Staggenborg, 2008). In more dense stands of soybean, a lower R/FR (red/far-red) light ratio beneath the canopy may be contributing to less branch production, thereby reducing individual plant yield (Kasperbauer, 1987; Carpenter and Board 1997; Board, 2000).

At defined populations, soybean intra-row plant spacing is not only influenced by population density, but also through inter-row spacing. Recent studies investigating the effects of row width have reported an increase in soybean yield due to narrow rows

(Ball et al., 2000; Bowers et al., 2000; Pedersen, 2008), where the most recent reported a 6-7% increase in yield between 76 and 38 cm rows. It is generally believed that the primary effect of decreased row width on soybean is that it creates more equal inter-row and intra-row plant spacing, causing less competition for resources and promoting higher yield (Weber et al., 1966; Miura et al., 1987; Ethredge et al., 1989).

In addition to population density, row width has also been reported to affect the R/FR light ratio in the canopy. A lower ratio of R/FR was found for 20 cm rows compared to 100 cm rows throughout the entire day (Kasperbauer, 1987). Both narrow rows and dense population stands have been reported to cause low R/FR light ratios beneath the canopy; however, they act differently in their branch yield production. This may be an indication that R/FR light may not be a primary factor determining branch yield as has been suggested by previous studies.

Studies have shown that in recent years the Midwest, eastern, and southeastern states that more adoption of conservation tillage practices are being implemented for glyphosate resistant soybean cultivars (Givens et al. 2009). Not only have studies reported that reduced tillage helps to better retain soil water content (Ojeniyi, 1986; Frederick et al. 1998), but also that reduced tillage maintains a lower and more consistent soil temperature (Johnson and Lowery, 1985). In a study conducted in Wisconsin it was recently reported that there was a 6% higher yield for soybean grown in conservational tillage (no-till) compared to conventional tillage (Pedersen and Lauer 2003).

Red and far-red light or other types of light frequencies such as blue light may also be important to investigate in addition to the other effects of using conservation

tillage practices. Myers et al. (1987) reported that an increased amount of supplemental red light in comparison to far-red light caused a significant increase in pod set. Hunt et al. (1989) reported that there was little difference between the R/FR ratio of light reflected from white and black mulches meant to simulate differences between conservational and conventional tillage. They did, however, report that there was more blue light reflected from the white mulch.

Abiotic and biotic factors within an agricultural environment are often times unpredictable, and thus there is always the potential for reduction in soybean stand. Teigen and Vorst (1975) reported that 50% stand reduction from 289,000 plants ha^{-2} occurring at V7 had no significant effect on yield; however, at R3, yield was found to be reduced. They reasoned that their findings were due to the fact that at R3 plants were already past the point of full bloom and several flowers might have already been aborted, rendering less capacity for increased pod set. Conley et al. (2008) observed that soybean was able to adequately compensate for stand reduction occurring at or before the R1 stage of development, as long as the final plant population was at least 247,000 plants ha^{-1}.

Although several studies have evaluated differences in main stem and branch yield due to various management practices, the effects on the nodal distribution of yield due to alternate management strategies have yet to be characterized. Studies suggest that we can produce similar yields with lower soybean density (Conley et al., 2008) and that planting in narrow rows can improve overall yield (Ball et al., 2000; Bowers et al., 2000; Pedersen, 2008). Also with increased use of conservation tillage practices

(Givens et al. 2009), management strategies are changing and their effects on yield and components need to be evaluated.

The objectives of this study are to: (i) determine the effects of population and cultivar relative maturity on yield and its distribution within the canopy; (ii) determine how population and row width affect yield distribution through their effects on inter-plant spacing; (iii) determine how various types of mulches affect yield through light quality; and (iv) determine soybean yield and distributional effects due to stand reduction at various times during the season.

Materials and Methods:

Experimentation setup, planting, and management were as described in chapter 2. Harvest sampling consisted of the same area utilized for height and nodal measurements (Chapter 2)

Yield Distribution

Yield distribution was evaluated by sorting the pods from the hand harvested samples into groups by nodal strata. Groups consisted of branches, nodes 0-6, 7-10, 11-14, and 15+ (where 0 represents the unifoliolate node). Total main stem yield was determined mathematically by taking the sum of all non-branch yield groups for each plot and total yield was determined by summing the yield of all groups. Yields were calculated on an as-is moisture basis, where seeds were dried down and then subsequently allowed to accumulate moisture at room temperature for at least 3 weeks prior to weighing. The number of pods, seeds, and total yield weight within each of

these groups was measured by hand counting and weighing, and then used to calculate seeds pod^{-1} and mg $seed^{-1}$ within each group for analysis.

Total Yield

Overall yield was determined by hand harvesting 1.5 m^2 from the interior of each row plot. For equidistant plots, a 5 X 5, 6 X 6, or 7 X 7 plant block from 19, 31 and 43 plants m^{-2} treatments, respectively, was harvested for overall yield determination from an area ranging from 1.0 m^2 to 1.3 m^2. Samples were later threshed and weighed using an Almaco plot combine (Nevada, IA). All plot harvests obtained were converted to g m^{-2} for analysis.

Statistical Analysis

All statistical analyses were conducted using PROC MIXED (SAS Institute, 2002) in SAS 9.1.2. Year and replication were considered random effects and all other variables fixed. Significance was reported on a basis of $P<0.05$ and mean separations were conducted using Fisher's Protected LSD (Steel and Torrie, 1980).

Results and Discussion:

Rainfall and weather conditions were the same as those described in chapter 2. No significant treatment effect on seeds per pod were noted in these studies and in only one instance was individual seed weight found to be affected. Thus, impacts on yield distribution are further discussed in terms of total weight, which would be directly

due to differences in pod set for all instances except where individual seed size was affected.

Maturity study:

There were no overall yield differences within the Maturity study. There were only found to be effects on yield distribution within the canopy. Population density was found to significantly affect branch yield (Table 1). Branch yield decreased as population was increased (Table 2). These effects of population density on branching are well known and similar trends have been reported by previous studies (Boquet, 1990; Carpenter and Board, 1997; Epler and Staggenborg, 2008).

The node 0-6 and 7-10 yields were also found to be significantly affected by population (Table 1). Yield for nodes 0-6 and 7-10 increased as population density increased (Table 2). Boquet (1990) also observed this trend within higher densities where more pods were set on main stem nodes instead of being extended out onto branch nodes.

A significant cultivar effect on node 0-6 yield was also found (Table 1). Node 0-6 yield was reduced with later relative maturity (Table 2). This was probably not due to yield tradeoffs node 0-6 and branch yield, as was seen due to population density, since there was no significant cultivar effect on branch yield due to maturity (Table 1). The latest relative maturity cultivar AG2802 produced the least yield on the node 0-6 group. This is in good agreement with findings from Grabau and Pfeiffer (1990b), who reported that for both the 0-10 and 0-15 cm portions of the plant there was a significantly higher percent yield for the earlier maturity cultivar (Pella, MG III)

compared to the later one (Mitchell 450, late MG IV). These results also agree with the earlier findings that later maturity increases LPH (Chapter 2) since an increase in LPH would occur in conjunction with less yield formation on the lowest node group. Additionally, population and maturity length were not found to have any effect on overall yield, so the upward movement in yield formation was causing larger yields within the upper portions of the canopy.

Plant Arrangement study:

Population density and row width were not found to affect overall yield within the Plant Arrangement study (Table 1). There were significant population effects on how the yield was distributed to branches, node 0-6, and node 7-10 (Table 1) due to increased population density (Table 2), showing the same trend as was seen in the Maturity study. The analysis of yields summed across groups, however, showed a significant row width effect (Table 1). Yields were higher for 25-cm rows compared to equidistant rows (Table 2). Lodging was not evident in either year at either location within the equidistant plots. This trend is similar to that obtained for overall yield for each row width treatment even though those results were not significantly different from one another (data not shown). This may be because, as was suggested by Egli (1994), some cultivars will respond better to narrow rows than others. Only cultivar AG2108 was tested in experimentation here and other cultivars might have responded differently to alternate row width.

Mulch study:

Experimentation with colored mulches revealed no significant effects on overall yield, or its distribution within the canopy. The increased LPH due to the red colored mulch (Chapter 2) without a concurrent effect on yield or its distribution agrees with the findings of Martin and Wilcox (1973), who reported that yield and lowest pod height were not closely associated. According to the spectroradiometer data (Chapter 2, Figure 1) differences in the frequencies of light reflected between mulch treatments were present. Horizontally and upwardly reflected R/FR light was lower for red mulch plots than control plots on 2 July, just prior to canopy closure (R2 stage of maturity (Chapter 2, Figure 2)). No other significant differences were found, so it may be that the effects of colored mulches on R/FR light are only occurring in the few days just prior to canopy closure. However, the lack of effect on yield due to colored mulches suggests that the differences in R/FR may not have been large enough or sustained through a long enough period to have an impact on yield. Differences in PAR between soil and red mulch were minimal (Chapter 2, Figure 3) and support the lack of yield effect found.

Timing of Thinning study:

Timing of thinning had significant effects on overall yield due to both location and thin time (data not shown). Location yields averaged across thinning treatments and years were 334 g m^{-2} at Waseca while St. Paul plots yielded only 260 g m^{-2} (data not shown). The higher yield found at Waseca might have been due to soybeans at that location having higher branching yield than at St. Paul. The branch

yield averaged across thinning treatments and years for each location, even though not significantly different, was 113 g m^{-2} at Waseca and 80 g m^{-2} at St. Paul (data not shown) and may indicate that greater branching was important in achieving greater overall yields.

Comparing overall yield means for thinning time averaged across locations showed that although numerically different, overall yield for R3 stand reduction (296 g m^{-2}) was not significantly different from V1 stand reduction (358 g m^{-2}) or the control (313 g m^{-2}), indicating that stand reduction through R3 was still able to produce yields comparable to the control. Stand reduction at R5 (239 g m^{-2}) showed significantly reduced yield compared to both V1 and the unthinned control. However, R5 thinning was found to not significantly differ from R3 thinning for overall yield, so it appears that the yield declined only gradually as stand reduction occurred later into maturity. In agreement with this study it was reported by Conley et al. (2008) that stand reductions at R3.5 or later significantly reduced yield compared to unthinned control. It was also reported by Conley et al. (2008) that soybean could adequately compensate for stand reduction by increased branching and pod set as late as R1 if the final population was no less than 247,000 plants ha^{-1}. However, the results here suggest that soybean are able to compensate to stand reduction as late as R3 if final stand is at least 185,000 plants ha^{-1}.

Yield distribution was significantly affected by thin time for branches, node 7-10, and main stem (Table 1). The V1 stand reduction treatment resulted in highest branching yield. Branch yield for the unthinned control was not found to differ from R3 or R5 stand reductions; however, R3 stand reduction had significantly greater

branch yield than R5 (Table 3). The control was found to have the highest node 7-10 and main stem yield compared to all other treatments (Table 3). Treatments V1 and R5 were found not to differ from each other for main stem yield; however, both were found to have significantly less main stem yield than the R3 stand reduction treatment (Table 3). In order to produce sufficient yield compared to the control, the canopy had to produce enough yield from the main stem and branches. Yield distribution differences produced with V1 stand reduction compared to the control resulted in similar differences to those seen between low and high population density in the Maturity and Plant Arrangement studies. Soybean stands thinned at R3 were somewhat less able to produce yield on branches in order to compensate for reduced stand numbers than the V1 treatment; however, the R3 treatment was able to increase main stem pod set. The increase in both branching and main stem yield produced similar yields for the R3 treatment compared to the unthinned control. The R5 stand reduction, treatment on the other hand, occurred too late in development for a sufficient increase in either branching or main stem yield within the canopy and thus overall yields suffered compared to the control.

Seed size tended to increase with later thinning; however, a significant effect was noted only in the node 11-14 group (data not shown). The R3 and R5 thinning produced larger seeds than V1 and unthinned control treatments (Table 4). This was seen without any significant effect on the number of pods, seeds or seeds pod^{-1}. Larger individual seed size was not found to increase total yield for nodes 11-14, which is supported by previous studies reporting that individual seed size was relatively

unimportant in determining yield (Pandey and Torrie, 1973; Egli et al., 1978; Frederick et al., 1998).

Conclusions:

Higher plant populations increased node 0-10 yield while simultaneously reducing branch yield, clearly demonstrating the tradeoffs between branch and main stem yield due to population. Planting later relative maturity cultivars reduced the yield on nodes 0-6 without any other effect on overall yield or its distribution, indicating that more yield was concentrated in the higher portions of the canopy. Colored mulches did not affect yield or its distribution within the canopy even though R/FR light was found to be lowest for the red mulch near canopy closure while soybean plants were at full bloom. This suggests that light quality may not play a role in within-canopy yield distribution or overall yield. Stand reduction from 43 to 19 plants m^{-2} revealed that plants were able to compensate to reduced stands and produce similar yields to the control through R3 stage of maturity. Soybean density and the length of exposure to this particular density appear to be the primary factors in determining growth pattern in terms of yield distribution. As length of exposure to a low population density is increased, the response will more closely simulate the response of an initially low population.

Tables:

Table 1. Analysis of variance for total (Total), branch (BRCH), main stem (MS), node 0-6, node 7-10, node 11-14, and node 15 and above (node 15+) yield groups for the maturity, Plant Arrangement, mulch and timing of thinning studies.

Study	Fixed Source of Variation	Df	Total	BRCH	MS	Node 0-6	Node 7-10	Node 11-14	Node 15+
								P > F	
Maturity	L (location)	1	NS	NS	NS	NS	NS	NS	NS
	P (population)	2	NS	*	NS	*	*	NS	NS
	C (cultivar)	2	NS	NS	NS	*	NS	NS	NS
	L x P	2	NS	NS	NS	NS	NS	NS	NS
	L x C	2	NS	NS	NS	NS	NS	NS	NS
	P x C	4	NS	NS	NS	NS	NS	NS	NS
	L x C x P	4	NS	NS	NS	NS	NS	NS	NS
Plant Arrangement	L	1	NS	NS	NS	NS	NS	NS	NS
	P	2	NS	*	NS	*	*	NS	NS
	R (row width)	3	*	NS	NS	NS	NS	NS	NS
	L x P	2	NS	NS	NS	NS	NS	NS	NS
	L x R	3	NS	NS	NS	NS	NS	NS	NS
	P x R	6	NS	NS	NS	NS	NS	NS	NS
	L x P x R	6	NS	NS	NS	NS	NS	NS	NS
Mulch	L	1	NS	NS	NS	NS	NS	NS	NS
	P	1	NS	NS	NS	NS	NS	NS	NS
	M (mulch)	2	NS	NS	NS	NS	NS	NS	NS
	L x P	1	NS	NS	NS	NS	NS	NS	NS
	L x M	2	NS	NS	NS	NS	NS	NS	NS
	P x M	1	NS	NS	NS	NS	NS	NS	NS
	L x P x M	2	NS	NS	NS	NS	NS	NS	NS
Timing of thinning	L	1	NS	NS	NS	NS	NS	NS	NS
	T (thin time)	3	*	*	*	NS	*	NS	NS
	L x T	3	NS	NS	NS	NS	NS	NS	NS

Significance levels * = < 0.05, ** = < 0.01, *** = < 0.001
NS = Not significant

Table 2. Means for total (Total), branch (BRCH), main stem (MS), node 0-6, node 7-10, node 11-14, and node 15 and above (node 15+) yield (g m^{-2}) groups for the maturity and Plant Arrangement studies.

	Total	BRCH	MS	Node 0-6	Node 7-10	Node 11-14	Node 15+
Maturity	---	---	---	---	---	---	---
Low (population)	413a	197a	213a	24.7b	79.4b	84.3a	25.5a
Mid (population)	362a	108b	254a	43.9a	114a	77.3a	18.7a
High (population)	357a	82.7b	274a	54.7a	130a	75.5a	13.0a
AG0803 (MG 0.8)	366a	106a	259a	64.2a	112a	69.8a	12.0a
AG2108 (MG 2.1)	378a	149a	229a	40.3b	113a	63.6a	11.7a
AG2802 (MG 2.8)	387a	133a	254a	18.9c	98.3a	104a	33.5a
Plant Arrangement	---	---	---	---	---	---	---
Low (population)	445a	250a	195a	25.2b	92.4c	63.4a	16.1a
Mid (population)	377a	139b	241a	40.0a	116b	69.8a	13.0a
High (population)	362a	99.1b	265a	51.0a	138a	69.3a	7.78a
Equid. (row width)	350b	144a	202a	30.2a	99.8a	63.6a	11.4a
25 cm (row width)	440a	188a	256a	39.4a	126a	75.6a	14.8a
51 cm (row width)	392ab	152a	240a	40.8a	118a	65.6a	14.3a
76 cm (row width)	396ab	162a	236a	44.6a	118a	65.2a	8.80a

+Mean separations conducted according to Fisher's Protected LSD test. Means with same letter within each box are not significantly different.

Table 3. Means for total (Total), branch (BRCH), main stem (MS), node 0-6, node 7-10, node 11-14, and node 15 and above (node 15+) yield (g m^{-2}) groups for timing of thinning studies.

	Total	BRCH	MS	Node 0-6	Node 7-10	Node 11-14	Node 15+
Control	352a	85.3bc	268a	51.6a	145a	65.4a	5.62a
V1	360a	166a	199c	26.7a	96.5b	58.2a	13.4a
R3	332a	114b	220b	46.0a	111b	56.0a	7.50a
R5	234b	61.9c	171c	34.5a	91.6b	42.9a	4.78a

+Mean separations conducted according to Fisher's Protected LSD test. Means with same letter within each box are not significantly different.

Table 4. Means for seed weight (mg $seed^{-1}$) within the total (Total), branch (BRCH), main stem (MS), node 0-6, node 7-10, node 11-14, and node 15 and above (node 15+) yield groups for the maturity, Plant Arrangement, mulch and timing of thinning studies.

	Total	BRCH	MS	Node 0-6	Node 7-10	Node 11-14	Node 15+
Control	168a	159a	170a	169a	177a	160b	159a
V1	160a	159a	165a	169a	170a	160b	153a
R3	176a	170a	178a	173a	182a	175a	175a
R5	183a	174a	186a	182a	190a	185a	184a

+Mean separations conducted according to Fisher's Protected LSD test. Means with same letter within each box are not significantly different.

Chapter 4

Summary

Relative maturity is important in determining LPH (Chapter 2) and within-canopy yield distribution (Chapter 3). Yield distribution to main stem nodes 0-6 was found to decrease in conjunction with an increase in LPH for later maturities without any other effects on overall yield. This suggests that harvest losses could be minimized with the use of later maturing cultivars. This study could have benefitted from an additional cultivar for each relative maturity tested to verify that the effects being seen were due entirely to maturity. It might also be interesting to determine if flowering date is a main determinant of LPH by tagging individual plants based on their beginning flowering time (R1) and then measuring the LPH to determine if a correlation exists between flowering time and LPH. The node number in addition to height measurement of the lowest pod should also be taken into account since this could verify if LPH differences seen were due to internode length or formation of pods on different nodes.

The effects of population on harvest efficiency were less clear than that of relative maturity. Increasing the population density did effectively raise LPH (Chapter 2), suggesting increased harvest efficiency. However, it also increased yield for main stem nodes 0-6 (Chapter 3). The branch yield and node 0-6 yield in relation to their height from the soil surface was not well quantified so it is difficult to make predictions about which would be more susceptible to cutterbar loss. The simultaneous increase in node 0-6 yield and decrease in branch yield due to increased population density make it difficult to recommend an optimal planting density that will adequately reduce harvest losses. It would be valuable for future studies to more clearly organize branching and

main stem yield according to the distance pods are located from the soil for a more direct comparison to cutterbar height.

In the Mulch study, LPH was maximized using red mulch, suggesting that the R/FR light ratio may have some impact on lowest pod formation (Chapter 2). Future investigation should utilize colored mulches of similar material (i.e., black and white plastics) to eliminate any confounding differences that may have caused the treatment differences seen here and determine whether or not the R/FR light ratio or blue light are having a major effect on the responses in LPH, yield, and yield distribution.

The Timing of Thinning study indicated that LPH was determined between R3 and R5 (Chapter 2). Differences in environment between years and locations varied and could have had an impact on the threshold at which LPH determination occurs. Future studies should have more intermediate treatments around R3 to R5 to determine if this really is a threshold change or if a linear trend exists between the two stages of development.

The results from the lowest pod studies showed that LPH increased with increasing population, later relative maturity, and the use of red mulch (Chapter 2); however, overall yield was not affected by altering any of these management strategies (Chapter 3). This lack of association between LPH and overall yield was also reported by Martin and Wilcox (1973) and again suggests that management and breeding practices directed to increase LPH can do so without negatively affecting yield.

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Appendix

Tables:

Table 1. Yield means (g m^{-2}) for Maturity study averaged across years for locations St. Paul and Waseca.

Maturity						
St. Paul				**Waseca**		
Variety (MG)	Population (plants m^{-2})	Yield (g m^{-2})		**Variety (MG)**	Population (plants m^{-2})	Yield (g m^{-2})
AG2108 (2.1)	19	374		AG2108 (2.1)	19	319
	25	361			25	358
	31	364			31	334
	37	370			37	337
	43	334			43	360
	49	318			49	318
	56	355			56	340
AG0803 (0.8)	19	326		AG0803 (0.8)	19	328
	31	329			31	346
	43	286			43	328
AG2802 (2.8)	19	292		AG2802 (2.8)	19	382
	31	274			31	394
	43	281			43	340

Table 2. Yield means (g m^{-2}) for Plant Arrangement study averaged across years for locations St. Paul and Waseca.

Plant Arrangement						
St. Paul				**Waseca**		
Row Width (cm)	Population (plants m^{-2})	Yield (g m^{-2})		**Row Width (cm)**	Population (plants m^{-2})	Yield (g m^{-2})
25	19	320		25	19	409
25	31	330		25	31	383
25	43	300		25	43	357
51	19	358		51	19	376
51	31	323		51	31	374
51	43	327		51	43	374
76	19	319		76	19	346
76	31	304		76	31	357
76	43	332		76	43	354
Equid. (23.1)	19	320		Equid. (23.1)	19	340
Equid. (18.0)	31	312		Equid. (18.0)	31	291
Equid. (15.2)	43	262		Equid. (15.2)	43	266
Equid. (13.5)	56	336		Equid. (13.5)	56	292
Equid. (11.2)	80	303		Equid. (11.2)	80	265

Equid. indicates equidistant treatment.

Table 3. Yield means (g m^{-2}) for the Mulch study averaged across years for locations St. Paul and Waseca.

Mulch						
St. Paul				**Waseca**		
Mulch	Population (plants m^{-2})	Yield (g m^{-2})		**Mulch**	Population (plants m^{-2})	Yield (g m^{-2})
Control	19	333		Control	19	389
Control	43	328		Control	43	348
Red	19	394		Red	19	395
Red	43	363		Red	43	332
White	19	425		White	19	354
White	43	352		White	43	347

Table 4. Yield means (g m^{-2}) for Timing of Thinning study averaged across years for locations St. Paul and Waseca.

Timing of thinning				
St. Paul			**Waseca**	
Timing of Thinning	Yield (g m^{-2})		**Timing of Thinning**	Yield (g m^{-2})
Control	267		Control	357
V1	320		V1	399
R3	267		R3	327
R5	187		R5	254

Figures:

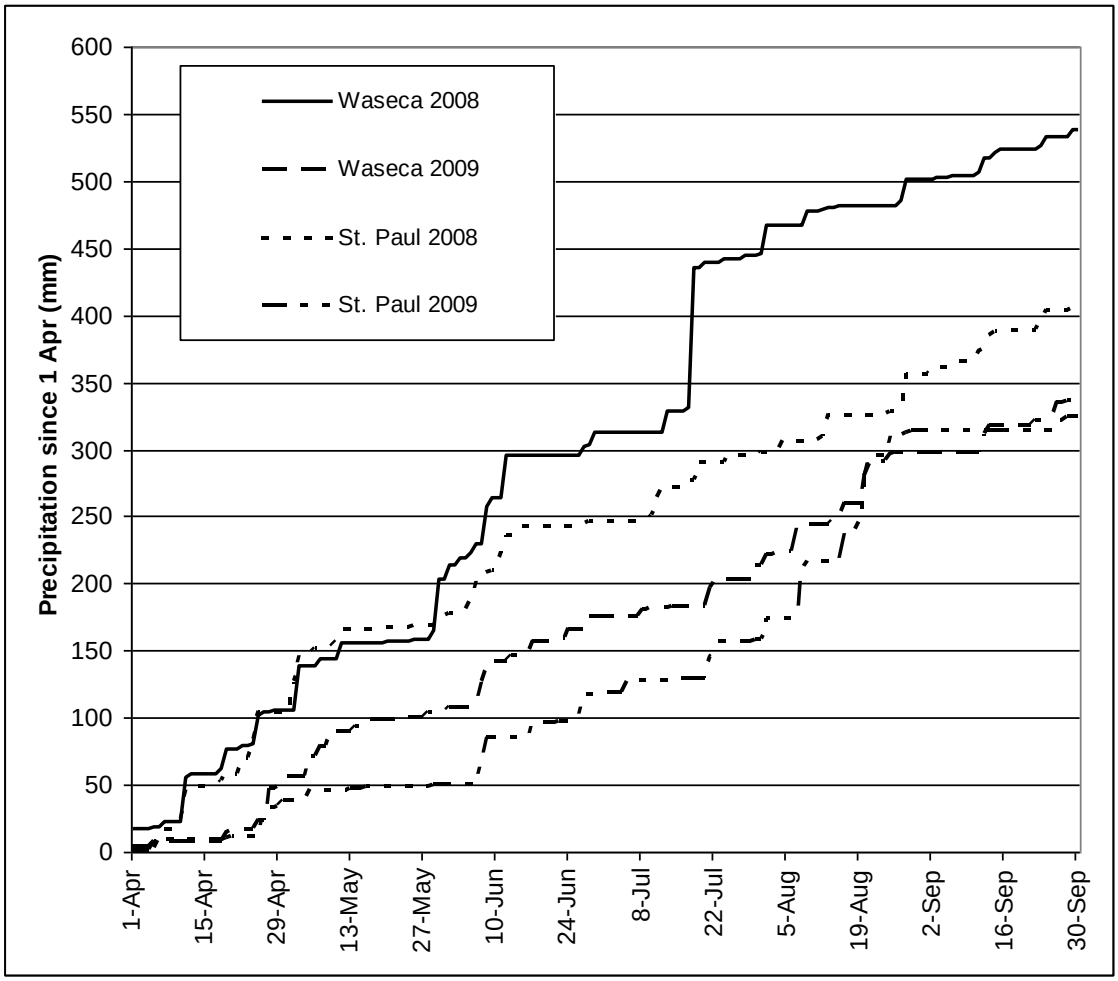

Figure 1. Precipitation (mm rainfall) from 1 Apr. to 30 Sep for locations St. Paul and Waseca in 2008 and 2009.

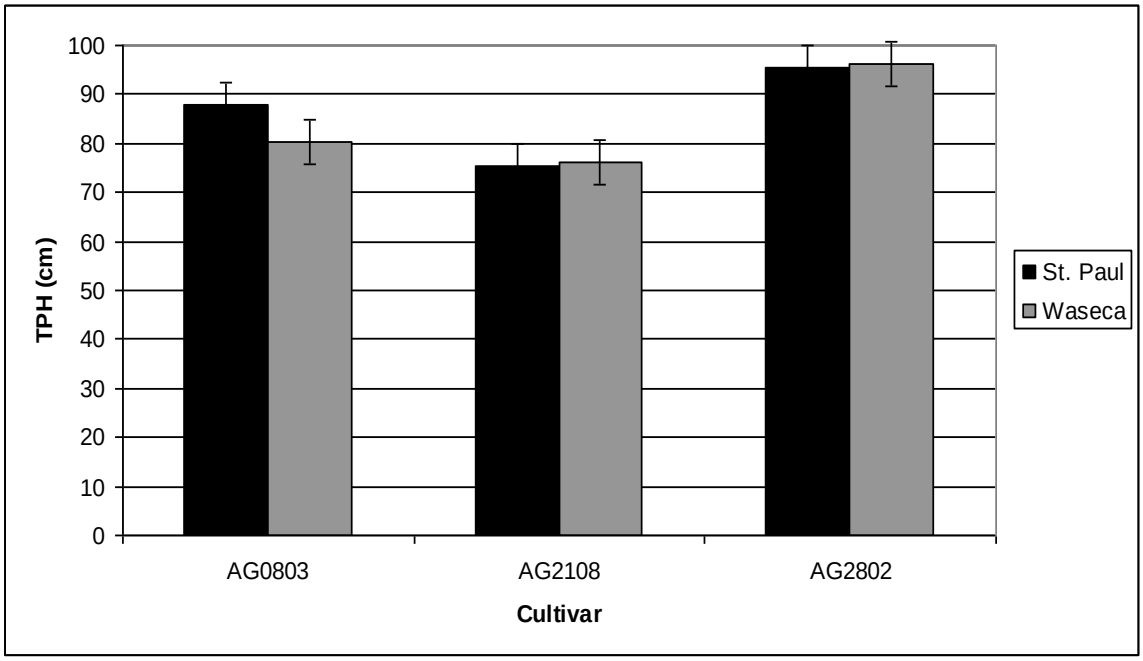

Figure 2. Plant height (cm) within the Maturity study for cultivars AG0803, AG2108 and AG2802, for St. Paul and Waseca averaged across population.
+Error bar lines represent ± standard error.

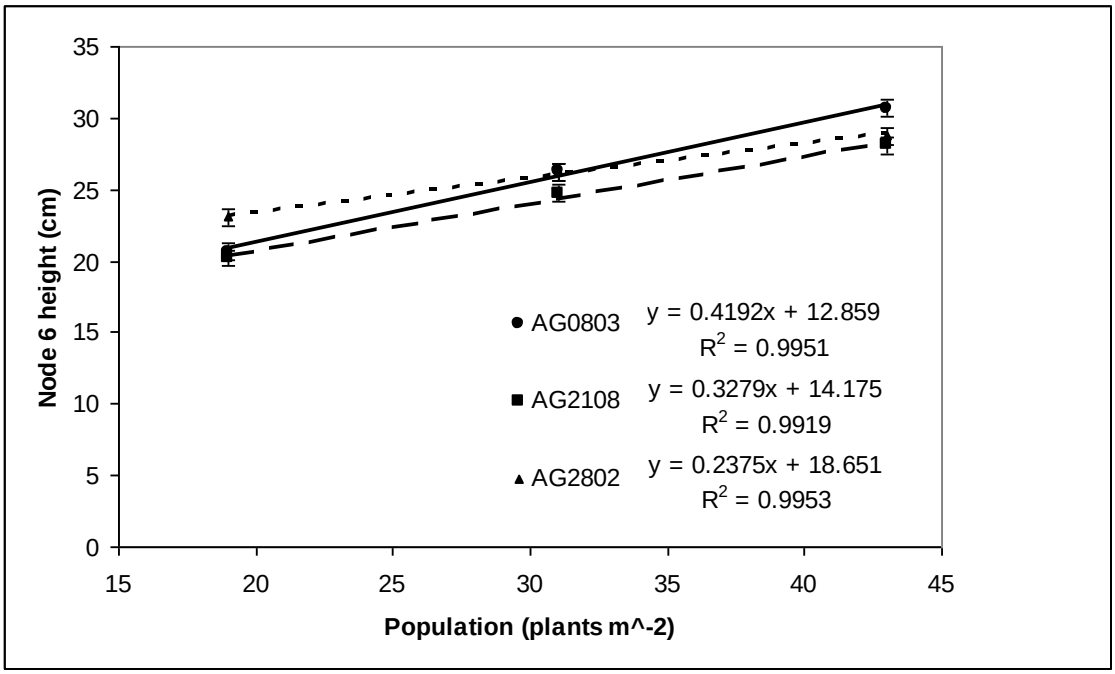

Figure 3. The height of node 6 (cm) means averaged across locations within the Maturity study plotted at low (19 plants m^{-2}), mid (31 plants m^{-2}), and high (43 plants m^{-2}) population densities and fitted with a linear trend line for each cultivar.
+Error bar lines represent ± standard error.

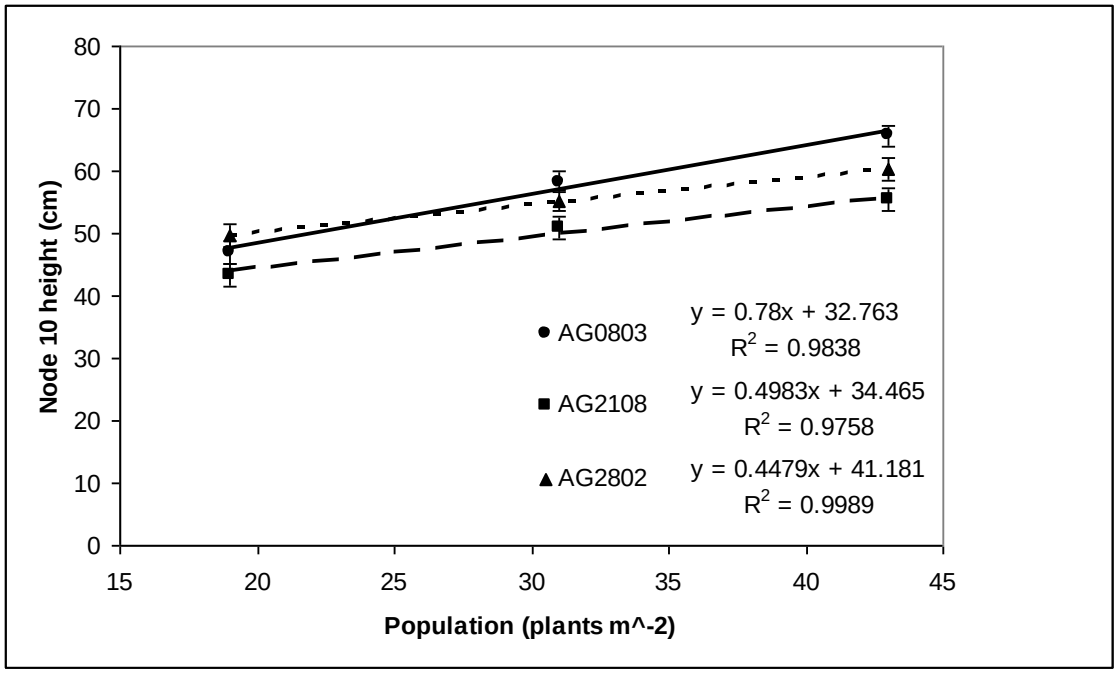

Figure 4. The height of node 10 (cm) means averaged across locations within the Maturity study plotted at low (19 plants m^{-2}), mid (31 plants m^{-2}), and high (43 plants m^{-2}) population densities and fitted with a linear trend line for each cultivar.
+Error bar lines represent ± standard error.

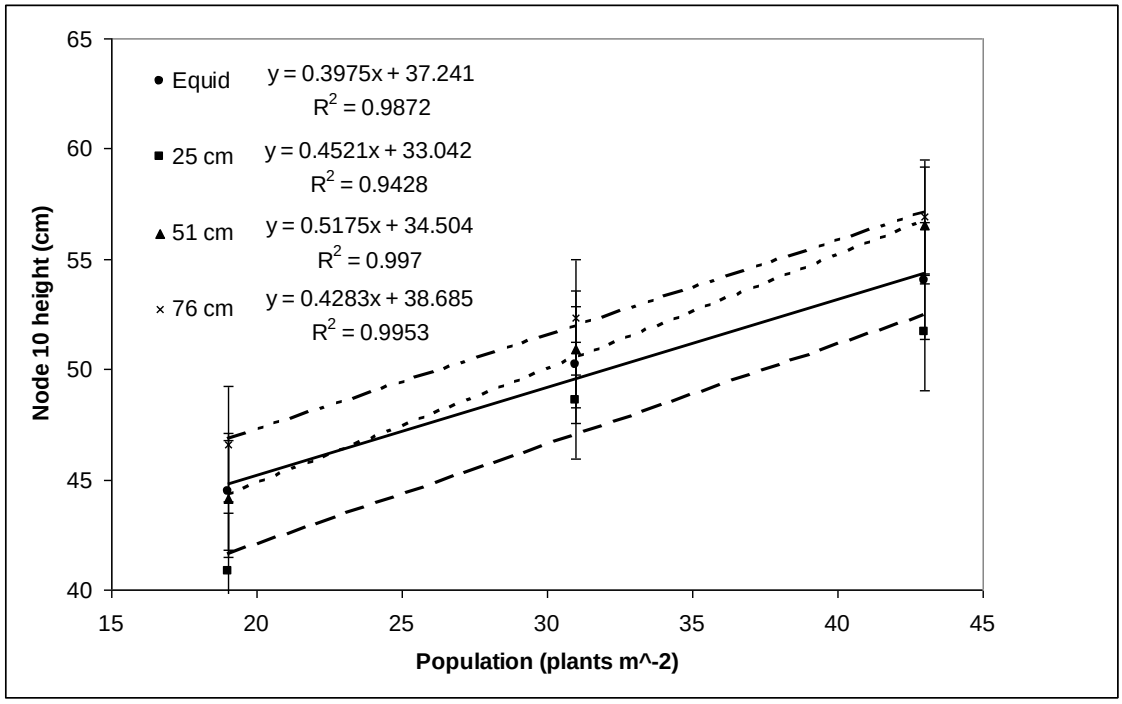

Figure 5. The height of node 10 (cm) means averaged across locations within the Plant Arrangement study plotted at low (19 plants m^{-2}), mid (31 plants m^{-2}), and high (43 plants m^{-2}) population densities and fitted with a linear trend line for each row width treatment.

+Error bar lines represent ± standard error.

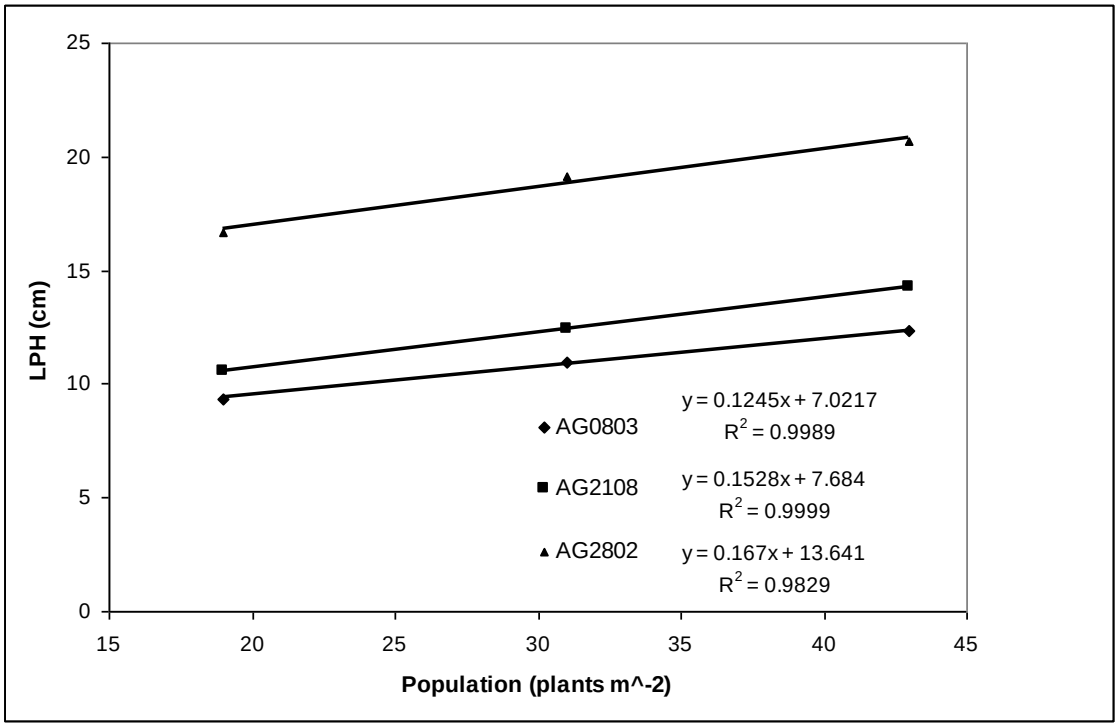

Figure 6. LPH (lowest pod height) means for the Maturity study averaged across years and locations for cultivars AG0803, AG2108 and AG2802.