OPTIMUM PLANT DENSITY FOR CROWDING STRESS TOLERANT PROCESSING SWEET CORN IN THE UPPER MIDWEST

BY

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THESIS

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ABSTRACT

Advances in grain yield of field corn (*Zea mays* L.) over the last quarter century have been driven in large part by the ability of modern hybrids to better tolerate higher plant densities (i.e., crowding stress) than their predecessors. Yield gains in processing sweet corn, however, pale in comparison to field corn. Recent studies have identified modern sweet corn hybrids with crowding stress tolerance (CST); however, such hybrids appear to be under-planted in the Upper Midwest – where most of the world's processing sweet corn is grown. Both contract growers and vegetable processors may realize improved sustainability by growing CST hybrids at optimum plant densities. In collaboration with vegetable processors and their contract growers, on-farm experiments with CST hybrids were conducted to: (1) identify optimum plant densities of CST hybrids under actual conditions in which the crop is grown and, (2) to determine the best approach to making recommendations on plant densities for individual fields in the Upper Midwest.

Optimum plant densities for CST processing sweet corn hybrid ranged from 65,900 to 79,500 plants ha^{-1} in the Upper Midwest. Also, optimum plant densities increased average profitability of both the processor and contract grower without compromising ear traits important to the sweet corn processing industry. Six candidate recommendation domains were compared to identify the best approach for making plant density recommendations for individual fields. This study identified the 'Production Area' recommendation domain model (RDM_{PA}) as the most appropriate for setting target plant densities for CST sweet corn. Fortuitously, the vegetable crop industry organizes field management decisions largely along the lines of the RDM_{PA} model; therefore, production area-specific plant densities recommendations have a familiar appeal to the practitioner. Vegetable processors and their contract growers stand to increase sweet corn profitability up to \$600 and \$82 ha^{-1}, respectively, by fully utilizing the genetic potential of CST hybrids in the Upper Midwest. This research reveals a relatively simple approach to improve a yield trend in processing sweet corn which has been largely stagnant for two decades.

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CHAPTER 1: LITERATURE REVIEW

1.1 Introduction

A standout amongst the most critical advancements in agrarian development has been the steady increase in field corn yield throughout the last century in the U.S. Corn Belt. From the late 1890s to the late 1930s, average grain yields were almost static in commercial field corn production. Since 1930, steady gains in yield have been observed (Figure 1.1).

The introduction of double–cross hybrids in the 1930s became one of modern agriculture's most noteworthy accomplishments. Double–cross hybrids were rapidly adopted. Double–cross hybrids displaced open pollinated cultivars almost completely by 1950 (Bennetzen and Hake, 2009, Wallace and Bressman, 1949). Double–cross hybrids remained the dominate type of field corn in the Midwest until the 1960s. Corn breeders selected higher yielding inbred lines, which allowed them to replace double–cross hybrids with single–cross hybrids (Crow, 1998). Single–cross hybrids are still by far most of the field corn that is planted today. The recent era of field corn production has given astonishing improvements in grain yield.

Improvements in field corn grain yield over the past ~80 years are attributed to genetic gains made by field corn breeding programs and to superior agronomic management practices adopted by growers. An estimated 50 – 70% of yield improvement is due to improved genetics, with the remaining attributed to superior agronomic management practices (Duvick, 2001). Improved production practices include soil fertility management, pest control, plant density, and row spacing (Tollenaar et al., 1994). Tollenaar et al. (1997) reported grain yield improvement of field corn hybrids has been associated with increased tolerance to plant densities higher than previously used, which reflect increased crowding stress tolerance (CST). Tolerance to intense intraspecific competition for available resources has improved more than any other environmental stress tolerance over the past ~50 years (Russell, 1991; Tokatlidis and Koutroubas, 2004, Tollenaar, 1991; Tollenaar and Lee, 2002). Field corn has undergone a remarkable increase in grain yield potential during this century due to heterosis and the release of more productive genotypes. The development of hybrids with greater tolerance to plant density was an important contributing factor to that accomplishment (Sangoi, 2001). Hence, modern hybrids are often grown at higher plant densities than their predecessors to attain maximum grain production.

Yield gain in sweet corn has not kept pace with the gains in field corn. Much research has been done on field corn to exploit its maximum yield limits, but relatively little work has improved sweet corn productivity. For instance, processing sweet corn in the U.S. has experienced only 16 percent compared to 32 percent yield improvement in field corn since 1998 (NASS, 2016). One way to improve the crop is breeding for traits that will directly add to yield. For instance, breeding for improved ear traits or abiotic stress tolerance. Among management practices, plant density is one factor which can be modified to realize increased yields in sweet corn**.**

Sweet corn is harvested at the milk-stage when seed moisture is between 70 and 80 percent, whereby the ideal kernel moisture content is subject to endosperm type. Total U.S. sweet corn acreage has not experienced any drastic change over the last decade, with 225,900 and 345,400 acres harvested annually for fresh market and processing, respectively (NASS, 2016). Processing sweet corn production is concentrated in the Upper Midwest (Illinois, Minnesota, Wisconsin) and Pacific Northwest (Oregon, Washington). However, 63 percent of the total processing sweet corn production by acreage comes from the Midwest (NASS, 2016). Nearly all processing sweet corn is grown under contract (NASS 2016), whereby the processor supplies the seed of specific hybrid(s) and decides the target planting density (Williams, 2012). Contract growers of processing sweet corn are paid based on the mass of the green ears the processor harvests from the field (Williams, 2012). Processors quantify the performance of sweet corn based on the percentage of ear mass accounted by fresh kernel mass (hereafter called recovery), cases of sweet corn produced per unit area (herafter called case production), and gross profit margin. Gross profit margin reflects the value of cases of sweet corn produced per hectare less seed cost and contract cost for green ear mass. In contrast for the fresh market, the primary yield metric is number of marketable ears per unit area (Williams, 2012).

1.2 Importance of optimum plant density

Plant density plays an important role in determining the agronomic attributes of sweet corn. Optimum plant density is a preequisite for obtaining maximum yields (Gustavo et al., 2006; Singh and Singh, 2002). Plant density affects plant architecture, alters growth and developmental patterns, and influences carbohydrate production and partitioning (Casal et al., 1985). Optimum plant density is a critical factor affecting the profitability of fresh market sweet corn because the number of marketable ears directly affects the grower's profitability (Rosen and Fritz, 1987).

Planting lower than optimum plant density results in relatively low per hectare production, and potentially more weed growth (Allard, 1999). The use of lower than optimum plant density delays canopy closure, thus decreasing seasonal interception of incident solar radiation in field corn (Westgate et al., 1997) Therefore, sweet corn should be planted at the optimum plant density to fully exploit available resources such as nutrients, sunlight, soil moisture to ensure satisfactory yield.

High plant density modifies plant growth, including an increase in plant height, reduction in leaf thickness, alteration in leaf orientation, and leaves become erect and narrow to intercept more sunlight (Singh and Singh, 2002). Changes in plant morphology and phenology increase the ability of the whole crop community to utilize available resources through increased plant density (Sangoi, 2001). Increasing plant density is one of the ways of increasing leaf area index (LAI) and capture of solar radiation (Moderras et al., 1998). However, high plant densities (especially higher than optimum plant density) also increase competition for light, nutrients and water. This may be detrimental to final yield because it stimulates apical dominance, induces barrenness, and ultimately decreases the number of ears produced per plant and kernels per ear (Sangoi and Salvador, 1998a). Moreover, plant densities higher than the optimum promote lodging and add to seed costs. Hence, knowledge of plant densities that give maximum benefit, without a detriment to crop performance and quality, would be valuable for decisions on crop seeding rates.

Recent research shows widely used processing hybrids differ greatly in CST and yield potential (Williams, 2015). A simplified research method was designed to identify processing sweet corn hybrids with superior tolerance to crowding stress. A total of 26 hybrids were grown under a uniformly high plant density and their processor variables (traits of importance to the processor, namely; recovery, case production, and gross profit margin) along with 17 additional crop traits from emergence to harvest were measured. Differences in CST among hybrids were detected not only among all 26 hybrids but also among the top 10 hybrids (Williams, 2015).

Studies have shown that hybrids with enhanced CST, when planted at their optimum plant density, out-perform hybrids with poor CST (Williams, 2012). Even though certain processing hybrids have improved CST, they continue to be under-planted by growers in the Upper Midwest (Williams, 2012). Both growers and processors could realize an increase in yield and profit by growing such hybrids at their optimum plant density (Williams, 2012). Research is needed to quantify the optimum plant density of such hybrids under the wide range of conditions under which the crop is grown.

1.3 Effects of plant density

1.3.1 Plant height

Moosavi et al. (2012) reported that plant height increased 15% when plant density of field corn was increased from 50,000 plants ha^{-1} to 140,000 plants ha^{-1}. Lashkari et al. (2011) stated for field corn, the maximum plant height (201 cm) was realized at the highest plant density (130,000 plants ha^{-1}), while the shortest plants (185 cm) were recorded at the lowest plant density (70,000 plants ha^{-1}). Park et al. (1989) found that increasing plant density in sweet corn from 40,000 plants ha^{-1} to 111,100 plants ha^{-1} increased plant height. Another study with field corn reported that plant height increases to a maximum and then decreases parabolically with increasing plant density. The greatest plant height was observed at 6 – 10 plants m^{-2}, and the decrease of plant height at ultra-high plant density can be attributed to limited mineral and nutrition, and light reduction in the lower canopy (Tetio-Kagho and Gardner, 1988).

Plants that grow in dense canopies receive a different quality of light, enriched with far-red (FR) and impoverished in red (R) radiation. This increased FR/R ratio triggers physiological events which lead to prioritization in the allocation of new assimilates to the main stem and thus, increasing plant height (Rajcan & Swanton, 2001).

1.3.2 Leaf area and leaf area index

Watson (1947) defined LAI as the one-sided green leaf area per unit ground surface area. Leaf area index and distribution of leaf area within field corn canopy are the major factors controlling total light interception, which influence photosynthesis, transpiration and dry matter accumulation (Fortin et al., 1994). At the early vegetative stage of growth, leaf area determines total light interception (Morrison et al., 1992). Increments in LAI result in more effective light interception (Tollenaar et al., 1997). Enhancements in light interception may allow modern hybrids to attain greater photosynthesis rates at high plant densities (Sangoi, 2001).

There are two ways of increasing LAI: breeding for increased leaf area per plant or increasing plant density (Namvar et al., 2011). Baron et al. (2006) and Williams (2012) stated that one of the ways of increasing LAI is to increase plant density in sweet corn. Williams (2012) found that as plant density increased from 43,000 to 86,000 plants ha^{-1}, sweet corn added LAI and intercepted more light. To be specific, each additional plant per m^2 added 0.23 m^2 of leaf area, resulting in increased light interception of 1.8%.

Pepper (1974) reported that increasing plant densities can promote utilization of solar radiation by field corn canopies. However, the efficiency with which intercepted solar radiation is converted into photoassimilates decreases at higher plant densities because of mutual shading (Buren, 1970). Several investigations have confirmed a decrease in leaf area per plant and an increase in LAI as plant density increased (Larson and Hanway, 1977). Bavec and Bavec (2002) reported that leaf area index is a major factor determining photosynthesis and dry matter (DM) accumulation.

Moderras et al. (1998) stated that increasing plant density is one of the ways to increase LAI, DM accumulation, and the capture of solar radiation within the canopy. Boyat et al. (1990) reported that increasing plant density bolstered leaf senescence, increased the shading of leaves, and reduced the net assimilation of individual plants. Their results also indicated that an increase in plant density from 20,000 to 130,000 plants ha^{-1} decreased the net assimilation per plant from 0.85 to 0.11 mg CO_2 m^{-2} s^{-1}, but increased grain yield per unit area. This increase in grain yield could, therefore, be accounted for the increase in LAI and net crop assimilation (Dwyer et al., 1992).

1.3.3 Stalk diameter and lodging

Lashkari et al. (2011) reported that stem diameter in field corn decreased with increasing plant density. The highest stem diameter (2.04 cm) was observed at 70,000 plants ha^{-1} and the lowest stem diameter (1.81 cm) was observed at 130,000 plants ha^{-1}. Moosavi et al (2012) stated for field corn that an increase in plant density from 50,000 to 80,000, 50,000 to 110,000, and 50,000 to 140,000 plants ha^{-1} decreased stem diameter by 16.2, 15.1 and 21.6%, respectively. They further argued that loss of stem diameter at higher plant density could have resulted from intensified inter-plant competition on environmental parameters (including light, water, space), resulting in decreased rates of photosynthesis and assimilate production that eventually caused the reduction of stem diameter.

Shoot lodging is a major constraint to maximizing grain yields in modern field corn production (Sibbale et al., 1992). At times, lodging can be so detrimental to negate any profits that might have occurred with the higher plant densities (Olson and Sander, 1988). The most serious effect of dense stands is the higher incidence of stalk breakage in hybrids of the 1940s (Stringfield and Thatcher, 1947). Stanger and Lauer (2006) reported an increase in lodging from 5 to 16% with an increase in harvest plant density of field corn from 64,220 plants ha^{-1} to 123,500 plants ha^{-1}.

Tall plants with thin stems are more likely to lodge (Gardener et al., 1985). In addition, Troyer and Rosenbrook (1991) reported that stalk breakage and ear dropping increase because crowded corn plants have smaller diameter stems and shanks due to mutual shading. Such changes make field corn stalks more susceptible to breakage before kernels reach physiological maturity.

1.3.4 Crop development

Plant densities resulting in inter-plant competition have important effects on vegetative and reproductive development of field corn (Tetio-Kagho and Gardner, 1988). High plant density affects the required interval for pollen shedding and silk emergence (Sangoi et al., 2002; Tokatlidis et al., 2004). Williams (2012) reported that as plant density in sweet corn increased from 43,000 to 86,000 plants ha^{-1}, crop development was delayed significantly. The study found that each additional plant per m^2 delayed silk emergence by 4.7 growing degree days (GDD). Sangoi et al. (2002) stated that the time gap between anthesis and silking (ASI) was linearly lengthened with the increase in plant density of field corn. To be precise, the increase in ASI was 0.92 days per each 10,000 added plants ha^{-1}. Amanullah et al. (2009) noted that field corn lost synchrony in flowering with increase in plant density from 60,000 plants to 100,000 plants ha^{-1}. They reported that higher plant density delayed days to 50% silking of the field corn. Ritchie and Alagarswamy (2003) stated that lengthening of ASI, and barrenness occurred more frequently in field corn when plant densities exceeded 100,000 plants ha^{-1}. Asynchronous flowering may limit grain production per ear due to lack of pollen, loss of silk receptivity, or early kernel abortion caused by the dominance of early formed ovaries from the base of the ear on the late formed from the tips (Cárcova & Otegui, 2001).

1.3.5 Ear number and barrenness

A one-year study on fresh market sweet corn in 1986 from Minnesota on variety ‘Jubilee’ under dryland conditions found that highest number of usable ears were observed at 55,000 plants ha^{-1} (Rosen and Fritz, 1987). Sarquis et al. (1998) reported that plant density strongly influences the rate and duration of crop growth and eventually fate of multiple ears. This study found that a 30% reduction in light interception by the canopy during the crop cycle was sufficient to completely suppress the development of a second ear. High plant density reduces light interception per plant and mutual shading likely reduces source capacity to supply the second ear with photoassimilate.

The failure of plants to produce ears (barrenness) has been reported as one of the major factors limiting optimum conversion of light energy to grain in field corn grown at high plant densities (Buren et al., 1974). Grain yield of many hybrids grown at exceptionally high densities is reduced by barrenness. Thus, it is essential to incorporate genotypes that are tolerant of high plant densities in crop production systems (Buren et al., 1974). High plant densities may promote hormonally-mediated apical dominance over the ears, resulting in barrenness (Sangoi and Salvador, 1998b). Thus, assimilates are partitioned to shoot rather than the ear, which results in a higher probability that the ear will not become functional (Sangoi, 2001). This accounts for barrenness at exceptionally high plant densities. Additionally, under stress conditions (e.g. drought, high plant density), ear barrenness results in lack of pollen, incomplete kernel pollination, and kernel abortion (Cárcova and Otegui, 2001).

1.3.6 Yield and yield components

Several studies documented the effect of increasing plant density on ear traits, such as ear mass, ear length, and ear number. Mack (1972) reported an increase in sweet corn planting density from 29,250 plants ha^{-1} to 44,250 plants ha^{-1} decreased individual ear mass by 6%. In a more recent trial in the Columbia basin, Waters (2013) reported ear mass per unit area was significantly greater at 71,610 and 86,420 plants ha^{-1} than at the 43,210 plants ha^{-1}. Also, plant density had a significant effect on the number of ears harvested, with the 71,610 plants ha^{-1} resulting in 42 percent and 27 percent more ears ha^{-1} compared to the 43,210 and 56,790 plants ha^{-1}, respectively. Further, he found a negative relationship between ear length and plant density He reported that the average ear length decreased from 22.4 cm to 21.8 cm as plant density increased from 43,210 to 71,610 plants ha^{-1}. Duncan (1985) showed that increasing plant density resulted in ear mass decrease in the individual plant because of inter-plant competition. In a recent study, Williams (2012) evaluated sweet corn hybrids grown at four different densities (from 43,000 plants ha^{-1} to 86,000 plants ha^{-1}) and concluded that filled ear length and recovery declined with increasing plant density.

Recently, a study reported that the number of marketable ears increased by ~20 percent as plant density increased from 65,000 to 80,000 plants ha^{-1} in fresh market sweet corn (Lawson, 2016). The study further stated that the average weight of individual ears decreased by nearly 2 percent as plant density increased from 65,000 to 87,500 plants ha^{-1}. The reduction in individual ear mass can be accounted for by poor tip fill at higher plant densities, i.e., up to 80,000 plants ha^{-1} (Lawson, 2016).

Another study with fresh market sweet corn from Connecticut reported that average ear weight decreased by 16 percent by increasing plant density from 65,340 plants ha^{-1} to 104,550 plants ha^{-1}. However, the gross income (product of the number of bags multiplied and the market price of one bag valued at $8) increased by $1,150 on increasing the plant density from 65,340 to 104,550 plants ha^{-1} (Durgy and Boucher, 2001).

Sangoi et al. (2002) reported that kernels per plant declined and kernel weight decreased by 16% as plant density for field corn increased from 25,000 to 100,000 plants ha^{-1}. Daynard (1983) reported that a reduction in the number of kernels per ear might result from fewer flower initials being formed prior to flowering, poor pollination due to asynchrony of tasselling and silking, and abortion of kernels after fertilization. Tokatlisdis and Koutroubas (2004) also reported that at higher plant densities, the reduced assimilate supply causes abortion of kernels, especially at the ear tip**.**

1.4 Plant density interactions

Crop seeding rate is an important management decision that affects plant density, and ultimately profitability, of sweet corn. Apart from plant density, other management practices and environment conditions also play a key role in determining crop performance. Therefore, the study of plant response to plant density should be investigated in relation to environmental and management aspects, including nitrogen, weed control, planting date, and water use efficiency.

1.4.1 Nitrogen

Nitrogen is an essential element for plant growth. Increasing nitrogen application in sweet corn increases the plant height, ear length, ear diameter, ear mass, and protein content. Also, LAI and root dry matter increase with increasing nitrogen supply (Oktem et al., 2010). Ta and Weiland (1992) reported that nitrogen is directly related to the translocation of sugars, mainly from the leaves to the other plant organs. Although nitrogen is an essential element for most of the crops and has contributed significantly towards increasing agricultural food production worldwide, a large amount of nitrogenous fertilizer lost into the environment can cause serious environmental issues (Chen et al., 2004). Additionally, excessive use of nitrogen-based fertilizers reduces profitability (Ghiberto et al., 2009).

Utilizing an optimum plant density may reduce the potential for loss of nitrate from sweet corn fields because of increased removal of nitrate by the plants. In studies with processing varieties of sweet corn in Oregon, total plant dry matter yield increased with increasing plant density (Mack, 1972; Moss and Mack, 1979). The accumulation of additional dry matter likely would remove excess nitrate from the field and the sequestration of nitrate as organically-bound nitrogen. Conceivably, increasing plant density should reduce the amount of nitrate available for leaching during the fall, winter, and early spring. Research with field corn (Guillard et al., 1995) indicates that nitrate is most susceptible to leaching during this period. Ciampitti et al. (2013) found that both macronutrient (N, P, K, Ca, Mg) and micronutrient (Zn, Mn, Cu, B,) intake increases as plant density is raised. However, groundwater is at high risk of nitrate contamination in the U.S. Midwest (Bernard et al., 1998). At optimum plant density (i.e., encompassing more plants per unit area than current), conceivably the crop will remove more soil nitrate, which may prevent nitrate loss to groundwater.

1.4.2 Weed control

Weed escapes are a serious problem in sweet corn and several studies investigated interactions between crop density and weed interference. Williams (2006) reported that season-long weed interference reduced sweet corn yields by 15% to 85%, depending on planting date. Sweet corn experienced yield losses at very low density (0.012 plants m^{-2}) of giant ragweed (*Ambrosia trifida*), a highly competitive weed species (Williams, 2010). Wild porso-millet *(Panicum miliaceum)* is one of the most abundant species throughout the processing sweet corn production areas in the U.S. (Williams et al., 2008). A study on 25 sweet corn hybrids found that wild porso-millet reduced ear number by 11 – 98% and ear mass by 24 – 82%, depending on the hybrid (So et al., 2009). Wild porso-millet, a C4 plant, tends to grow more rapidly and vigorously at higher light intensities; however, its growth is hindered under dense crop canopies because of reduced light availability. Light-demanding weed species like *Abutilon theophrasti*, *Calystegia sepium,* and *Digitaria sanguinalis* receive a low amount of light under high density of sweet corn, thereby impact weed fitness (Simic et al., 2012). Increased plant density in sweet corn decreased the number of weed species, the number of plants per weed species, and weed biomass (Simic et al., 2012). Another study reported that increasing plant density from 40,000 to 100,000 plants ha^{-1} reduced weed biomass by up to 50% and increased LAI in field corn (Tollenaar et al., 1994). Not only does an optimum plant density make the crop more competitive, but also improves herbicide performance (Simić et al., 2007).

1.4.3 Planting date

Apart from soil fertility, temperature regime, and water supply, planting date and choice of hybrid are major management decisions affecting field corn production (Ramankutty et al., 2002). Days to maturity of the hybrid are determined by planting date, primarily due to variation in temperature and environment during crop growth (Zaji et al., 2015). Williams (2008) reported late-June planted sweet corn had lower yields than early-May planted sweet corn due to lower water supply and increased disease incidence in late-June plantings. Early-July planted sweet corn took 23% to 35% fewer days from crop emergence to silking period, however, mid-June and early-July plantings also resulted in plants with fewer leaves and slower rates of leaf appearance (Williams, 2008). A study from Wisconsin reported that an interval of three weeks in the planting dates showed no effect on plant height but did influence days to silking and yield components of crosses of several open-pollinated sweet corn cultivars (Revilla and Tracy, 1997). Instead of early-May, a late-June planting of an 82-day hybrid in Illinois resulted in 22 cm taller plants with 18% more total shoot biomass and 43% less LAI (Willaims and Lindquist, 2007). Late-June planted sweet corn was more tolerant to interference from velvetleaf (*Abutilon theophrasti*) and common lambsquarters (*Chenopodium album* L.) compared with an early-May planting (Williams and Lindquist, 2007).

1.4.4 Water use efficiency

Water use efficiency of the crop depends on genotype, management, local weather conditions, available soil moisture, and soil texture (Garcia et al., 2009). Based on an experiment conducted on *sugary (su)* type sweet corn, Braunworth and Mack (1987) reported that maximum yield occurred within a range of 449 – 518 mm of water applied while maximum water use efficiency corresponded to 313 mm of water applied (each irrigation was scheduled when available soil moisture was reduced by 50% of initial i.e., from 90 mm to 45 mm). Limpus et al. (2010) reported that increasing plant density of sweet corn from 65,000 plants ha^{-1} to 95,000 plants ha^{-1} increased dry biomass, irrigation water use efficiency, and total water use by 20%, 22%, and 17%, respectively. Another study from the western Georgia (USA) reported that water use for sweet corn at 60,000 plants ha^{-1} was reduced from 268 mm to 122 mm for the April 10 planting date under irrigated conditions and March 27 planting date under rainfed conditions, respectively (Garcia et al., 2009).

1.4.5 Environment

Environmental factors including temperature, precipitation, humidity, and radiation are essential to crop growth and development. Site characteristics (soil texture, slope, organic matter), weather variables (rainfall, temperature, growing season length), and production inputs (fertilizer, pesticides) are major contributing factors to variation in the field corn grain yield; all influence optimum plant density (Shanahan et al., 2004). Location, primarily latitude, is an important factor affecting the optimum plant density. Assefa et al. (2016) reported that as latitude increased from 30° N to 50° N, higher plant densities were required to attain the same yield level as of lower latitudes. At similar plant densities, lower yield in field corn at higher latitudes can be due to decreased amount of solar radiation and reduced crop growing season (Peltonen-Sainio, 2012; Mueller et al., 2015).

Ogola et al. (2005) reported that high-density planting increased biomass under irrigated conditions but reduced biomass under rainfed conditions. They stated that under rainfed conditions, as the plant density increased, water became a limiting factor for biomass production. Dry matter production of field corn in semi- arid environments may (Nadar, 1984; Pilbeam et al., 1995) or may not (Pilbeam et al., 1994) increase as plant density increases, depending on the availability of water. Lower plant densities are recommended for rainfed conditions than irrigated conditions. For instance, recommended sweet corn plant densities in Minnesota under irrigated conditions are 66,000 plants ha^{-1}, while 55,000 plants ha^{-1} perform best under rainfed conditions (Fritz et al., 2010). Similarly, Boerboom et al. (1999) reported optimum sweet corn plant densities varied under irrigated (55,000 plants ha^{-1}) and dryland conditions (45,000 plants ha^{-1}) for Wisconsin. Stanger and Lauer (2006) reported that optimum plant densities varied within Wisconsin. They conducted field corn experiments at ten different locations varying in soil and climate across Wisconsin. While highest yields were obtained at 102,400 plants ha^{-1} for most locations, a plant density of 74,100 plants ha^{-1} produced maximum yield at Chippewa Falls. Thus, it would be erroneous to recommend one plant density for all fields. Instead, different environments under which sweet corn is planted should be identified and trials conducted prior to recommendations.

1.5 Recommendation domains for decision-making

The term "recommendation domain" was introduced in CIMMYT Economics manual on the use of partial budgets for economic analysis of agronomic data (Perrin et al., 1976). A recommendation domain (RD) is defined as "a group of roughly homogeneous farmers with similar circumstances for whom we can make more or less the same recommendation" (Byerlee et al., 1980). Thus, a recommendation domain will be comprised of a group of farmers within an agroclimatic zone who share similar farms and farming practices. Natural circumstances (e.g. climate, soil, biotic factors) and socio-economic factors (e.g. farm size, labor accessibility, power source) are commonly used factors in forming recommendation domains (Harrington and Tripp, 1984). For instance, in one of the South American highlands, CIMMYT (1981) identified two basic recommendation domains for farming: flat lands and steep lands. Major differences in the methods of land preparation, choice of cultivars and weed management practices were reported between domains.

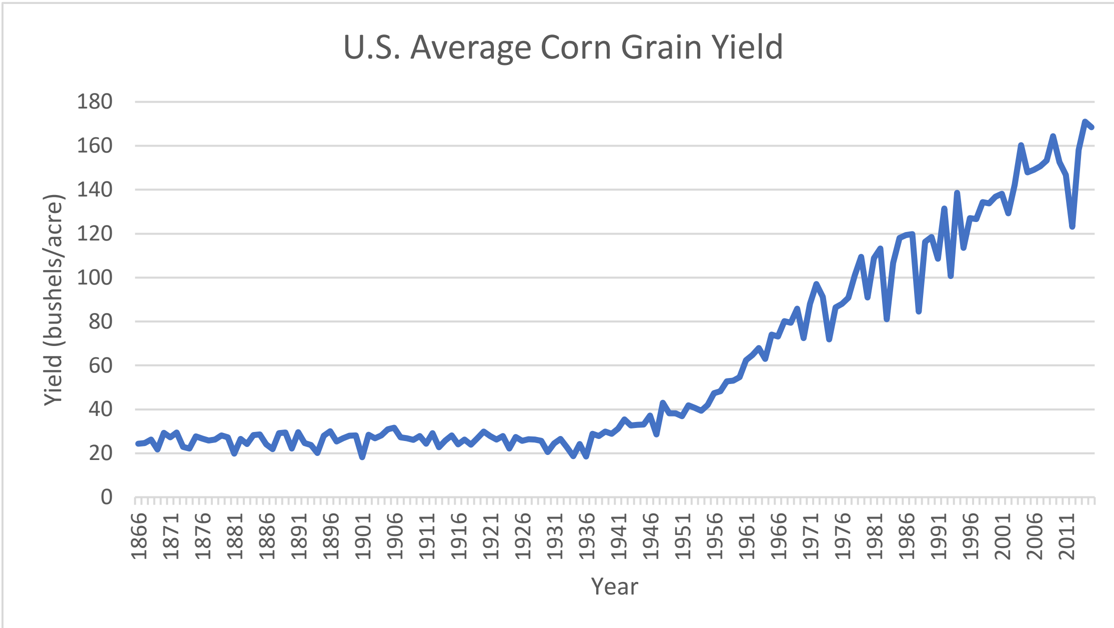
By grouping similar fields together, recommendation domains can be helpful in providing agronomic recommendations tailored to the growing conditions. Previous studies have reported that targeting sites under the same recommendation domain with the new technology, and for which the technology is suitable, increases the likelihood of adoption of new technology (Phiri et al., 2004, Kalcic et al., 2015). Recommendation domains prevent extrapolating results from the better environments to the poorer environments (Hildebrand, 1984). Further, appropriate recommendation domains can avoid two equally undesirable situations of (a) offering a different recommendation for individual growers (too expensive) or, (b) offering a single recommendation for the whole grower population (Harrington and Tripp, 1984).

1.6 Summary

If field corn serves as any example, improving productivity of sweet corn will involve utilizing modern hybrids that maintain individual plant yield under higher plant densities than their predecessors were grown. Currently, processing sweet corn hybrids that tolerate crowding stress exist; however, they are under-planted largely because research on optimum plant density is severely limited. Plant density affects several sweet corn growth and development traits that are important to commercial production. Several management and environmental factors may interact with plant density, such that crop response to plant density is unlikely to be constant across all production fields. The sweet corn processing industry would benefit from research that: 1) identifies optimum plant densities of crowding stress tolerant germplasm under actual conditions in which the crop is grown, and 2) sheds light on the best approach to making recommendations on plant densities for individual fields in the upper Midwest.

1.7 Figure

Figure 1.1 Improvement in average grain yields of field corn in the U.S. over last 150 years (NASS, 2016)



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CHAPTER 2: OPTIMUM PLANT DENSITY FOR CROWDING STRESS TOLERANT PROCESSING SWEET CORN

2.1 Abstract

Grain yield improvement of field corn (*Zea mays L.*) is associated with increased tolerance to higher plant densities (i.e., crowding stress). Processing sweet corn hybrids that tolerate crowding stress have been identified; however, such hybrids appear to be under-planted in the processing sweet corn production area of the Upper Midwest. Using crowding stress tolerant (CST) hybrids, the objectives of this study were to: (1) identify optimum plant densities in the Upper Midwest; (2) quantify gaps in production between current and optimum plant densities; and (3) enumerate changes in yield and ear traits for shifting from current to optimum plant densities. Using a CST shrunken-2 processing sweet corn hybrid, plant density trials were conducted over thirty fields across the states of Illinois, Minnesota and Wisconsin, from 2013 to 2017. Linear mixed-effects models were used to identify the optimum plant density corresponding to maximum ear mass (Mt ha^{-1}), case production (cases ha^{-1}), and profitability to the processor ($ ha^{-1}). Kernel moisture, indicative of plant development, was unaffected by plant density. Ear length, filled ear length, recovery, and ear number plant^{-1} declined linearly with increasing plant density. Nonetheless, there was a large economic benefit to the grower and processor by using plant densities higher than current in all environments. This research shows increasing plant densities of CST hybrids could improve processing sweet corn green ear yield and processor profitability up to 1.18 Mt ha^{-1} and $525 ha^{-1}, respectively.

2.2 Introduction

Over the last 50 years, field corn (*Zea mays L.*) in the United States has demonstrated drastic improvements in grain yield, with national average yields increasing from 5 Mt ha^{-1} in 1966 to 11 Mt ha^{-1} in 2016 (NASS, 2017). Advancements in field corn yield can be attributed to both availability of genetically improved hybrids and adoption of superior agronomic management practices (Duvick and Cassman, 1999). Further, the genetic yield improvements largely were due to increased stress tolerance (Tollenaar and Wu, 1999). Modern hybrids show more tolerance than their predecessors to several abiotic and biotic stress factors along with enhanced responsiveness to inputs such as nitrogen, water and light (Tokatlidis and Koutroubas, 2004; Tollenaar and Wu, 1999). Meanwhile, individual plant yield potential of modern hybrids does not differ substantially from that of old hybrids (Sangoi et al., 2002; Tokatlidis and Koutroubas, 2004). Previous studies have reported that gains observed in grain yield are plant density dependent (Duvick and Cassman, 1999; Tokatlidis and Koutroubas, 2004; Tollenaar and Lee, 2002).

Tolerance to intense intraspecific competition for available resources has improved more than any other environmental stress tolerance over the past ~50 years (Tollenaar, 1991; Tollenaar and Lee, 2002). This can be attributed to the shift in hybrid evaluation philosophy in the early 1980s in the North America; where instead of emphasizing on relatively high precision per location at few locations, breeders tested hybrid response to many locations, including environments with crowding, nutrient and water stresses (Bradley et al., 1988). This selection criteria, with more reliance on yield stability, is considered responsible for increased stress tolerance in modern hybrids (Duvick and Cassman, 1999; Tollenaar and Lee, 2002).

While grain yields in field corn have shown 140 percent increase over the last five decades, sweet corn has failed to realize such yield improvements. Processing sweet corn, one of the most widely produced processing vegetable crops in the United States, has shown only a 16 percent yield gain over the last two decades (NASS, 2017). Genetic improvements of sweet corn have primarily focused on manipulation of different endosperm mutants, specifically shrunken-2 (*sh2*), brittle1 (*bt*), sugary 1 (*su1*), and sugary enhancer 1 (*se*) to develop better tasting and longer shelf-life products (Lertrat and Pulam, 2007). Also, there is evidence of increased host plant resistance to some of the common plant diseases (common rust, maize dwarf mosaic, northern corn leaf blight) prevalent on sweet corn in the North America (Pataky et al., 2011). However, there has been little investigation into sweet corn plant density relationships with yield and yield components.

Recent research shows widely used processing sweet corn hybrids differ greatly in crowding stress tolerance (CST) and yield potential (Williams, 2015). Williams (2016) reported two categories of traits, namely photosynthetic capacity and source-sink relationships associated with crowding stress tolerance in processing sweet corn. Genes involved in photosynthesis, glycolysis, cell wall development, carbohydrate/nitrogen metabolic processes, and chromatin and transcription regulation processes, are possible mechanisms behind CST in processing sweet corn (Choe et al. 2016). Crowding stress tolerant maize hybrids, when planted at their optimum plant density, out-perform hybrids with poor CST (Mansfield and Mumm, 2014; Williams, 2015).

Crowding stress tolerance is a heritable trait in sweet corn (Shelton and Tracy, 2013). Even though certain processing sweet corn hybrids have above-average CST, field surveys in the Upper Midwest report the plant density has changed little the last two decades, averaging 56,000 plants ha^{-1} (Williams, 2012). The optimum plant density for CST hybrids was high as 70,200 plants ha^{-1} (Williams, 2012). Crowding stress tolerant sweet corn could be grown at higher plant densities than current. However, the production gaps - the difference in yield between using current and optimum plant densities - are unknown.

There is extensive literature on field corn plant density interactions with yield and yield components. Meanwhile, fewer studies address plant density and yield relationships in sweet corn. Furthermore, the existing literature mostly investigates optimum plant density in fresh-market sweet corn (Morris et al., 2000; Rangarajan et al., 2002), which does not apply to the unique hybrids and yield parameters of processing sweet corn (Williams, 2012).

The goal of this research was to determine the extent to which CST could improve yield of sweet corn grown for processing. Using CST hybrids, the objectives of this study were to: (1) identify optimum plant densities based on case production, green ear mass, gross profit margin, and sweet corn production area in the U.S. Midwest; (2) quantify production gaps between current and optimum plant densities; and (3) based on optimizing gross profit margin, enumerate changes in yield and ear traits for shifting from current to optimum plant densities.

2.3 Materials and Methods

To address aforementioned objectives, the general experimental approach involved growing CST hybrids over a range of plant densities under variable environments of the Upper Midwest. This required a collaborative effort among the authors, two vegetable processors, and their contract growers. A common research protocol was implemented on-farm, either nested in contract fields or at a university research farm. All aspects of crop management reflected the realities of processing sweet corn production in each production area. A detailed description of the experimental approach is provided below.

2.3.1 Germplasm

Previous research (Williams, 2015) on 26 *sh2* endosperm type processing sweet corn hybrids documented large variability in crowding stress response (Table 2.1). The two most CST hybrids were selected for this research, specifically ‘DMC 21-84’, a hybrid developed by Del Monte, and

‘GG 641’, a hybrid developed by General Mills. Both hybrids were grown widely in the region, providing numerous contract growers and individual fields from which to select study sites. Early in the project, GG 641 was withdrawn from the project. Given the limited availability of access to fields grown with known CST hybrids, and to avoid confounding plant density response with genetic background, DMC 21-84 was the single hybrid used in the project.

2.3.2 Description of Sites

The study was conducted at 30 site-years (hereafter called ‘fields’), located in areas of high strategic importance for sweet corn production in Illinois, Minnesota and Wisconsin, from 2013 to 2017 (Table 2.2). Soil texture varied from clay loam to silty loam to sand. Soils greater than 50% sand were sprinkler irrigated, whereas most other soils were rainfed. Planting date ranged from April 24 to June 19. As such, harvest ranged from July 20 to September 26. Sweet corn was grown in rotation with other summer annual crops and conventional tillage practices were used in all fields. With the exception of harvest, trials were maintained such that crop management practices (i.e., irrigation, nutrient management, disease and pest control, weed control) were not differentiated between the trial and the field in which the trial was nested. Fields were selected from four production areas. Production areas were named Illinois-irrigated, Illinois-rainfed, Minnesota-rainfed and Wisconsin-irrigated to indicate the state and water supply of each field.

2.3.3 Experimental Design

All trials were laid out as a randomized complete block design. Treatments consisted of ten target plant densities, arranged as one replicate of 42,000, 57,000 72,000, 86,000, and 101,000 plants ha^{-1}, and a second replicate of 49,000, 64,000, 79,000, 94,000, and 109,000 plants ha^{-1}. Plot size varied by field according to available space and size of planting equipment; however, all sweet corn was grown on a 76 cm row spacing.

2.3.4 Data collection and Analysis

2.3.4.1 Weather data

Daily precipitation, minimum air temperature, and maximum air temperature were obtained from the Midwestern Regional Climate Center (2017) using the nearest active weather station for each site. Growing degree days were calculated using daily minimum and maximum air temperature and a base temperature of 10℃.

2.3.4.2 Harvest data

Sweet corn is harvested at the 'milk' stage (R3). For *sh2* hybrids, ideal kernel moisture is 76 percent. In this study, harvest date of contract fields was decided by the processor. Trials were harvested promptly before machine harvest of the field in which trials were nested, or in the case of the university research farm, when kernel moisture was 76%. The harvest area was within two interior rows (i.e., to avoid border effects) from each plot over a length of 6.1 meter. Green ears measuring ≥ 4.5 cm in diameter (hereinafter referred to as marketable ears). Marketable ear number, green ear mass, and plant density were recorded. A subsample comprising ten randomly selected green ears was taken from each plot for measurements on kernel mass, kernel moisture, ear length and filled ear length. Specifically, subsampled green ears were husked by hand and kernels were removed from the cob using an industry-grade hand-fed corn cutter (A&K Development, Eugene, OR). Husked ear mass and cob mass were recorded. Kernel mass was calculated as the difference between husked ear mass and cob mass. Thereafter, recovery was calculated as the percentage of subsample green ear mass accounted by kernel mass. Fresh kernel samples (~100 g) were used to determine kernel moisture content gravimetrically.

In contract fields, plant density and yield of the grower's field were hand harvested at three random locations outside the trial, as described above. These data were used to quantify current plant density and yield measurements at the current plant density. At the university research farm site, the current plant density was assigned 58,000 plants ha^{-1}, the average plant density in the Upper Midwest (Nick George, personal communication).

2.3.4.3 Economic analysis

Nearly all processing sweet corn in the U.S. is grown under contract (NASS, 2017), whereby the processor supplies the seed of specific hybrids and decides the planting density (Williams, 2012). Growers of contract fields are paid (hereafter called 'contract cost') based on the mass of green ears (complete ears with husk leaves) the processor harvests from the field (Williams, 2012). Processors quantify the performance of sweet corn based on recovery, cases[1] of sweet corn produced per unit area (hereafter called 'case production'), and gross profit margin. Gross profit margin reflects the value of cases of sweet corn produced per hectare less seed cost and contract cost for green ear mass production.

[1] Each case carries 6.13 kg of kernels, moisture – corrected at 76 percent

Hybrid seed cost was assumed to be \$ 4.22 per 1,000 kernels. Contract cost (\$ ha^{-1}) was calculated using \$82 as a fixed amount[2] paid per unit metric ton of green ear mass harvested from the grower's field. Similarly, gross returns (\$ ha^{-1}) to processor were calculated as product of total kernel case production (cases ha^{-1}) and unit case price, fixed at \$9.5[2]. Finally, the processor's gross profit margin (\$ ha^{-1}) was calculated by subtracting seed cost and the contract cost from gross returns. Economic estimates were verified by the Midwest Food Products Association (Nick George, personal communication).

2.3.4.4 Soil analysis

Soil samples were collected at harvest using a soil probe with composite soil samples for each field composed of at least six cores with core diameter 2 cm and core depth 15 cm. Samples were then sent to A&L Great Lakes Laboratories, Fort Wayne, IN for soil characterization based of chemical (pH, micro and macro nutrient availability) and physical (particle size distribution) attributes.

2.3.5 Statistical Analyses

2.3.5.1 Linear mixed effects modeling

Data were analyzed by fitting linear mixed effects models (LMEs) using the *nlme* package of R 3.1-131 (Pinheiro et al., 2017). Individual models were fit to predict gross profit margin (\$ ha^{-1}), green ear mass (MT ha^{-1}) and, case production (cases ha^{-1}), hereinafter collectively referred to as 'processor variables'. Each model was a second order polynomial mixed effects model with field-level random intercept and slope structure and plant density (plants ha^{-1}) as the fixed effect. Field-level maximum values were calculated from the estimates of the best linear unbiased predictors (BLUPs) of random effects in the linear mixed effects model; the corresponding plant density (plants ha^{-1}) was regarded as optimum plant density for maximizing crop response.

Additionally, linear mixed effects models with field as a random effect (random intercept and slopes) were constructed to study the fixed effect of plant density treatment on different response variables; namely, average ear length (cm), average filled ear length (cm), ear number per plant, green ear mass per plant (kg $plant^{-1}$), kernel moisture (%) and kernel recovery (%).

Subsequent residual analysis was performed to check the normality assumption for all models. For all analyses, significance was declared at $P < 0.05$.

[2] All unit prices were assumed constant through the course of this study.

2.4 Results

2.4.1 Linear mixed effects models

Plant density affected all processor variables. In general, processor variables initially increased with plant density until reaching a peak at optimum plant density, and then began to decrease with greater plant density (Figure 2.1). Conditional R^2, (Nakagawa and Schielzeth, 2012) the total amount of variation explained by the fixed and random effects using linear effects models, was 0.77, 0.74, and 0.73 for green ear mass, case production, and gross profit margin, respectively. Crop response to plant density varied within and across production areas (Figure 2.1).

2.4.1.1 Optimum plant densities

Mean optimum plant density for maximum *green ear mass* ranged from 73,000 plants ha^{-1} in Minnesota-rainfed to 79,500 plants ha^{-1} in Illinois-irrigated (Figure 2.2A). However, no differences in optimum plant density for maximum green ear mass were observed among production areas.

Mean optimum plant density for maximum *case production* ranged from 67,300 plants ha^{-1} in Minnesota-rainfed to 80,300 plants ha^{-1} in Illinois-irrigated (Figure 2.2B). Mean optimum plant densities for Illinois-irrigated, Illinois-rainfed, and Wisconsin-irrigated production areas were greater than the Minnesota-rainfed production area.

Similarly, the mean optimum plant density for maximum *gross profit margin* ranged from 65,900 plants ha^{-1} in Minnesota-rainfed to 79,300 plants ha^{-1} in Illinois-irrigated (Figure 2.2C). Mean optimum plant density for Minnesota-rainfed was less than the mean optimum plant density at the other three production areas.

2.4.2 Production gaps

Green ear mass yields at plant densities optimized for maximum *green ear mass* were higher than those observed at current plant densities across all four production areas (Table 2.3). Overall, increasing plant density from current plant densities (mean of 58,500 plants ha^{-1}) to green ear mass-optimized plant densities (mean of 77,000 plants ha^{-1}) added an additional 1.18 Mt ha^{-1} of green ear mass.

Case production at plant densities optimized for maximum *case production* also were higher than those observed at current plant densities in Illinois-irrigated, Illinois-rainfed and Wisconsin-irrigated (Table 2.3). Minnesota-rainfed did not show any significant increase in case production at optimum plant density as compared of at current plant density. Overall, increasing plant density from current plant densities (mean of 58,500 plants ha^{-1}) to case production-optimized plant densities (mean of 73,000 plants ha^{-1}) added 74 cases ha^{-1}.

Likewise, gross profit margin at plant densities optimized for maximum *gross profit margin* also were higher than those observed at current plant densities in Illinois-irrigated, Illinois-rainfed and Wisconsin-irrigated (Table 2.3). Minnesota-rainfed did not show a significant increase in gross profit margin at optimum plant density as compared to current plant density (Table 2.3). Overall, increasing plant densities from current plant densities (mean of 58,500 plants ha^{-1}) to gross profit margin-optimized plant densities (mean of 73,000 plants ha^{-1}) raised gross profit margin by \$525 ha^{-1}.

2.4.3 Effect on Yield and Ear traits

Yield traits, specifically green ear mass and case production, were greater at plant densities optimized for maximum *gross profit margin* than those observed at current plant densities for all four production areas (Table 2.4). Overall, shifting from current to gross profit margin-optimized plant densities increased green ear mass and case production by 1.13 Mt ha^{-1} and 75 cases ha^{-1}, respectively.

Ear traits including ear number $plant^{-1}$, ear mass $plant^{-1}$, filled ear length and average ear length were affected by plant density (Table 2.5). Overall, increasing from current plant density to gross profit margin-optimized plant density resulted in a subtle, yet significant decline in ear number and ear mass by 0.08 ears $plant^{-1}$ and 0.06 kg $plant^{-1}$, respectively. Filled ear length showed a nearly two-fold reduction (mean of 0.8 cm) compared to average ear length (mean of 0.5 cm) on shifting from current to gross profit margin-optimized plant density. Overall, recovery declined by 0.24 percent by increasing plant densities from current plant density to gross profit margin-optimized plant density (Table 2.5). However, only Minnesota-rainfed showed a significant decrease in recovery (~1 percent). Kernel moisture, an indicator of crop development, was unaffected as plant densities increased from current to gross profit margin-optimized plant densities across all four production areas.

2.5 Discussion

The experimental approach used in this study enabled us to quantify the extent to which modern CST hybrids can be used to immediately improve sweet corn production. Optimum plant densities for one of the several available CST hybrids were identified. By locating experimental sites at areas of high strategic importance for processing sweet corn production in the Upper Midwest, this research took into account relevant spatial and temporal variability in which the crop is produced (e.g. soil types, planting dates, and local climate). Locating experiments in growers' fields captured real diversity in crop management practices, including nutrient management and pest control. Previous research has shown that on-farm experiments accelerate adoption of new farm technology, compared to pilot projects, by demonstrating results under real-world conditions (Francis et al., 1995).

While some sweet corn germplasm has improved considerably for CST, plant densities have remained constant for decades in the Upper Midwest. Since the mid-1980s, recommended plant densities for processing sweet corn in Minnesota and Wisconsin have ranged from 45,000 to 54,300 plants ha^{-1} (Boerboom et al., 1999; Rosen and Fritz, 1987). Two decades later, surveys of growers' fields showed little change in plant density (Williams 2012). Our results demonstrate that, regardless of the processor variable, current plant densities are too low for CST sweet corn, by 10,000 to 18,000 plants ha^{-1}. These results are consistent with previous studies in field corn that report increased CST in modern hybrids allows using higher plant densities than their predecessors (Duvick et al., 2004; Lee and Tollenaar, 2007; Tollernaar et al., 1994; Tollenaar and Wu, 1999).

Processing sweet corn prices in the U.S. have stagnated in recent years while acreage has been in decline, thereby challenging the economic sustainability of the crop. Our results reveal that both processors and their contract growers will benefit from using gross profit margin-optimized plant densities of CST hybrids. Overall green ear mass and case production increased by an average of 1.18 Mt ha^{-1} and 74 cases ha^{-1}, respectively. Furthermore, these economic gains were achieved without altering crop management practices other than crop seeding rate, which was factored into the economic analysis. Moreover, there may be an environmental benefit to this research. Dry matter accumulation increases with plant density and promotes sequestration of nitrate as organically bound nitrogen (Mack, 1972; Moss and Mack, 1979). Although beyond the scope of this research, increasing plant density could reduce the amount of soil nitrate available for leaching following sweet corn harvest.

Ear number per plant and ear mass per plant decreased from current plant density to at optimum plant density. These results were expected, as individual yield potential of modern field corn hybrids has not changed over time (Sangoi et al., 2002; Tokatlidis and Koutroubas, 2004).

Lawson (2016) also reported constant per-plant yield potential in fresh market sweet corn. Williams (2014) showed that ear number per plant is a relatively poor predictor of case production and gross profit margin in processing sweet corn (ρ = 0.679 and 0.661, respectively). Sweet corn ear size and shape are clearly important in the processing industry. For instance, slightly tapered ears are necessary to orient ears correctly using automated processing equipment (Hallauer, 2000). Moreover, excess variability in ear size and shape interferes with kernel cutting (Szymanek, 2012). Our results show ear traits at plant densities, optimized for maximum gross profit margin, remain suitable for the mechanized processing.

Kernel moisture and recovery showed minimal differences at current and optimum plant densities. Kernel moisture at optimized plant densities was within the desired range (74 – 78 percent) required for processing. This suggests that crop maturity was not delayed at optimum plant density. Also, sweet corn maturity is associated with kernel eating quality such as flavor and texture (Tracy, 2001). Overall, mean recovery across production areas showed minimal decline (~0.2 percent) at optimum plant density. Regardless, total case production increased due to more ears per hectare at optimum plant densities than current plant densities. Among all production areas, Minnesota-rainfed was the only that showed significant decline in recovery at optimized plant density, which may be due to an interaction between environmental factors and agronomic practices. Tollenaar and Lee (2006) documented that kernel number and weight in field corn depend on light interception, leaf senescence, efficiency of utilization of intercepted light by canopy and leaf photosynthesis throughout the grain-filling stage. Cakir (2004) reported that water deficit at tasseling and ear formation can result up to 35% decrease in kernel set in field corn.

2.6 Conclusion

Despite the fact that the U.S. is the world's leader in innovative technology and production of sweet corn seed and products, processing sweet corn yields have stagnated the last two decades. Historic yield improvements in field corn are largely the result of utilizing increased plant densities of CST germplasm. If field corn serves as any example, improving productivity of sweet corn will involve utilizing modern hybrids that maintain individual plant yield under higher plant densities than their predecessors. Earlier studies have documented CST germplasm is being underplanted (~ 56,000 plants ha^{-1}) in the Upper Midwest, and this work shows that the optimum plant densities for CST processing sweet corn ranges from 65,900 to 79,500 plants ha^{-1}, depending on production area. Optimum plant densities increased profitability of both the processor and contract grower up to \$700 ha^{-1} and \$105 ha^{-1}, respectively, without negatively affecting ear traits important to processing. This study demonstrates that the processing sweet corn industry could benefit from CST germplasm, and planting such hybrids at densities that fully utilize their genetic potential.

2.7 Figures and Tables

Figure 2.1 Linear mixed effects models of field level for plant density effect on (A) green ear mass (Mt ha^{-1}), (B) case production (cases ha^{-1}) and, (C) gross profit margin (\$ ha^{-1})

Thick black line shows production-area mean fixed effect. Grey lines show individual field relationships (best linear unbiased predictors, BLUPs), as estimated from the random effects structure.

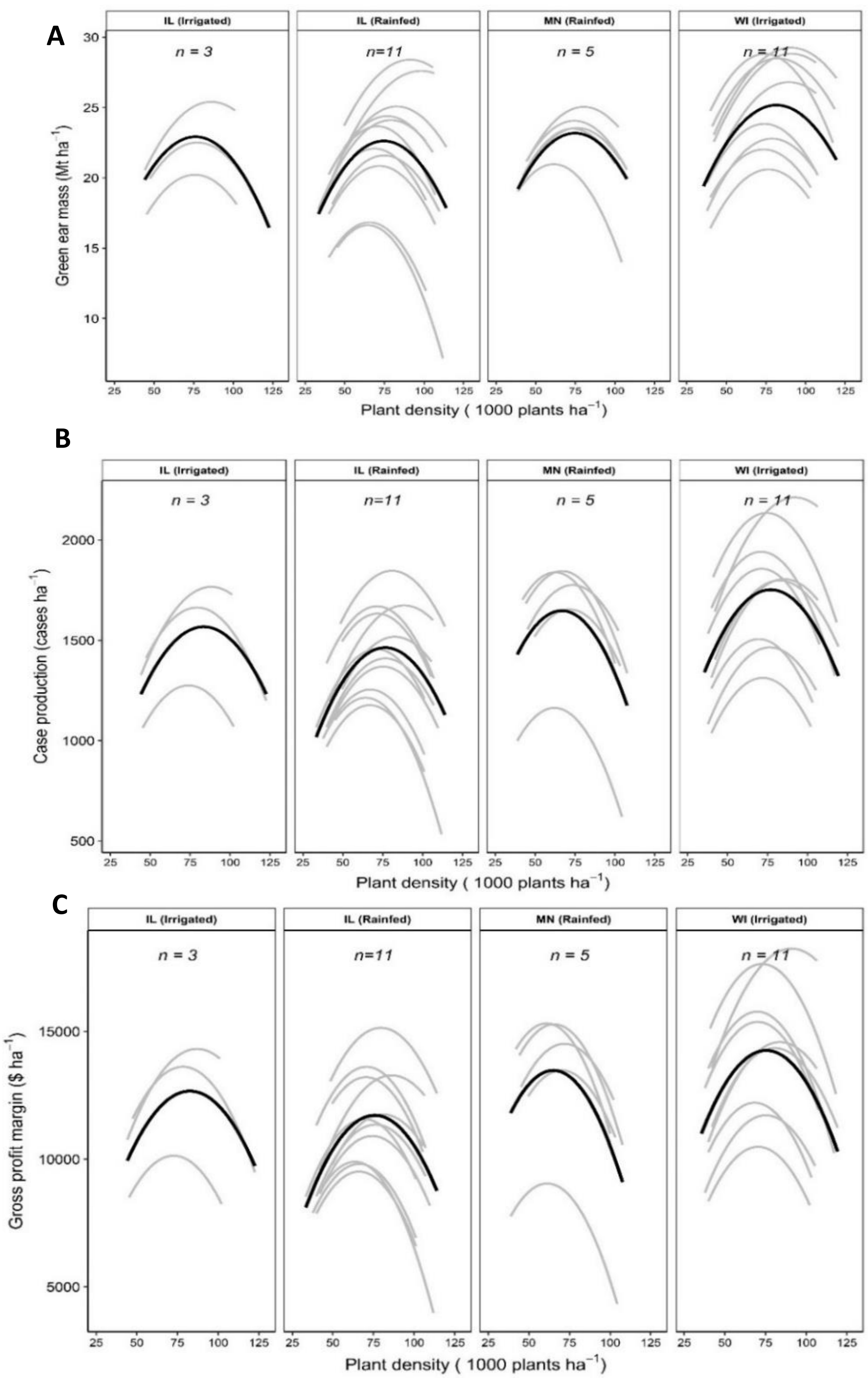

Figure 2.2 Box plots comparing optimum plant density distributions of a CST hybrid across different production-areas; plant densities are optimized for (A) maximum green ear mass (Mt ha^{-1}), (B) maximum case production (cases ha^{-1}) (C) maximum gross profit margin (\$ ha^{-1}). Black asterisk represents the mean value. Number of observations, by production area: $N_{IL(irrigated)}$ =3, $N_{IL(rainfed)}$ = 11, N_{MN} = 5, N_{WI} = 11. Different letters denote significant differences in mean values at α = 0.05 based on pairwise t-tests.

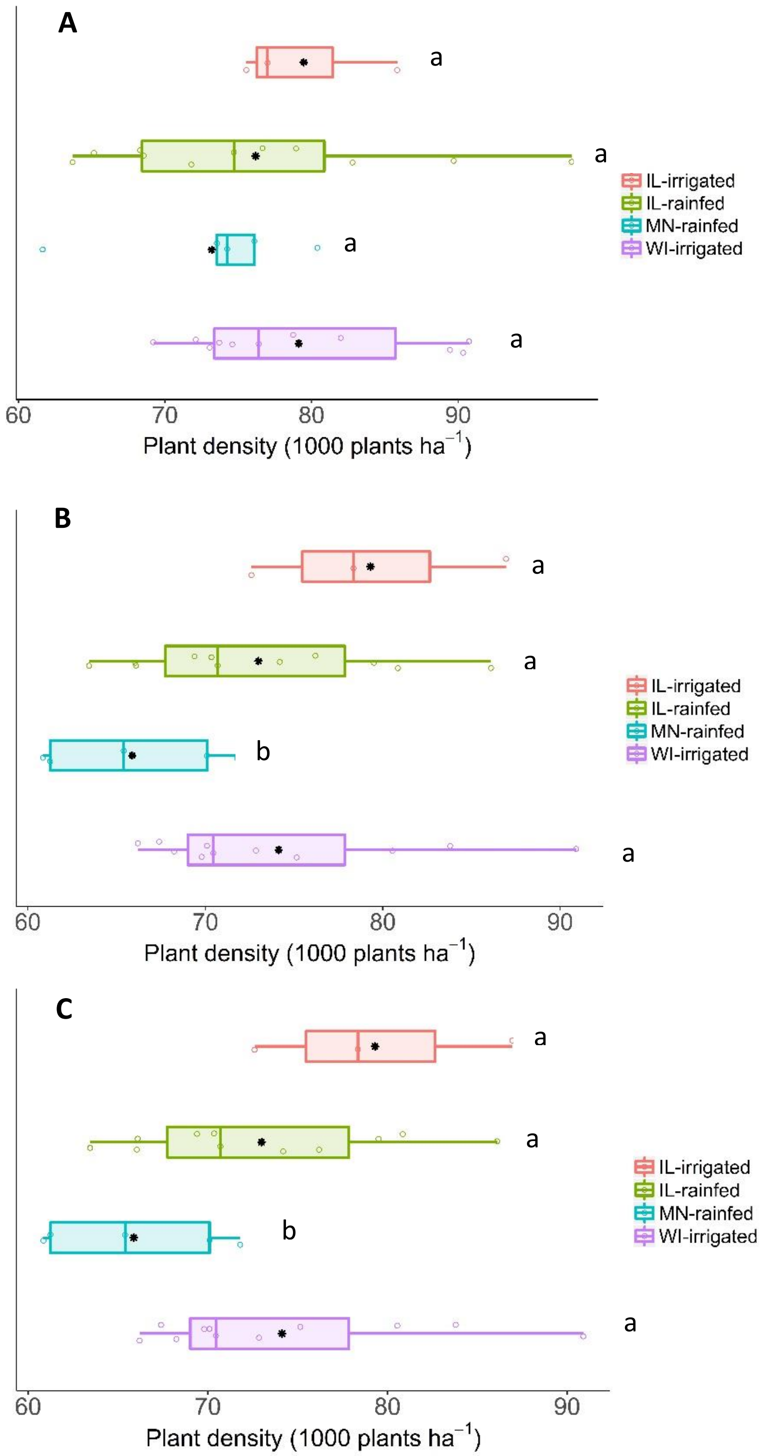

Table 2.1 Gross profit margin from top 10 shrunken-2 processing sweet corn hybrids, grown under supraoptimal N fertilization and crowding stress (72,000 plants ha^{-1}) in field trials over a 3-yr period near Urbana, IL. Means separation by Bonferroni-corrected multiple comparisons at $p < 0.05$. (adapted from Williams, 2015)

Rank	Hybrid	Gross profit margin
		US$ ha^{-1}
1	GG 641	16,700a
2	DDMC 21-84	15,800ab
3	GG 605	15,600abc
4	DMX 22-90	5,500abc
5	DMC 22-85	14,700abc
6	XTH 1679	14,200abc
7	DMX 21-30	14,000abc
8	Fortitude	13,300bc
9	ACX SS1508DY	13,100bc
10	XTH 1079	12,800c

Table 2.2 Brief site characterization of all thirty fields employed in On-farm study.

Year	State	County	Name	Soil texture	Water supply	Planting date	Harvest date
2013	IL	LaSalle	MD_Y13	Silt loam	Rainfed	19-Jun	6-Sep
2014	IL	Champaign	FF_Y14	Silt loam	Rainfed	27-May	11-Aug
2014	IL	Champaign	VC_Y14	Silt loam	Rainfed	27-May	13-Aug
2014	IL	DeKalb	TYLR1_Y14	Silt loam	Rainfed	6-Jun	29-Aug
2014	IL	DeKalb	TYLR2_Y14	Silt loam	Rainfed	6-Jun	29-Aug
2014	IL	LaSalle	UTI_Y14	Silt loam	Rainfed	14-Jun	5-Sep
2014	WI	Portage	OKR_Y14	Loamy sand	Irrigated	19-Jun	18-Sep
2014	WI	Portage	PMT_Y14	Muck sand	Irrigated	5-Jun	9-Sep
2014	WI	Portage	WYN_Y14	Loamy sand	Irrigated	23-May	25-Aug
2015	IL	Champaign	FF_Y15	Silt loam	Rainfed	22-May	5-Aug
2015	IL	Champaign	VC_Y15	Silt loam	Rainfed	22-May	6-Aug
2015	IL	Mason	HV_Y15	Sandy loam	Irrigated	29-Apr	20-Jul
2015	MN	Brown	HOFF_Y15	Clay loam	Rainfed	10-Jun	4-Sep
2015	MN	Redwood	HOFS_Y15	Clay loam	Rainfed	10-Jun	4-Sep
2015	WI	Portage	PMT_Y15	Loamy sand	Irrigated	2-Jun	3-Sep
2015	WI	Portage	WY_Y15	Loamy sand	Irrigated	13-May	20-Aug
2015	WI	Waushara	MRT_FY15	Loamy sand	Irrigated	16-Jun	15-Sep
2016	IL	Champaign	FF_Y16	Silt loam	Rainfed	16-May	1-Aug
2016	IL	Champaign	VC_Y16	Silt loam	Rainfed	16-May	1-Aug
2016	IL	Mason	HV_Y16	Sandy loam	Irrigated	20-Apr	22-Jul
2016	MN	Brown	HOFS_Y16	Clay loam	Rainfed	13-Jun	31-Aug
2016	WI	Adams	AIR_Y16	Loamy sand	Irrigated	1-Jun	23-Aug
2016	WI	Portage	P15_Y16	Muck sand	Irrigated	8-Jun	6-Sep
2016	WI	Portage	TIMM_Y16	Loamy sand	Irrigated	19-Jun	14-Sep
2017	IL	Champaign	M11_Y17	Silt loam	Rainfed	24-Apr	28-Jul
2017	IL	Champaign	VC_Y17	Silt loam	Irrigated	16-May	7-Aug
2017	MN	Brown	HOFS1_Y17	Clay loam	Rainfed	10-Jun	7-Sep
2017	MN	Brown	HOFS2_Y17	Clay loam	Rainfed	11-Jun	7-Sep
2017	WI	Portage	PL1_Y17	Sand	Irrigated	30-May	31-Aug
2017	WI	Portage	PL2_Y17	Loamy sand	Irrigated	23-Jun	26-Sep

Table 2.3 Comparison of green ear mass (Mt ha^{-1}) of a crowding stress tolerant hybrid at current plant density and plant density optimized for maximum green ear mass (Mt ha^{-1}), case production (cases ha^{-1}) and gross profit margin (US dollars ha^{-1}). Asterisk represents significant differences between values at current and maximum at α = 0.05 based on pairwise t-tests.

Yield measure	Production area	Current plant density	Optimum plant density	Difference in plant density	Current yield	Maximum yield	Difference in yield
			plants ha^{-1}			Mt ha^{-1}	
Green ear mass	IL-irrigated	61,300	79,500	18,200*	21.74	22.77	1.03*
	IL-rainfed	58,400	76,200	17,800*	21.60	22.78	1.18*
	MN-rainfed	55,800	73,200	17,400*	22.33	23.44	1.11*
	WI-irrigated	58,400	79,100	20,700*	23.91	25.30	1.39*
Overall mean		**58,475**	**77,000**	**18,525***	**22.40**	**23.57**	**1.18***
			plants ha^{-1}			cases ha^{-1}	
Case production	IL-irrigated	61,300	79,300	18,000*	1,480	1,570	90*
	IL-rainfed	58,400	73,000	14,600*	1,400	1,475	75*
	MN-rainfed	55,800	65,900	10,100*	1,610	1,655	45
	WI-irrigated	58,400	74,100	15,700*	1,685	1,770	85*
Overall mean		**58,475**	**73,075**	**14,600***	**1,544**	**1,618**	**74***
			plants ha^{-1}			dollars ha^{-1}	
Gross profit margin	IL-irrigated	61,300	79,300	18,000*	12,000	12,700	700*
	IL-rainfed	58,400	73,000	14,600*	11,300	11,800	500*
	MN-rainfed	55,800	65,900	10,100*	13,200	13,500	300
	WI-irrigated	58,400	74,100	15,700*	13,800	14,400	600*
Overall mean		**58,475**	**73,075**	**14,600***	**12,575**	**13,100**	**525***

Table 2.4 Effect on yield traits of a crowding stress tolerant hybrid for shifting from current plant density to plant density optimized for maximum gross profit margin ($ ha^{-1}) across different production-areas. Asterisk represents significant changes at α = 0.05 based on pairwise t tests.

Yield trait	Production area	Response at current plant density	Response at optimum plant density	Difference
		Mt ha^{-1}		
Green ear mass	IL-irrigated	21.74	22.75	1.01*
	IL-rainfed	21.6	22.71	1.11*
	MN-rainfed	22.33	23.21	0.88*
	WI-irrigated	23.91	25.20	1.29*
	Overall mean	**22.58**	**23.71**	**1.13***
		cases ha^{-1}		
Case production	IL-irrigated	1,478	1,569	91*
	IL-rainfed	1,400	1,474	74*
	MN-rainfed	1,609	1,655	46
	WI-irrigated	1,684	1,770	86*
	Overall mean	**1,547**	**1,622**	**75***

Table 2.5 Effect on ear traits of a crowding stress tolerant hybrid for shifting from current plant density to plant density optimized for maximum gross profit margin ($ ha^{-1}) across different production-areas. Asterisk represents significant changes at α = 0.05 based on pairwise t tests.

Ear Trait	Production area	Response at current plant density	Response at optimum plant density	Difference
			ears per plant	
Ear number per plant	IL-irrigated	0.97	0.86	-0.11*
	IL-rainfed	1.00	0.91	-0.08*
	MN-rainfed	1.00	0.96	-0.04*
	WI-irrigated	1.05	0.96	-0.09*
	Overall mean	1.02	0.93	-0.08*
			kg plant^{-1}	
Ear mass per plant	IL-irrigated	0.36	0.29	-0.07*
	IL-rainfed	0.37	0.31	-0.06*
	MN-rainfed	0.40	0.36	-0.04*
	WI-irrigated	0.42	0.35	-0.07*
	Overall mean	0.39	0.33	-0.06*
			cm	
Average ear length	IL-irrigated	19.4	19.0	-0.4*
	IL-rainfed	19.1	18.7	-0.4*
	MN-rainfed	19.9	19.4	-0.6*
	WI-irrigated	19.3	18.8	-0.5*
	Overall mean	19.3	18.9	-0.5*
			cm	
Filled ear length	IL-irrigated	17.9	16.9	-1.0*
	IL-rainfed	17.6	16.9	-0.8*
	MN-rainfed	18.8	17.8	-1.0*
	WI-irrigated	18.3	17.5	-0.8*
	Overall mean	18.1	17.3	-0.8*
			(%)	
Recovery	IL-irrigated	43.36	43.53	0.17
	IL-rainfed	42.22	42.16	-0.06
	MN-rainfed	45.74	44.77	-0.97*
	WI-irrigated	45.43	45.25	-0.18
	Overall mean	44.10	43.86	-0.24*
			(%)	
Kernel moisture	IL-irrigated	77.02	76.96	-0.06
	IL-rainfed	77.32	77.34	0.02
	MN-rainfed	77.05	77.06	0.01
	WI-irrigated	77.47	77.60	0.13
	Overall mean	77.30	77.35	0.05

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CHAPTER 3: UNDERSTANDING VARIABILITY IN OPTIMUM PLANT DENSITY AND RECOMMENDATION DOMAINS FOR CROWDING STRESS TOLERANT PROCESSING SWEET CORN

3.1 Abstract

Recent research shows significant economic benefit if the processing sweet corn industry grew crowding stress tolerant (CST) hybrids at their optimum plant densities, which exceed current plant densities by approximately 14,500 plants ha^{-1}. However, optimum plant density of individual fields varies over years and across the Upper U.S. Midwest, where processing sweet corn is concentrated. The objectives of this study were to: (1) determine the extent to which environmental and management practices affect optimum plant density and, (2) identify the most appropriate recommendation domain for making decisions on plant density. To capture spatial and temporal variability in optimum plant density, on-farm experiments were conducted at thirty fields throughout the Upper Midwest from 2013 – 2017. Exploratory factor analysis of 12 environmental and management variables revealed two factors – one related to growing period and the other defining soil type, which explained the maximum variability observed across all the fields. These factors were then used to quantify the strength of associations with optimum plant density. Pearson's partial correlation coefficients of 'growing period' and 'soil type' with optimum plant density were low (ρ_1 = -0.14 and ρ_2 = -0.09, respectively) and non-significant (P = 0.47 and 0.65, respectively). To address the second objective, six candidate recommendation domain models (RDM) were developed and tested. Linear mixed effects models describing crop response to plant density were fit to each level of each candidate RDM. The difference in profitability observed at the current plant density for a field and the optimum plant density under RDM level represented the additional processor profits ($ ha^{-1}) from a field**.** The RDM built around 'Production Area' (RDM_{PA}) appears most suitable, because plant density recommendations based on RDM_{PA} maximized processor profits as well grower returns than any other RDM. Compared to current plant density, processor profits and grower returns increased by $448 ha^{-1} and $82 ha^{-1}, respectively at plant densities under RDM_{PA}.

3.2 Introduction

Optimum plant density is essential to maximizing yield in field corn (Maddonni et al., 2006; Singh and Singh, 2002). Plant density affects plant architecture, alters growth and developmental patterns, and influences carbohydrate production and partitioning (Casal et al., 1985). Plant density interactions with environment and crop management practices also can affect crop performance. Shanahan et al. (2004) demonstrated field-scale management of plant density as an economically feasible option for field corn production in the western U.S. Corn Belt.

Geographic location and environmental factors such as temperature, precipitation and radiation influence plant density decisions. Assefa et al. (2016) reported that as latitude increased from 30° N to 50° N, higher plant densities were required to attain the same yield level as at lower latitudes. At similar plant densities, lower yield in field corn at higher latitudes can be due to decreased amount of solar radiation and reduced crop growing season (Peltonen-Sainio, 2012; Mueller et al., 2015). In southern climates, Thompson et al. (2012) found that higher nighttime temperatures were unfavorable for field corn yields and reduced crop yield in above-average plant densities.

Water supply is essential in decision-making for plant density in sweet corn. Compared to irrigated production systems, lower plant densities are recommended for rainfed production. For instance, sweet corn plant densities recommended for irrigated production systems in Minnesota average 66,000 plants ha^{-1}, while 55,000 plants ha^{-1} are recommended for rainfed production systems (Fritz et al., 2010). Higher plant densities can be detrimental for field corn yields during periods of extended water shortage in rainfed production systems (Norwood, 2001; Tokatlidis et al., 2011, Tokatlidis et al., 2015). When drought is a threat, Norwood (2001) suggested hybrid maturity and planting date should be considered when making decisions on plant density.

Previous studies have reported that widely used processing sweet corn hybrids differ greatly in crowding stress tolerance (CST) and yield potential (Williams, 2012; Williams, 2015). Williams (2012) reported that processing sweet corn germplasm with improved CST was under-planted by growers in the Upper Midwest. Dhaliwal (2018) quantified optimum plant density for CST processing sweet corn in the same region. The study reported that CST sweet corn is under-planted around 14,500 plants ha^{-1} averaged across thirty fields in the region. Using optimum plant density for CST sweet corn, vegetable processors can realize up to \$700 ha^{-1} additional profits (Dhaliwal, 2018). However, optimum plant density varied across space and time. Conceivably, making recommendations for plant density of CST sweet corn tailored to address field-scale variability may increase profitability of both growers and vegetable processors. Vegetable processor profitability is measured as gross profit margin (\$ ha^{-1}), which in this instance is the value of cases of sweet corn produced per hectare less the contract price paid to the grower and seed costs, measured in \$ ha^{-1}. Grower returns (\$ ha^{-1}) depend on the total green ear mass of sweet corn harvested by processor.

A recommendation domain is defined as “a group of roughly homogeneous farmers with similar circumstances for whom we can make more or less the same recommendation” (Byerleeet al., 1980). Natural circumstances (e.g. climate, soil, biotic factors) and socio-economic factors (e.g. farm size, labor accessibility, power source) are commonly used factors in forming recommendation domains (Harrington and Tripp, 1984). For instance, two recommendation domains for farming a region of South American highlands were identified; specifically, flat lands and steep lands (CIMMYT 1981). Major differences in the methods of land preparation, choice of cultivars and weed management practices were reported between recommendation domains.

Previous studies have reported that targeting sites under the same recommendation domain with the new technology, and for which the technology is suitable, increases the likelihood of adoption of new technology (Kalcic et al., 2015; Phiri et al., 2004). Recommendation domains prevent extrapolating results from better environments to poorer environments (Hildebrand, 1984). Furthermore, appropriate recommendation domains can avoid two equally undesirable situations of (a) offering a different recommendation when unnecessary, which adds cost, or (b) offering a single recommendation when multiple recommendations are needed (Harrington and Tripp, 1984). Moreover, effective recommendation domains can guide policy makers in allocating resources appropriately (Harrington and Tripp, 1984).

The goal of this work was to determine the best approach for making plant density recommendations that would maximize the economic benefit of increasing plant densities of CST sweet corn. A previous study with fresh market sweet corn from Connecticut reported gross returns increased by \$1,150 ha^{-1} on increasing the plant density from 65,340 to 104,550 plants ha^{-1} (Durgy and Boucher, 2001). Stanger and Lauer (2006) reported variation in optimum plant density for field corn in the Upper Midwest based on local soil and climatic conditions. This may be evidence of different recommendation domains for plant density in this region. Therefore, scaling similar recommendations for fields with similar agroecological conditions can facilitate effective adoption of optimum plant densities. The objectives of this study were to: (1) determine the extent to which environmental and management practices affect optimum plant density, and (2) identify the most appropriate recommendation domain for making decisions on plant density.

3.3 Materials and Methods

To capture variability in optimum plant density of CST sweet corn, on-farm experiments were conducted in collaboration with vegetable processors in the Upper Midwest. Fields were located in areas of high strategic importance within the states of Illinois, Minnesota and Wisconsin across a 5-year period. For complete details of the field experiment, see Dhaliwal (2018). In brief, a total of 30 fields were included. Each experiment was laid out as an RCBD with two replications. Ten levels of plant density were tested, ranging from 42,000 plants ha^{-1} to 109,000 plants ha^{-1}. Green ear mass yield and the corresponding gross profit margin (\$ ha^{-1}) were calculated for each plant density level, and the plant density that would return maximum gross profit margin was considered the optimum plant density (Dhaliwal, 2018).

All experiments were nested with growers' fields and managed by growers using their standard practices, including irrigation, fertilization, and pest management. Therefore, crop responses in this research reflect contemporary production of sweet corn grown for processing throughout the Upper Midwest.

3.3.1 Environmental and management variables

Based on previous literature on plant density associations with environmental and crop management variables, twelve variables were studied. Environmental variability was accounted by climatic, edaphic, and topographic variability. Climatic variability was characterized using growing degree days (GDD) and precipitation across the growing season. Daily precipitation, minimum air temperature, and maximum air temperature were obtained from the Midwestern Regional Climate Center (2017) using the nearest active weather station for each site. The GDDs were calculated using daily minimum and maximum air temperature and a base temperature of 10℃. Further, GDDs were determined from planting to tassel (GDD_{pt}) and from tassel to harvest (GDD_{th}). Edaphic factors included soil texture and percent organic matter. Soil samples were collected at harvest using a soil probe. Composite soil sample for each field was composed of at least six cores with core diameter 2 cm and core depth 15 cm. Soil samples were characterized for chemical (pH, micro and macro nutrient availability) and physical (particle size distribution) attributes (A&L Great Lakes Laboratories, Fort Wayne, IN). Topographic variability was accounted by latitude and longitude of the centroid of each field. Crop management variables included planting date, harvest date, and days between planting and harvest. Dates were expressed as day of year.

3.3.2 Exploratory factor analysis and Pearson's partial correlation analysis

Exploratory factor analysis, a commonly used multivariate technique for dimension reduction (Johnson, 1998), was used to study covariance relationships among environmental and crop management variables. Since variables were on different scales, and to prevent variables with high variances from skewing the analysis, a correlation matrix was used for exploratory factor analysis. Exploratory factor analysis was performed using *factanal* package in RStudio (R Core Team, 2017) with varimax rotation for extracting orthogonal factor loadings. Orthogonal factor loadings are helpful as they can be interpreted similar to correlations. Factors with eigenvalues greater than 1 were retained out of the 12 potential factors (Kaiser, 1960). Retained factors (i.e., latent variables) represent underlying, unobservable factors. Factor scores were extracted using the *psych* package in RStudio (Revelle, 2017). Factor scores are the linear combinations of factor loadings and set of original variables that retain most of the variability.

Pearson's partial correlation analysis was conducted on factor scores and optimum plant density of fields. The goal was to identify strength of associations between latent variables and optimum plant densities. All tests were declared significant at $\alpha = 0.05$.

3.3.3 Criteria for construction of recommendation domains

Recommendation domains can be a useful tool when choosing a target plant density for an individual field when among-field variability in optimal plant density is large (Harrington and Tripp, 1984). The idea is to group fairly homogenous fields together that benefit from a common recommendation. There are many criterion of grouping fields, hence, numerous potential recommendation domains.

Based on data available for site characterization, six candidate recommendation domains models (RDM) were developed and tested (Figure 3.1). Candidate RDMs included 'Overall', 'Water Supply', 'State', 'Production Area', 'Planting Date' and 'Yield Level' (Figure 3.1). With the Overall RDM (RDM_O), all fields were grouped into a single recommendation domain. In essence, the RDM_O uses a single plant density recommendation for the entire Upper Midwest. With Water Supply (RDM_{WS}), fields were grouped by water supply; specifically, irrigated (N= 14) and rainfed (N = 16). The RDM_{WS} recognizes sweet corn grown under rainfed conditions may have a different optimal density than irrigated sweet corn. State (RDM_{ST}) grouped fields by state; specifically, Illinois (N = 14), Minnesota (N= 5) and Wisconsin (N = 11). The RDM_{ST} attempts to account for potential differences in growing conditions and management that may exist among the three primary states in which sweet corn is grown for processing in the Midwest. Under Production Area (RDM_{PA}), both state and water supply were considered; therefore, fields were grouped into Illinois-irrigated (N = 3), Illinois-rainfed (N = 11), Minnesota-rainfed (N = 5) and Wisconsin-irrigated (N = 11). The RDM_{PA} also differentiates fields by the local factory that will process sweet corn grown in the vicinity. Sweet corn planting in the Upper Midwest commences the first week of April and continues into the first week of July. For Planting Date (RDM_{PD}), fields were grouped as 'early' if planted on or before April 30 (N = 3), 'mid' if planted between May 1 and June 10 (N = 19), and those planted after June 10 were considered 'late' planted (N = 8). Finally, in Yield Level (RDM_{YL}), fields were grouped according to yield. Cluster analysis was used to group fields with similar yields together, resulting in three categories: low yielding (N = 12), medium yielding (N = 14) and high yielding fields (N = 4). Cluster analysis results are reported in Figure S1.

3.3.4 Identification of the best recommendation domain

Earlier study modelled gross profit margin response to plant density to identify the optimum plant density that would maximize gross profit margin for individual fields (Dhaliwal, 2018). The same fields were classified under different recommendation domains and linear mixed effects models were fit to predict maximum gross profit margin under each candidate recommendation domain. Each model was a second order polynomial mixed effects model with domain level random intercept and slope structure and plant density as a fixed effect. Best linear unbiased predictors (BLUPs) were extracted from each model and were used to identify the maximum gross profit margin for different levels in each candidate recommendation domain. Then, plant density corresponding to maximum gross profit margin was considered optimum plant density for the respective domain level. Grower returns also were calculated corresponding to optimum plant density for each domain level using the linear mixed effects model coefficients that were established in previous study by Dhaliwal (2018).

The difference between gross profit margin observed at the current plant density for the field and the RDM level was identified as additional processor profits (Figure 3.2). Similarly, additional grower returns were calculated as difference between grower returns at RDM level optimum plant density and the field's current plant density. Additional processor profits and grower returns were then averaged for each RDM level to calculate mean RDM values. It is noteworthy that vegetable processors decide the target plant density for processing sweet corn and their profitability is given by gross profit margins, hence, the RDM that maximized processor profits was declared the best practical choice for making decisions on plant density in CST sweet corn. The Kolmogorov-Smirnov test was used to identify differences ($\alpha = 0.05$) in additional processor profitability and grower returns between RDMs (Massey, 2012).

3.4 Results and Discussion

Across the 30 sweet corn fields tested in this research, optimum plant density ranged from 60,850 plants ha^{-1} to 90,900 plants ha^{-1}, corresponding to a maximum gross profit margin ranging from \$9,000 ha^{-1} to \$18,250 ha^{-1} (Table 3.1). Previously, Williams (2012) reported CST tolerant processing sweet corn is under-planted at an average plant density of 56,000 plants ha^{-1} in the Upper Midwest. Dhaliwal (2018) demonstrated shifting from current to optimum plant densities for CST processing sweet corn increased profitability of both the processor and contract grower up to \$700 ha^{-1} and \$105 ha^{-1}, respectively, without negatively affecting ear traits important to processing.

3.4.1 Environment and Management

Fields varied in crop management and environmental conditions. Planting dates ranged from April 24 to June 19. As such, harvest dates ranged from July 20 to September 26 (Table 3.1). Total crop duration ranged from 76 to 100 days (Table 3.2). Heat units accumulated during vegetative and reproductive growth (i.e., GDD_{pt} and GDD_{th}) also varied. Soil texture varied from clay loam to silty loam to sand. Soils greater than 50% sand were sprinkler irrigated, whereas most other soils were rainfed. Fields received variable precipitation, ranging from 20.3 cm to 59.5 cm from planting to harvest (Table 3.2). Fields used in this research represent the wide range of conditions in which processing sweet corn is grown in the Upper Midwest.

Several environmental and crop management variables were correlated. Latitude was positively correlated with planting date ($\rho = 0.636$), harvest date ($\rho = 0.823$), and crop duration ($\rho = 0.615$; Table 3.3). Late planting dates are observed at higher latitudes pertaining to the environmental conditions, especially air temperature and soil conditions. Sweet corn growers have found that cold wet soils lead to slow germination in shrunken-2 (*sh-2*) sweet corn. Hassell et al. (2003) reported *sh-2* type sweet corn hybrids require slightly higher temperatures for germination than sugar enhanced (*se*) and sugary (*su*) sweet corn. They found *sh-2* type sweet corn hybrids took minimum time for germination at air temperature around 22°C (Hassell et al., 2003).

Ciampitti et al. (2017) also reported planting date for field corn increased from 60^{th} to 100^{th} day of year as latitude increased from 25°N to 35°N.

As expected, edaphic factors including sand, silt and clay variables were highly correlated with each other (ρ = -0.976 to 0.752). Likewise, GDD_{pt} was positively correlated to planting date (ρ = 0.549) and, GDD_{th} was negatively correlated to planting date (ρ = -0.753) and harvesting date (ρ = -0.719).

Exploratory factor analysis identified underlying common factors explaining most of the variation in environmental and crop management variables. Two factors were retained and, collectively, accounted for 62.6 percent of the total variance (Table 3.4). Factor 1 had positive loadings for planting date, harvest date, latitude, and GDD_{pt}, whereas GDD_{th} had a negative loading in factor 1. Factor 1 was interpreted as the 'growing period' factor. Longitude, sand, and clay loaded positively into factor 2 (Table 3.4). Factor 2 was interpreted as the 'soil type' factor. Communality values were high for most of the variables (h^2 = 0.57 to 0.99), indicating the factor analysis model satisfactorily explained total variability contributed by individual environmental and crop management variables. Kaspar et al. (2004) reported the factor comprised of high positive loadings from silt, clay and negative loadings from sand, slope and soil color were positively associated with field corn yield in dry growing seasons of central Iowa. However, the same factor was negatively associated with grain yields in wet growing seasons. Such outcomes were determined to be the result of soil physical properties favoring soil water retention, which was beneficial to the crop in dry years, but damaging in wet years due to extended periods of saturated soils (Kaspar et al., 2004).

Despite the logical outcome of factor analysis, neither 'growing period' or 'soil type' factors were main drivers of variability in optimum plant density. Pearson's partial correlation coefficients of 'growing period' and 'soil type' with optimum plant density were low (ρ_1 = -0.14 and ρ_2 = -0.09, respectively) and non-significant (P = 0.47 and 0.65, respectively). Apparently, there were other unmeasured variables responsible for varied optimum plant densities. A common limitation encountered with on-farm studies is the limited access to the growers' farms, thus setting a trade-off between the quality and quantity of data accessed from those farms (Francis, 1995). Moreover, multivariate techniques like exploratory factor analysis perform best when the number of observations exceeds the number of variables by one order of magnitude (Everitt, 1975; Nunnally, 1978).

3.4.2 Recommendation Domains

Optimum plant density under RDM_O was 73,100 plants ha^{-1} (Figure 3.1). The average current plant density is 56,000 plants ha^{-1}(Dhaliwal, 2018; Williams, 2012). Increasing plant density from current to the level determined by RDM_O, vegetable processors and contract growers can realize a profit increase averaging \$430 ha^{-1} and \$81 ha^{-1} (Table 3.5). Recommended plant density for CST sweet corn under RDM_O is higher than the previously reported optimum plant densities for sweet corn in the Upper Midwest (Boerboom et al., 1999; Fritz et al., 2010).

Optimum plant density under RDM_{WS} for irrigated and rainfed fields was 76,000 and 70,700 plants ha^{-1}, respectively (Figure 3.1). Using the plant density recommendations under RDM_{WS}, growers can realize additional \$72 ha^{-1} and \$94 ha^{-1} in rainfed and irrigated fields in the Upper Midwest (Table 3.5). Under RDM_{WS}, irrigated fields showed \$155 ha^{-1} more in processor profits than fields under rainfed conditions (Table3.5). Recommended plant densities under RDM_{WS} agree with the findings of previous studies that report fully irrigated production systems can sustain higher plant densities compared to rainfed systems (Boerboom et al., 1999; Fritz et al., 2010). Piana et al. (2008) reported 107,000 plants ha^{-1} was optimum plant density for field corn under irrigated conditions. Similarly, Silva et al. (2010) and Takasu et al. (2014) reported optimum plant density for maximum grain yield in irrigated field corn were 100,000 plants ha^{-1} and 90,000 plants ha^{-1}, respectively. In a Minnesota study of field corn, optimum plant densities were reduced 12.5% when rainfall exceeded long-term averages by approximately 50% during the growing season (Porter et al., 1997). Water becomes a limiting factor for biomass production in field corn at higher plant densities under rainfed conditions (Ogola et al., 2005).

Under RDM_{ST}, optimum plant densities for fields in Illinois, Minnesota and Wisconsin were 77,600 plants ha^{-1}, 64,700 plants ha^{-1} and 75,300 plants ha^{-1}, respectively (Figure 3.1). Based on RDM_{ST}, plant density recommendations were more profitable for processors in Illinois (\$443 ha^{-1}) and Wisconsin (\$509 ha^{-1}) than Minnesota (\$266 ha^{-1}) (Table 3.5). These results were consistent with Coulter (2010) and Stanger and Lauer (2006) who reported economic optimum plant densities for field corn were similar for Wisconsin (83,000 plants ha^{-1}) and Illinois (79,800 plants ha^{-1}). In contrast, Rockel and Coulter (2011) reported plant densities in range of 81,700 to 107,900 plants ha^{-1} maximized grain yields in field corn in the southern Minnesota. Maximum gains in grower returns were observed in Wisconsin (\$97 ha^{-1}) at plant density recommendations under RDM_{ST}.

Under RDM_{PA} fields were grouped based on both water supply and state. Optimum plant densities under RDM_{PA} ranged from 65,000 to 82,600 plants ha^{-1} (Figure 3.1). Based on recommendations from RDM_{PA}, vegetable processors can realize additional profits ranging from \$268 ha^{-1} to \$600 ha^{-1}. Optimum plant density in field corn differs among latitude zones in the United States (Assefa et al., 2016). Three decades ago, field corn grain yield in Illinois was maximized at 56,300 plants ha^{-1} to 76,750 plants ha^{-1}. In the present work, Minnesota-rainfed processor profit was \$268 ha^{-1} and grower returns were \$63 ha^{-1} by following plant density recommendations under RDM_{PA}.

The RDM_{PD} identified optimum plant densities for fields grouped by three planting date windows (Figure 3.1). Under RDM_{PD}, early-planted fields (76,100 plants ha^{-1}) had higher optimum plant densities than mid- (72,700 plants ha^{-1}) and late-planted fields (73,800 plants ha^{-1}). Williams (2008) reported late-June planted sweet corn had lower yields than early-May planted sweet corn due to lower water supply and increased disease incidence in late-June plantings. Early-July planted sweet corn took 23% to 35% fewer days from crop emergence to silking period, however, mid-June and early-July plantings also resulted in plants with fewer leaves and slower rates of leaf appearance (Williams, 2008). Similarly in field corn, Nafziger (1994) recorded higher grain yields in early-April plantings compared to late-May plantings. Conceivably, using higher plant densities for early planting dates would allow the crop to take advantage of favorable growing conditions which include more days of available solar radiation, potentially avoid some diseases, and risk of late-season drought. Currently, vegetable processors reduce plant densities 5-10% for the latest planting dates (C. Bahr, pers. comm.).

Under RDM_{YL}, optimum plant densities for low –, medium –, and high – yielding fields were identified. The RDM_{YL} showed optimum plant density for low-yielding fields (68,100 plants ha^{-1}) was lower than medium-yielding (72,800 plants ha^{-1}) and high-yielding fields (76,000 plants ha^{-1}). These results show a similar trend as field corn, as evidenced by low-yielding environments (less than 7 Mt ha^{-1}) were limited to 73,000 plants ha^{-1} whereas high-yielding environments (greater than 13 Mt ha^{-1}) required at least 100,000 plants ha^{-1} (Assefa et al., 2016).Plant density recommendations under RDM_{YL} resulted in the maximum additional processor profits (\$737 ha^{-1}) and grower returns (\$126 ha^{-1}) in the high – yielding fields (Table 3.5). Contrarily, low – yielding fields showed the least gains in processor profits and gross returns among all three yield levels.

Gains in processor profit or grower returns were the differences between gross profit margin or gross returns observed at the current plant density for the field and the RDM level. The RDM mean additional processor profits and grower returns is the average value across all of a RDM's levels. Kolmogorov-Smirnov tests showed that mean additional processor profits and grower returns were statistically similar across RDMs (data not shown). Nonetheless, for the vegetable crop industry will benefit from increasing plant density of CST hybrids, they need research-based guidance on determining plant density, and practical differences exist among RDMs.

Plant density recommendations under RDM_{PA} resulted in the maximum gain in processor profits (\$448 ha^{-1}) and grower returns (\$82 ha^{-1}), as well making it the most suitable RDM for deciding plant densities for fields across the Upper Midwest. Also, RDM_{PA} reduced the variability for additional processor profits and grower returns within each level (i.e., production area) as shown by smaller standard deviations relative to other RDMs (Table 3.5). Plant density recommendations based on RDM_{PA} make the most of genetic potential of CST processing sweet corn hybrids. Also, RDM_{PA} can be viewed as an improved version of RDM_{WS} and RDM_{ST} as it accounts for both water supply and state factors. Moreover, adopting recommendations for optimum plant density from RDM_{PA} would be quite feasible. The four levels of RDM_{PA} are already distinct within the vegetable processing industry. Typically, one or more processing plants exist within each state. Contract sweet corn production is managed by field supervisors assigned to the four levels of RDM_{PA}. Those field supervisors make decisions for their contract fields within their assigned territory, including plant density. Therefore, plant density recommendations based on RDM_{PA} are most likely to lead to successful adoption across fields in the Upper Midwest to realize increased profitability to both processors and their contract growers.

3.5 Conclusion

Variability in optimum plant density for CST sweet corn exists in fields across the Upper Midwest; however, a research-based approach to guide plant density recommendations is lacking. To maximize profitability from using increased plant densities of CST sweet corn, processors should decide plant densities tailored to the local growing conditions. Of six different recommendation domains tested, plant density recommendations under RDM_{PA} maximized gains in processor profits ($448 ha^{-1}) and grower returns ($82 ha^{-1}). Moreover, RDM_{PA} groups fields into a structure the sweet processing industry already utilizes for field-level decision making.

3.6 Figures and Tables

Figure 3.1 Linear mixed effects model for relationship between gross profit margin (\$ ha^{-1}) and plant density (plants ha^{-1}) under six candidate recommendation domain models (RDM). The peak of each curve identifies the optimum plant density of each RDM level.

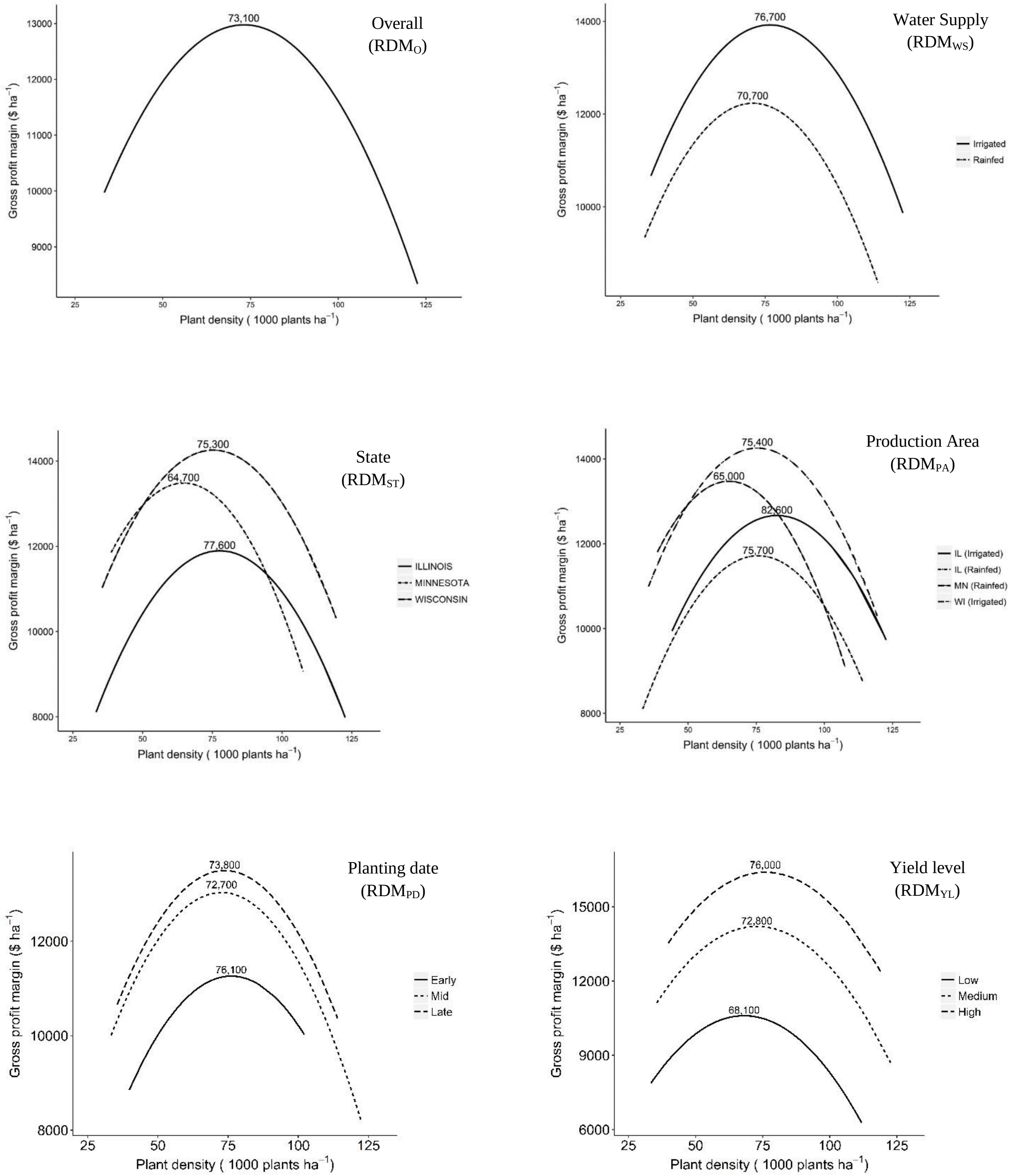

Figure 3.2 Calculation of additional processor profits ($ ha^{-1}) for a field in a given level of a recommendation domain model (RDM). Red line represents the optimum plant density (plants ha^{-1}) for maximum gross profit margin ($ ha^{-1}) under a level of a RDM (solid black curve). Blue line represents current plant density for an individual field (dotted black curve). The difference in gross profit margin observed at the optimum plant density under RDM level and current plant density of a field give additional processor profits from the field.

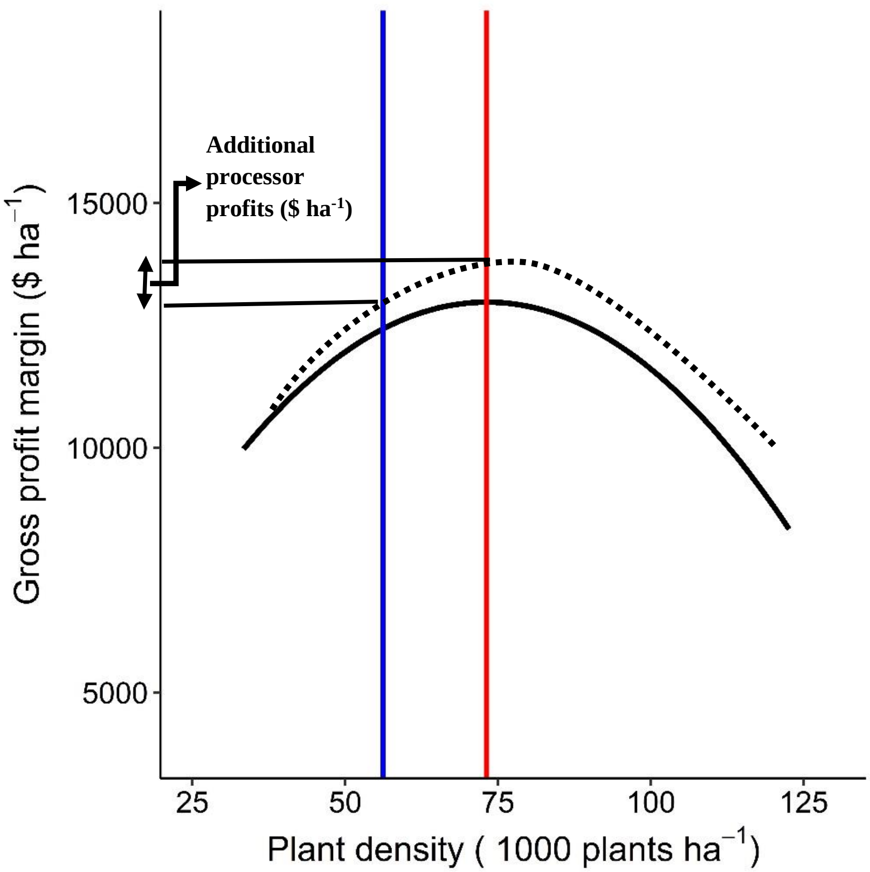

Table 3.1 Brief description of the thirty fields in which optimum plant density for processing sweet corn was quantified in field trials in Illinois (IL), Minnesota (MN), and Wisconsin (WI) from 2013 to 2017.

Year	State	County	Soil type	Water supply	Planting date	Harvest date	Optimum plant density* (plants ha^{-1})	Maximum gross profit margin* ($ ha^{-1})
2013	IL	LaSalle	Silt loam	Rainfed	19-Jun	6-Sep	80,850	11,750
2014	IL	Champaign	Silt loam	Rainfed	27-May	11-Aug	86,100	13,280
2014	IL	Champaign	Silt loam	Rainfed	27-May	13-Aug	70,350	13,210
2014	IL	DeKalb	Silt loam	Rainfed	6-Jun	29-Aug	66,100	9,820
2014	IL	DeKalb	Silt loam	Rainfed	6-Jun	29-Aug	69,400	11,570
2014	IL	LaSalle	Silt loam	Rainfed	14-Jun	5-Sep	79,500	15,140
2014	WI	Portage	Loamy sand	Irrigated	19-Jun	18-Sep	70,450	10,480
2014	WI	Portage	Muck sand	Irrigated	5-Jun	9-Sep	68,250	12,220
2014	WI	Portage	Loamy sand	Irrigated	23-May	25-Aug	80,550	14,350
2015	IL	Champaign	Silt loam	Rainfed	22-May	5-Aug	76,200	11,360
2015	IL	Champaign	Silt loam	Rainfed	22-May	6-Aug	63,450	9,890
2015	IL	Mason	Sandy loam	Irrigated	29-Apr	20-Jul	72,600	10,140
2015	MN	Brown	Clay loam	Rainfed	10-Jun	4-Sep	71,800	14,520
2015	MN	Redwood	Clay loam	Rainfed	10-Jun	4-Sep	70,100	13,480
2015	WI	Portage	Loamy sand	Irrigated	2-Jun	3-Sep	75,150	11,720
2015	WI	Portage	Loamy sand	Irrigated	13-May	20-Aug	69,800	15,780
2015	WI	Waushara	Loamy sand	Irrigated	16-Jun	15-Sep	66,200	16,130
2016	IL	Champaign	Silt loam	Rainfed	16-May	1-Aug	70,700	13,610
2016	IL	Champaign	Silt loam	Rainfed	16-May	1-Aug	74,200	10,910
2016	IL	Mason	Sandy loam	Irrigated	20-Apr	22-Jul	86,950	14,320
2016	MN	Brown	Clay loam	Rainfed	13-Jun	31-Aug	61,250	9,050
2016	WI	Adams	Loamy sand	Irrigated	1-Jun	23-Aug	67,400	12,100
2016	WI	Portage	Muck sand	Irrigated	8-Jun	6-Sep	70,100	15,380
2016	WI	Portage	Loamy sand	Irrigated	19-Jun	14-Sep	90,900	18,250
2017	IL	Champaign	Silt loam	Rainfed	24-Apr	28-Jul	66,050	9,510
2017	IL	Champaign	Silt loam	Irrigated	16-May	7-Aug	78,350	13,630
2017	MN	Brown	Clay loam	Rainfed	10-Jun	7-Sep	65,400	15,270
2017	MN	Brown	Clay loam	Rainfed	11-Jun	7-Sep	60,850	15,320
2017	WI	Portage	Sand	Irrigated	30-May	31-Aug	72,850	17,640
2017	WI	Portage	Loamy sand	Irrigated	23-Jun	26-Sep	83,800	14,590

* Optimum plant density and maximum gross profit margin adapted from Dhaliwal, 2018.

Table 3.2 Summary statistics of the environmental and crop management variables of thirty fields in which optimum plant density for processing sweet corn was quantified in field trials in Illinois, Minnesota, and Wisconsin from 2013 to 2017. Universal Transverse Mercator (UTM) uses a 2-dimensional Cartesian coordinate system to give locations on the surface of the Earth. GDDpt and GDDth represent growing degree days observed during planting-tassel and tassel-harvest, respectively.

Variable	Units	Mean	Standard deviation	Minimum	Maximum
Latitude	UTM	4717924	219871	4436816	4920895
Longitude	UTM	330573	46532	249609	396723
Planting date	day of year	150.7	16.7	111	174
Harvest date	day of year	236.8	18.1	201	269
Crop duration	days	87.1	7.0	76	100
Organic matter	%	4.5	3.1	0.7	16.8
Sand	%	44.6	36.2	5	94
Silt	%	36.4	26.4	1	71
Clay	%	19	11.8	4	38
Precipitation	cm	37	10.3	20.3	59.5
GDD_{pt}	heat units	1070	83.6	825	1179
GDD_{th}	heat units	615.3	93.7	452	852

Table 3.3 Pearson's correlation coefficients between environmental and crop management variables of thirty fields in which optimum plant density for processing sweet corn was quantified in field trials in Illinois, Minnesota, and Wisconsin from 2013 to 2017. Coefficients with * and ** are significant at α = 0.05 and α = 0.01, respectively. GDDpt and GDDth represent growing degree days observed during planting-tassel and tassel-harvest, respectively.

	Latitude	Longitude	Planting date	Harvest date	Crop duration	Organic matter	Sand	Silt	Clay	Precipit-ation	GDDpt
Latitude	1										
Longitude	-0.601**	1									
Planting date	0.636**	-0.156	1								
Harvest date	0.823**	-0.384*	0.923**	1							
Crop duration	0.615**	-0.624**	0.006	0.391*	1						
Organic matter	0.057	0.25	0.211	0.111	-0.217	1					
Sand	0.711**	-0.858**	0.175	0.439*	0.721**	-0.213	1				
Silt	-0.796**	0.889**	-0.263	-0.521**	-0.723**	0.159	-0.976**	1			
Clay	-0.396*	0.638**	0.052	-0.179	-0.588**	0.297	-0.876**	0.752**	1		
Precipitation	-0.12	0.065	-0.233	-0.297	-0.213	0.155	-0.158	0.101	0.259	1	
GDDpt	0.18	0.271	0.549**	0.442*	-0.165	0.298	-0.166	0.104	0.275	-0.294	1
GDDth	-0.603**	0.298	-0.753**	-0.719**	-0.066	-0.023	-0.35	0.398*	0.181	0.019	-0.413*

Table 3.4 Exploratory factor analysis results, based on varimax rotation, using the correlation matrix of environmental and crop management variables from thirty fields in which optimum plant density for processing sweet corn was quantified in field trials in Illinois, Minnesota, and Wisconsin from 2013 to 2017. Factor loadings from variables that were greater than 0.400 in magnitude are in bold.

	Orthogonally rotated loadings[a]		
Variable	**$Factor_1$**	**$Factor_2$**	Communality (h^2)
Latitude	**0.675**	**-0.648**	0.88
Longitude	-0.146	**0.883**	0.81
Planting date	**0.964**		0.95
Harvesting date	**0.932**	-0.293	0.97
Organic matter	0.227	0.225	0.12
Sand	0.136	**-0.968**	0.99
Clay	0.149	**0.810**	0.99
Precipitation	-0.207		0.15
GDD_{pt}	**0.562**	0.268	0.39
GDD_{th}	**-0.699**	0.225	0.57
Eigen values	3.22	3.05	
Total variance (%)	32.1	30.5	**62.6**
Common variance (%)	51.3	48.7	**100**

[a]varimax rotation

Table 3.5 Mean additional processor profits ($ha^{-1}) and grower returns ($ ha^{-1}), standard error, and sample size for each level of the six candidate recommendation domain models (RDM). RDM mean additional processor profits and grower returns was determined using the weighted average of RDM levels. For a description of how additional processor profits were calculated, see Figure 1.

Recommendation domain model (RDM)	RDM level and mean	Sample size	Additional processor profitability ($ ha^{-1})	Standard error ($ ha^{-1})	Additional grower returns ($ ha^{-1})	Standard error ($ ha^{-1})
Overall	**RDM$_{O}$ mean**	**30**	**430**	**72**	**81**	**10**
Water supply	Irrigated	14	524	113	94	12
	Rainfed	16	370	89	72	13
	RDM$_{WS}$ mean	**30**	**442**	**77**	**82**	**11**
State	Illinois	14	443	132	75	78
	Minnesota	5	266	107	62	15
	Wisconsin	11	509	133	97	14
	RDM$_{ST}$ mean	**30**	**438**	**58**	**81**	**9**
Production-area	IL-Irrigated	3	600	180	76	5
	IL-Rainfed	11	429	146	76	24
	MN-Rainfed	5	268	110	63	15
	WI-Irrigated	11	509	134	98	14
	RDM$_{PA}$ mean	**30**	**448**	**55**	**82**	**7**
Planting date	Early	3	290	189	39	31
	Mid	19	437	71	81	11
	Late	8	475	223	97	23
	RDM$_{PD}$ mean	**30**	**432**	**36**	**81**	**11**
Yield level	Low	12	336	66	54	11
	Medium	14	451	106	90	12
	High	4	737	255	126	34
	RDM$_{YL}$ mean	**30**	**443**	**90**	**81**	**17**

3.7 Literature cited

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APPENDIX A: SUPPLEMENTAL FIGURE

Figure A.1 K-means clustering results on yield components for all fields. Yield components included case production (cases ha^{-1}), ear number per plant, ear mass per plant (kg $plant^{-1}$), green ear mass (Mt ha^{-1}), and gross profit margin (\$ ha^{-1}) of individual fields.