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INTERCROPPING CORN AND SOYBEAN: PROFITABILITY OF DIFFERENT AGRONOMIC MANAGEMENT TECHNIQUES

RAEANN L. HUFFMAN

91 Pages

Intercropping is the practice of growing multiple crops together in the same field. This is not commonly implemented in Midwest agriculture - instead, current monoculture practices have garnered attention because of the negative environmental impacts of monoculture farming. For this study, corn and soybean were intercropped in a production agriculture setting to investigate the benefits to the producer and the environment. Intercropping corn and soybean crops may reduce the need for added nitrogen (N) fertilizer, saving money on inputs and potential loss of N from the farm to the environment. Soybeans within the system may utilize less of the soil N leaving more N, available for the corn crops. Soybean plants are legumes and form a symbiotic relationship with bacteria in the soil, *Bradyrhizobium japonicum*, which allows the soybean plant to fix plant-unavailable N into a plant-available form. Therefore, corn plants within the intercropping system would require little, if any, synthetic N fertilizers.

An intercropping system may decrease the loss of N associated with greenhouse gases and acid rain components. The loss of N through leaching and denitrification are seen in monoculture practices where N fertilizer is used. The cause of the negative environmental impacts is from the over application of nutrients that are lost from the soil profile. The macronutrients which crops require in large amounts include nitrogen (N), phosphorous (P), and potassium (K). N, P, and K are being lost in large amounts increasing the creation of laws in

many areas, like the Chesapeake Bay and the Lake Erie watershed, are limiting how much and when fertilization can occur. The proposed intercropping system could increase farmer profit without any additional N fertilizer applied.

This study compares monoculture and intercropped systems of corn and soybean. All plots are treated the same for fertility in that no supplemental macronutrients were applied. The monoculture treatments were 38-cm corn (narrow-row corn), 38-cm soybean (narrow-row soybean), 76-cm corn (wide-row corn), and 76-cm soybean (wide-row soybean). Populations were constant for the monocropping treatments: 83,980 corn plants ha⁻¹ (34,000 plants ac⁻¹) and 345,000 soybean plants ha⁻¹ (140,000 plants ac⁻¹). These four monoculture treatments were compared to two intercropping treatments, intercropped corn and soybean with a corn population of 27,993 plants ha⁻¹ (11,333 plants ac⁻¹) and intercropped corn and soybean with a corn population of 55,985 plants ha⁻¹ (22,666 plants ac⁻¹). Since producers are constantly manipulating different cropping systems, this study took into consideration differences in the effect of row orientation and row spacing on yield. Thus, this study compares current monoculture production to intercropping to determine if intercropping could be profitable while requiring fewer environmentally-insensitive inputs.

Throughout the study, various statistical analyses were conducted to evaluate if there were any differences between the six treatments. Results evaluating the impact of row orientation and row spacing on corn and soybean production showed that both row orientation and row spacing did not significantly influence corn and soybean productivity. Comparing corn leaf tissue, corn intercropped with soybean contained a significantly greater N concentration within the plant tissue than monoculture corn ($p = 0.0006$). This difference was visually observed

during the 2020 growing season. Further, the results showed that intercropped corn and soybean produced a greater weight of seed per plant than any of the monoculture treatments.

Profitability of the monoculture and intercropped treatments was further evaluated to compare the two cropping systems. Two different analyses were conducted, comparing the different prices of corn and soybean at a set market price, and then comparing the different treatments at a range of potential prices. On 19 October 2020 the grain was sold at Prairie Central Co-operative in Lexington, IL. The price received for soybean was \$10.24 bu⁻¹, and corn was \$3.79 bu⁻¹. The intercropping profit was significantly greater than all the monoculture treatments. Since grain prices vary significantly from year to year, different ranges of prices were further evaluated using historical prices from the past 10 years. This resulted in a price range of \$3.00 to \$6.00 for corn prices and \$8.00 to \$14.00 for soybean prices. Different price combinations were evaluated and showed that the intercropping treatment was more profitable than the monoculture treatments at most combinations of corn and soybean prices. Further, the profitability of intercropping compared favorably to traditional monocrop corn grown in the Midwest using N fertilizer. Results of this study show that intercropped corn and soybean may be more profitable and benefit the environment from reduced inputs of N fertilizer.

KEYWORDS: intercropping, profitability, input costs, monocropping, row spacing, planting population, row orientation

INTERCROPPING CORN AND SOYBEAN: PROFITABILITY OF DIFFERENT
AGRONOMIC MANAGEMENT TECHNIQUES

RAEANN L. HUFFMAN

A Thesis Submitted in Partial
Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Agriculture

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INTERCROPPING CORN AND SOYBEAN: PROFITABILITY OF DIFFERENT
AGRONOMIC MANAGEMENT TECHNIQUES

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CHAPTER I: GENERAL INTRODUCTION TO INTERCROPPING AND PROFITABILITY

Production of agronomic crops have been an essential part of the agriculture industry in the United States for many years. Corn (*Zea mays*) and soybean (*Glycine max*) are two major agronomic crops that are produced in the Corn Belt. Corn is a cereal crop that was originally domesticated in Mexico over 9,000 years ago (Bonavia, Espinoza, and Grobman, 2013). Teosinte was originally a tall, annual tillering grass plant with stout, planophile leaves and multiple small ears. It has been modified throughout the years to have the structure and characteristics that include the ability to tolerate being planted at high-density populations and producing one large ear on each stalk. Soybean is a legume that was originally domesticated in East Asia dating back 6,000 to 9,000 years ago (Sedivy, Wu, and Hanzawa, 2016). Originally soybean plants were tall, vining plants and they have been modified to resemble a short bush-like plant with flowers at each node.

Genetic modifications and changes in production practices have led to a continuous increase in yield. In farming operations, profit is an essential component and one that must be maintained. Profit is the difference between the earnings amount and the expense amount in production. Input costs is the amount in cost that was incurred to produce something. Further, revenue can be defined as income, which is money that is received for work or sale of a product and expenses can be defined as the cost required to produce something (seed cost). Profit can increase with yield increases, or reduced input costs, and is driven by the market prices of the crops produced. When the market value increases it can increase the profit, depending on production costs, or when the number of bushels produced increases (without input costs increasing) and profit can increase with an increased amount of grain produced. Therefore, profit

is an essential component to a farming operation. Crop productivity can be determined by harvested seeds and added inputs or costs.

Since monoculture corn and soybean (one species of crop on a given piece of land) have contributed to the detriment of the environment (Altieri, 2009), a different type of cropping system has been introduced in the United States called intercropping. Intercropping is the practice of producing two or more species of crops on one piece of land, at the same time. There is limited research on intercropping specifically corn and soybean in a commercial ag system. This cropping system is derived from the foundation of the ‘three sisters of Native American lore’, the three sisters being beans, corn, and squash (Ngapo, et al., 2021). Corn would provide the support for the vining bean plants and allow them to climb, and squash would be a ground cover to help with moisture retention and discourage any predators because of their spines. This idea of intercropping is being introduced to commercial agriculture. Based on current research, it is believed that intercropping can aid in the increase in production, land-use efficiency, nutrient-use efficiency, and profitability all while reducing the negative impacts on the environment (Fan et al., 2020; Raseduzzaman and Jensen, 2017).

Ethanol, food additives, oil, and livestock feed are just a few important product commodities that are made from corn and soybean (Sedivy, Wu, and Hanzawa, 2016). Corn and soybean production are two crops that are among the top five most produced crops in the United States (Meade et al, 2016). In 2020, there was 82.5 million acres of corn plants harvested that yielded 14.5 billion bushels and 82.2 million acres of soybean plants harvested that yielded 4.1 billion bushels in the United States (NASS, 2020). The Midwest (Corn Belt) is largely known for its large role in corn and soybean production. The midwestern states that comprise of this region are Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin (NASS, 2017).

There are over 127 million agricultural acres in the Midwest and 75% of that area is planted as corn or soybean crops (NASS, 2017). Focusing on the state of Illinois, in 2020, there were 2.1 billion bushels of corn harvested, making the total production worth 9.2 billion dollars (NASS, 2021). Also, in 2020, there were 604 million bushels of soybean plants harvested resulting in a production value of 7 billion dollars in the state of Illinois (NASS, 2021). Corn and soybean production in Illinois make up a large amount of the total corn and soybean production in the United States.

Corn and soybean production in the state of Illinois surpasses the production of any other crop within the state. This study was conducted to compare the difference in monoculture farming to an intercropping system. Monoculture farming has attracted attention and is being examined due to the litany of negative impacts that monoculture corn and soybean production have on the environment. These issues include over-applied nutrients/chemicals, changes in production practices, and market volatility (Knörzer et al., 2009; Mulvaney, Khan, and Ellsworth, 2009). The negative impacts, environmental and economic, predominately stem from the over-application of chemicals, both pesticides and fertilizers, that are being applied to agronomic fields.

Two very common cropping mechanisms that are being manipulated and changed by producers in monoculture production are row orientation and row spacing. Row orientation is commonly orientated in a north-south or east-west manner, or perpendicular to the slope. North-south and east-west oriented rows can affect the amount of light that is intercepted by the crop canopy and how much penetrates to the soil below (Philbrook and Oplinger, 1989). Row spacing affects the distribution of the crops within a field and can be influenced by the manipulation of row spacing. Row spacing can vary based on available equipment, crop variety, or geographical

location (Farnham, 2001). Again, these two systems can be manipulated depending on the equipment that is available to the producer. These different techniques can influence the overall crop yield and can contribute to the overall differences in inputs. Throughout this experiment, these two techniques, row orientation and row spacing, will be analyzed through the observations.

Since the agriculture industry is everchanging and evolving, producers are constantly searching for the ‘next best thing’ to stay up to date with practices in the industry. Within this study intercropping corn and soybean is being examined. Different intercropping systems have been around for thousands of years, but it is not commonly being practiced in commercial agriculture in the United States. Knörzer et al. describes it as an ancient and traditional cropping system, yet it has the potential to contribute to modern and sustainable agriculture (2009). This is a common practice that is being utilized in other countries such as areas in Africa, Asia, Latin America, with different types of crops, and in some organic production systems and even in areas with a short growing season (Hoerning et al., 2019; Anders, Potdar, and Francis, 1996). Utilizing this intercropping technique in corn and soybean production in Illinois could aid to better utilization of resources that are available, especially when, comparing it to different monoculture systems while decreasing the amount of chemicals that are being applied to the crops.

Intercropping has been practiced within different species of crops for thousands of years, increasing land productivity and utilization. Commonly, different combinations of legumes (dicotyledon) and cereals (non-legumes, monocotyledon) are more effective when utilizing this technique of intercropping (Anders, Potdar, and Francis, 1996). Intercropping legumes and cereals when nutrients or water is limited can cause a mutualistic relationship between the crops,

and can be described as the crops being complementary to one another. One study planted peanuts and corn within an intercropping system, finding that there too is a greater benefit within this system due to the non-competitive relationship for N between the two crops (Searle et al., 1981). With the presence of a legume within the cropping system it allows the soil N to be utilized by corn plants to produce grain, instead of the legumes. Not only does this work with monocot/dicot, but also dicot/dicot. There was a study that was conducted that intercropped sunflower and soybean together. Planting these two dicots together resulted in significantly greater yield response within the intercropping system when compared to the individual crops (de la Fuente et al., 2014). Another study was conducted by interseeding a short season crop (pennycress), into mature corn (Hoerning et al., 2019). This was done to suppress potential late season weed germination. These examples of intercropping cereal and legume, dicot and legume, and cereal and dicot can support furthering the research on corn and soybean intercropping.

The purpose of this study is to examine profitability between the different treatments of monoculture corn, monoculture soybean, and an intercropping system. The first objective of this study is to highlight the changes in plant phenotypes in response to the different production practices. This objective will be used to compare the different monoculture treatments to the intercropping system, via seed weight, yield, and profitability. The second objective of this study is to examine profitability among the different cropping systems and how it can influence the overall profitability of a given system. This objective will be measured by calculating the profit of each plot based on seed costs and the yield that was produced. Since there is limited research on intercropping systems that contain corn and soybean in Illinois, these objectives will help determine how the intercropping system compares to the different monoculture systems in terms of both productivity and profitability.

CHAPTER II: LITERATURE REVIEW

There is a need to continue to better the methods of producing corn and soybean, including reevaluating cropping systems like intercropping. Corn and soybean production in the United States comprise of a major portion of the agronomic crops that are produced. Over the past 60 years, corn production has increased tremendously. The total amount of corn produced in the United States was 3.9 billion bushels in 1960 and has increased to 14.2 billion bushels of corn produced in 2020 (NASS, 2020). Observing soybean production over the past 60 years has also reflected a steady increase in bushels produced. The total amount of soybean crop produced in the United States was 555 million bushels in 1960 and has increased to 4.1 billion bushels of soybean produced in 2020 (NASS, 2020). These increases in overall production were influenced somewhat by the increase in acreage and engineering ingenuity by making machinery more efficient; however, it is largely due to the improvement in genetics contributing to a greater yield. The reflections of the historical increases in overall production in both corn and soybean production has led to an increased interest in examining different cropping systems for producing corn and soybean. This literature review will contain background from two common cropping systems within monoculture production that are currently being practiced by producers in the United States, row orientation and row spacing. It will also introduce a specific cropping system, intercropping, that is not commonly practiced by producers in the United States or by large scale production. Through discussing the importance of these cropping systems and management techniques, it will highlight the demand for further research to be conducted due to the negative impacts that agronomic inputs, like fertilizers and pesticides, place on the environment.

Manipulation of cropping techniques

Producers are manipulating crop growth via row orientation, row spacing, and intercropping techniques. There are different reasons why these techniques are being utilized, including yield advantage, weed suppression, and soil health (Borger, Hashem, and Pathan, 2010; Bruin and Pedersen, 2008). Row orientation and row spacing are manipulations that are implemented during planting and can have long-term seasonal effects on the overall yield. Row spacing influences interplant competition for light, nutrients, and water. (Bernhard and Below, 2020; Diepenbrock, Long, and Feil, 2001). Therefore, row orientation can have an impact on the amount of plant-to-plant competition that occurs within a row. Intercropping two or more crops such as corn and soybean can aid in increasing benefits in the production of two cash crops (Raseduzzaman and Jensen, 2017). The type and amount of biological diversity can be influenced by intercropping two or more crops on a given piece of land. Crop manipulation has been practiced for decades because it can generate many benefits that pertain to the producer.

Through manipulation of different planting techniques (row orientation, row spacing, or intercropping) can be utilized to suppress or control weeds or disease. For instance, row orientation and row spacing can impact the amount of sunlight that reaches the soil surface, affecting the soil temperature and moisture content. In narrow rows conditions are more favorable environment for the presence of disease to occur due to a higher moisture level, lower canopy temperature, and reduced amounts of sunlight that can penetrate through the canopy to the soil. Narrow rows are less favorable for the presence of weeds to germinate and grow due to the reduced amount of sunlight that reaches the soil surface. In wide rows conditions are more favorable for the growth of weeds because large amounts of sunlight can reach the soil surface, initiating weed germination. In turn, wide rows are less favorable for the presence of disease due

to more air flow, dryer soil conditions, and more available sunlight to penetrate the soil surface. Therefore, producers have been implementing integrated pest management practices for decades, including biological, chemical, cultural, and mechanical control measures (Hammond et al., 2006). Soil moisture, weed germination, and disease presence can be controlled through crop manipulation as a source of integrated pest management practices. These planting techniques will now be examined.

Row Orientation

Corn and soybean are two types of crops that can be planted in different directions or row orientations. Row orientation can be defined as the configuration of row direction determined by the producer at the time of planting and can be arranged predominantly in North-South (NS) or East-West (EW) directions (Karlen and Kasperbauer, 1989). Row orientation can vary based on geographical location, proximity to neighboring objects, shape of the field, gradient of the land, and angle of the sun; however, all else equal, producers will generally plant in a NS orientation. In times when the field is much longer on one axis, the producer may plant parallel to the long axis of the field. Proximity to the equator plays a role in the impact of this management technique (Borger, Hashem, and Pathan 2010). As farm ground nears the equator, the NS orientation allows plants to have higher levels of light absorption. As the latitude increases (as the location moves away from the equator), orientation can vary because the benefit of the NS orientation changes with the season due to the Earth's tilt (Borger, Hashem, and Pathan 2010). At a latitude of 40°N, like that of Illinois and the Corn Belt, the benefit of the NS orientation is maximized at the spring and fall solstice when the sun rises in the East and sets in the West. The growing season takes place as the sun is more in the Northern part of the sky reducing the benefit

of the NS orientation (Borger, Hashem, and Pathan, 2010). Overall, row orientation can influence the amount of sunlight that is available to the different crops.

Row orientation is relevant to production agriculture because plants require sunlight for photosynthesis. Photosynthesis is the plants' process of capturing light from the sun and converting it into chemical energy that is required to sustain plant life (Ke, 2001). Row orientation can have an influence on the amount of available sunlight a crop receives, it can also affect the amount of sunlight that is able to penetrate through the canopy to the soil surface. When sunlight is available at the soil surface through the crop canopy it can influence the emergence of weed seeds, since increased sunlight can increase the rate of weed germination (Borger, Hashem, and Pathan, 2010). Increased sunlight below the crop canopy at the soil surface heats the soil and drives moisture out of the soil. Maximizing the amount of light intercepted by the crop minimizes the crops' need to compete with weeds for the essentials of water, sunlight, and nutrients, making row orientation relevant to production agriculture.

Also relevant to production agriculture is a wasteful use of energy like undergoing photorespiration. Plants which utilize C₃ photosynthesis, like soybean plants, do not have photosynthetic adaptations to reduce that possibility of undergoing photorespiration. In this type of photosynthesis, carbon dioxide (CO₂) enters the plant leaf tissue into the mesophyll through the stomata. A CO₂ molecule in a mesophyll cell is combined with RuBP (ribulose biphosphate) by RuBisCO (Ribulose-1, 5-bisphosphate carboxylase-oxygenase), resulting in 2,3-carbon sugars. These sugars then proceed through the Calvin Cycle to produce a sugar for the plant and a RuBP is left to then go back for the process to begin again. This specific photosynthetic process is found in a large portion of plants (about 85%), which includes soybeans. Therefore, this process

of photosynthesis can be affected by the amount of direct sunlight, heat, and lack of moisture that occurs throughout the day, which can be influenced by row orientation.

Row orientation has a direct influence on the amount of sunlight intercepted by soybean plants. Changes in the amount of light can influence the distribution of the photosynthates within the architecture of the plant (Karlen and Kasperbauer, 1989). When sunlight is perpendicular to the crop rows more sunlight can be utilized by the crops. Alternatively, when the sunlight is parallel to the crop rows, greater amounts of light can penetrate to the soil surface. Some studies indicated that row orientation did not have an influence on overall crop yield (Philbrook and Oplinger, 1989; Hiebsch, Salumu, and Gardner, 1990). But, one study found that when rows were planted in a NS orientation there was an increase in utilization of light, they assumed that this occurred due to the sun only being parallel to the crop rows once a day, at solar noon (Ranson, et al.). Plants in EW-orientated rows do not have as much direct sunlight available due to the crop rows being parallel to the sun's path, but the difference is minimal as the crop rows are only parallel to the sun twice a day during morning and evening times (Hiebsch, Salumu, and Gardner, 1990). The literature concludes that row orientation in soybean production did not have an influence on soybean production and yield.

Monocot plants, like corn, utilize C₄ photosynthesis. C₄ photosynthesis occurs when carbon dioxide enters the leaf tissue through the stomata and those molecules are converted to a four-carbon molecule (malate) by PEP carboxylase. Then the four-carbon molecule is transported from the mesophyll cells to the bundle sheath cells. In the bundle sheath cells CO₂ is evolved and since there is no oxygen, there is effectively no photorespiration in C₄ plants. Then the PEP carboxylase is cycled back to the mesophyll cells. The energy from the sun is utilized to produce sugar for the plant (RuBP is left to then regenerate the cycle again). The energy that is

produced by this process is then utilized by the plant to produce reproductive structures. Thus, this process of photosynthesis can be affected by the amount of shading that occurs throughout the day and the length of the shade that occurs, which can be influenced by row orientation (Tian et al., 2019). The proximity of neighboring crops of different heights can be influenced by row orientation, because the amount of direct sunlight that a plant receives can be affected by the amount of shade that is being cast from those plants (Karlen and Kasperbauer, 1989). Therefore, the proximity of neighboring plants can influence the amount of shade that can be cast from other plants, which in turn can influence the ability to carry out photosynthesis.

Also, in agronomic production fields, such as corn fields, weed pressure can also be influenced by row orientation. The amount of weed pressure can be influenced by the amount of sunlight that is able to penetrate through the canopy and reach the soil surface triggering the emergence of different weeds. This can be a problem as the crops will have to compete with the weeds for essential resources (Borger, Hashem, Powles, 2015; Karlen and Kasperbauer, 1989). Overall, row orientation in corn production can influence the amount of light that is available to the crops.

Row Spacing

Along with the different orientations that crops can be planted in, row spacing can also vary. Row spacing can be described as the barren land that is present between the planted crop rows. Narrow rows will be described as anything less than 76-cm and wide rows can be described as anything 76-cm or greater (Farnham, 2001; Bernhard and Below, 2020). In production systems, this can vary based on geographic location and equipment that is available. Previous studies in corn and soybean production have found that there are advantages in production when planted in narrow rows (Lambert and Lowenberg-DeBoer, 2003; Bernhard and

Below, 2020). In narrow-planted rows, the rate of photosynthesis can increase due to majority of the sunlight being utilized by the canopy. In corn and soybean production, it was found that in narrow-planted rows the crops are more evenly distributed allowing for an improvement in the efficiency of light interception, assisting in an increase in yield potential (Flénet, et al., 1996).

The space between the plants within a row (or intra-row plant spacing) can vary based on the different row spacing. At the same population, the space between the plants within a row increases as the rows get narrower. Within a row, this increases the amount of space that is available to each plant and decreases the amount of space that is available on each side of the plant when the plant population stays the same. For example, a study that was conducted by Bernhard and Below expressed the difference in intra-plant spacings in corn production, in a plot with 76-cm spaced rows the intra-plant distance within the row was 14.0-cm and in 51-cm spaced rows the intra-plant distance within the row increased from 14.0-cm to 21.0-cm, while both being planted at the same population of 94,000 plants ha^{-1} (2020). In a plot with 76-cm spaced rows the intra-plant distance within a row is 15.2-cm (6-in) and in a 38-cm spaced row the intra-plant distance within a row increases from 15.2- to 30.5-cm (12-in) when planted at a consistent population of 83,980 ha^{-1} (34,000 plants per acre). Decreasing the space between the rows can be used to space the plants, better utilizing the available land. In return, when the row spacing is too narrow it can cause too much crop competition, because the intra-row spacing can become wider than the row spacings.

Row spacing in agronomic production can also have an influence on time to canopy closure. In narrow rows, the canopy can fully close quicker than the canopy of wide-spaced rows, protecting the soil from more exposure to the sun (Walker et al., 2010; Hock et al., 2006). Canopy closure can be a vital factor to the reduction of stress during times of inadequate growing

conditions such as drought and extreme temperature. For example, when the canopy is closed (quicker canopy closure) the plants can better utilize sunlight. This can also aid in the soil's ability to retain soil moisture, since the sunlight does not have the availability to penetrate through the canopy to the soil surface. Weed suppression can also be influenced by how quickly the canopy were to fully close, due to the inability of the weeds early- to mid-growing season to have available sunlight. Mid- to late-season weeds will be the types of weeds that will be controlled through this cropping technique due to the timing of the canopy closure and weed emergence.

Row spacing in soybean production is another important cropping technique. When comparing narrow- and wide-planted rows, research has reflected that narrow-planted rows can be more efficiently harvested (Neugschwandtner, et al., 2019). Row spacing in soybean production has shown that it can affect the architecture of the crop, especially the leaf area index. The leaf area index (LAI) is the means of measurement for the amount of foliage contributing to the crop canopy, influencing the amount of light penetration that occurs throughout the stages of maturity (Lambert and Lowenberg-DeBoer, 2003). Wide-planted rows can alter the height of the crop and studies have shown that wide planted soybean plants are shorter statured and may have more branches, while narrow-planted soybean plants are taller and tend to have a reduced number of branches (Cox and Cherney, 2011). Widening the rows can decrease yield or production potential of soybean crops because the intra-plant spacing within the row is decreasing. Further, wide row soybean plants can also produce more branches, but that is only valuable if the branches have pods on them otherwise it is a waste of energy. But wide-planted rows allow for more air movement to occur throughout the canopy, which can influence the amount of the disease or fungus growth that may occur throughout the canopy (Yang and Navi,

2006). Multiple studies have found that overall soybean production was higher in narrow-planted rows versus wide-planted rows (De Bruin and Pedersen, 2008; Lambert and Lowenberg-DeBoer, 2003). This is due to a potential increase in LAI, allowing for greater amounts of light interception within the soybean canopy to take place increasing the amount of photosynthesis to occur. Also, row spacing can vary based on the date that planting was to take place. When the soybean crop is planted later in the growing season, narrow planted rows can aid making up a difference in yield.

Row spacing in corn production has similar attributes as it does in soybean production. In current agronomic practices producers are moving in the direction of narrower-spaced rows, as they are searching for ways to increase yield (Farnham, 2001). Again, row spacing can influence the timing of full canopy closure. Thus, the narrower the rows are planted the quicker the canopy is going reach full closure during the growing season. Narrow rows can be utilized to control the plant-to-plant or intra-plant spacing within a row. At the same population narrow-planted rows feature an increase in plant-to-plant spacing within a row (Bernhard and Below, 2020). Increasing the plant-to-plant spacing allows the crops to better utilize different resources such as, light, nutrients, water, and land (Tollenaar and Wu, 1999). Row spacing can also have an influence on plant stress caused by different weather conditions. Corn plants tend to undergo stress during times of hot, droughty weather conditions because in times that moisture is limiting the plants are unable to uptake and transport nutrients. Narrow-spaced rows allow the canopy to close quicker, allowing the soil to be covered avoiding penetration from the sun. Planting corn in narrow-spaced rows has been seen to increase the overall productivity of the crop especially in Northern climates.

Environmental impacts caused by corn and soybean production

Production agriculture is heavily dependent on chemical fertilizers and pesticide that can have negative impacts on the environment. Specifically, the three most essential fertilizers that agronomic crops require the application of are nitrogen (N), phosphorous (P), and potassium (K). The two forms of inorganic P that can be utilized by crops are HPO_4^{2-} and H_2PO_4^- . In the soil P is very reactive and binds to positively charged nutrients, like calcium or zinc, to stay within the soil (soil particles contain a negative charge) which allows them to be available for plant uptake. K in the soil is found as a K^+ cation, and since it is positively charged it can bind to the negatively-charged soil particles. Thus, these nutrients are readily available within the soil profile for plant uptake.

N is a very mobile nutrient and can be found as an ion in the soil and as a gas in the atmosphere. The N in the soil is about 95% organic N (contains a carbon), but it is not readily available to plants. The inorganic forms of N in the soil that are plant available are NH_4^+ (ammonium) and NO_3^- (nitrate). Ammonium is a positively-charged cation that can be strongly attracted to the negatively-charged soil particles. This form is available to the plants and is tightly attached to the soil particles, reducing the potential loss. Ammonium in the soil can be lost via leaching when excess amounts of water are moving through the soil, ammonium attaches the water molecules and moves throughout the soil profile out of the rootzone. Nitrates are negatively charged and more mobile within the soil than ammonium. Due to its negative charge, nitrate can easily be lost through leaching, which is the downward movement through the soil via water movement/penetration. Nitrate can be taken up by plants, but for it to be utilized by plants for growth it must first be converted to ammonium inside the plant. The atmosphere is also composed of about 78% of N (inorganic gas), which is found in two forms N_2 (N gas) or N_2O

(nitrous oxide) but N_2 is the only form that can be fixed through N fixation in legumes to a plant-available form. Commonly, when producers are applying a source of N fertilizer, they are applying N in forms of NH_4^+ and NO_3^- .

Environmental concerns have triggered changes in the agriculture industry because climate change, ozone depletion, and eutrophication have gained attention world-wide. Due to the food demand constantly growing the environmental impacts will worsen if the current systems is utilized (Lee et al., 2020). Surface runoff, leaching, and volatilization are the common loss pathways that excess nutrients/chemicals are being lost from agricultural land. Surface runoff is when the water does not penetrate the soil, but rather is lost via water movement flowing over the soil (Hatfield, 2014). Nutrients that are present in the soil, especially N, can be lost as water moves over or through the soil surface, causing contamination in water sources like eutrophication or algae blooms. Since drainage systems are commonly found in poorly-drained land, leaching can be another loss pathway for nutrients if excess water is present (Hatfield, 2014). Leaching is when the nutrients that are present within the root zone travel with water deeper into the soil where they are no longer available to the plants (Hatfield, 2014). The water and nutrients that are being leached can find their way to groundwater sources, such as aquifers, wells, water tables, or be lost into drainage tiles.

The different loss pathways of nutrients can be both economically and environmentally taxing on producers. First, nutrients cost a significant amount of money. Any of these nutrients that are lost and not available to crops is wasted money. Lost, excess nutrients can have a negative impact on the environment, like surface water sources. Large amounts of lost nutrients can have a negative impact on aquatic life. The litany of harmful impacts on the environment is a

concerning factor for the future of agriculture. This research will document a different cropping system that could reduce or have fewer negative impacts on the environment.

Intercropping

Monoculture, or conventional farming is a common practice within production agriculture. It is common in production agriculture because producers realize high yields using large machinery on large pieces of land. On the other hand, intercropping is a cropping technique that dates way back to ancient times and is not commonly practiced within corn and soybean production in the United States. Intercropping is the practice of cultivating two or more crops on the same parcel of land (Mousavi and Eskandari, 2011; Foroutan-pour, Duilleul, and Smith, 1999). There is currently a limited amount of research that has been conducted on the different intercropping systems within the United States (Knörzer et al, 2009). It is actively being practiced in countries that have small parcels of land available for agricultural use due to the ability to diversify production and more efficiently utilize land. There are different types of intercropping systems that have been practiced and they consist of row intercropping, mixed intercropping, strip intercropping, and relay intercropping (Mousavi and Eskandari, 2011). Specifically, row intercropping is cultivating two or more crops simultaneously on the same piece of land and are planted in repeating sets of rows (Mousavi and Eskandari, 2011). Row intercropping will be the intercropping technique that will be utilized within this study.

Different producers can utilize intercropping systems with different crops or sizes of fields. It has been documented that cereals and legumes (such as corn and soybean), are commonly intercropped together because they have a complementary relationship with one another (Midmore, 1993). Corn and soybean are different and complementary to one another in many ways including that corn is a monocot and soybean is a dicot. Monocot (monocotyledon)

plants have parallel vasculature in their leaves whereas dicot (dicotyledon) plants have veins that are arranged in a branch-like formation that extend out from a middle vein (net-like veins) on the leaf (Grabowski, 2015). The root architecture of these plants are another major difference; monocots have a fibrous root system while dicots have a taproot system. Due to the differences in the architecture and depths that they can reach, it creates adequate space and complimentary dimension for the intercropped plants (Fan et al., 2020). Corn is a plant that aggressively utilizes the soil nutrients, especially N. Soybean is a plant that can be a restorative crop, producing plant-usable N for itself (Zaeem et al., 2019). This is due to the symbiotic relationship that soybeans form with bacteria in the soil, *Bradyrhizobia spp.* bacteria. The nodules that are located on the roots of the soybean plants fix unavailable N into a plant-usable form.

Corn and soybean can also be complementary to one another because they have two different photosynthetic processes. Corn is a C₄ plant and soybean is a C₃ plant. In C₄ plants the optimum temperature is approximately 35°C and the optimum temperature for C₃ plants is approximately 25°C. The difference in temperatures is significant between the two different crops within the intercropping treatment and could be caused by the height differences between the crops. Corn is taller than the soybean plants within the system causing a shadow from the corn plants onto the soybean plants which could reduce their temperature. In addition, corn plants have a much higher light saturation point than soybean plants in order to carryout photosynthesis. Again, this can allow soybean plants to be intercropped within the corn rows, due to the difference in height and the amount of shade that is cast upon the soybean plants. There is also a difference in photorespiration that the two types of crops carryout. Photorespiration is a wasteful process that the plants can undergo when RuBisCO binds to O₂ instead of CO₂. In C₄ plants photorespiration is very low and in C₃ plants it can be high

(estimated to take up 30 to 50% of the net photosynthesis that takes place), especially when C3 plants are stressed (Meacham-Hensold, 2020). By planting the two crops together it can aid in the advantage for the soybean plants during hot, dry days because the corn functions as a source of protection from the environment.

Intercropping is a relevant cropping technique because it offers sustainability and diversification, where these two things are currently lacking in corn and soybean production (Raseduzzaman and Jensen, 2017). Producing corn and soybean within an intercropping system can increase the crop diversity by producing two or more harvestable cash crops on a piece of land (Willey, 1990; Mouosavi and Eskandri, 2011). Increasing the crop diversity on a piece of land can also provide stability for the operation because if one cash crop fails there is a second cash crop being produced. Intercropped soybean can also aid in sustainability, because soybean plants have been found to aid in the reduction in soil carbon losses and N losses, improving soil fertility and yield (Jun-bo et al., 2018). To balance sustainability and high yield, the soybean crop might not yield as much within intercropping systems as they would in monoculture systems, so the corn yield would make up the difference (Jun-bo et al., 2018). Through this type of cropping system, the diversification can aid in a better utilization of land. When space can be a limiting factor in production, multiple crops can be produced on a small space of land aiding to better utilization of available resources (Jun-bo et al., 2018). Therefore, corn and soybean intercrop system is relevant to today's agriculture systems because it aids in both sustainability and diversification.

Intercropping is not commonly practiced in corn and soybean production in the United States, but it can be relevant. Conventional corn production relies heavily on the application of synthetic N fertilizers which leads to environmental problems (Jun-bo et al., 2018). Intercropping

corn with soybean can reduce the amount of added N fertilizer because the *Bradyrhizobium* in the nodules on the soybean plants can fix N, thus soybean do not need the application of synthetic N fertilizer. Environmental impacts that are caused by production row crops is largely due to the addition of added synthetic fertilizers. Intercropping soybean plants within corn plants can help reduce the amount of added synthetic N that is required by crops without adding to the negative environmental impacts.

Farm Finance

Synthetic N fertilizer not only has negative environmental impacts, but it also has a substantial monetary cost. One of the ways to increase profit is to reduce input costs. On the farm, profitability is based on the overall crop revenue subtracting the total costs of expenses. Grain production operations make decisions largely on how much profit can be made. Crop revenue is determined by the market and the time at which the producer would sell their grain. Essentially, profitability is used to determine the financial standing of the operation and how that operation can make changes based on their financial standing to better improve it if needed (Langemeier, 2017). Profitability can be measured in three different ways, return on assets, return on equity, and operating profit margin. In this study, profitability will be measured using the net farm income and total input costs, this will result in profitability. Utilizing profitability can allow a clear comparison of the different cropping systems (corn vs soybean) based on how much they yield in terms of profit (\$). Yield in dollars is a relevant way to compare corn and soybean productivity, due to the possibility of the number of bushels produced being different. For instance, 50-bushel soybean and 150-bushel corn cannot be evenly compared unless they are compared based on profitability. This tool can help farmers make decisions on the next season's crop, cropping systems, and what they could do to be more profitable. Market prices that drive

profitability are ever-changing due to supply and demand within the market. Supply and demand can dictate commodity prices (corn and soybean) as well as the amount that is being sold.

Therefore, when determining the crop and the planting sequence that is going to take place, profitability and supply and demand are the driving forces to the ultimate decision that the producer must make.

Conclusion

Different cropping systems have been observed to aid in reducing the negative environmental impacts that are caused by production agriculture. Row orientation, row spacing, and intercropping practices are relevant techniques within both corn and soybean production. Row orientation can influence the amount of light that the crops receive and are able to utilize. Light utilization in crop production is an essential aspect to the system because plants require light to successfully carry out photosynthesis. Row orientation does not seem to have a significant impact on the overall crop productivity at Midwest latitudes. Row spacing can have an influence on land utilization, reduction of crop stress, and time to canopy closure, it can also influence the amount of sunlight penetration that occurs by the crops. Thus, narrow-planted rows are favored because they have better light utilization, improved land utilization, increased intra-row plant spacing, and quicker canopy closure than wide-planted rows. Cultivating two or more crops on one piece of land (intercropping corn and soybean) can have added benefits in sustainability and diversification. Due to the limited research on corn and soybean intercropping systems, further research should be conducted on productivity and profitability on the different cropping systems when comparing the intercropping systems to monoculture systems.

CHAPTER III: METHODOLOGY

Experimental Space History

This study took place at the Illinois State University Research Farm in Lexington, Illinois; 40.671695°N, -88.771025°E. The experimental site was managed in a no-till system. The 2019 crop was corn and it was harvested in early September for silage, leaving little biomass from the corn plants on the surface of the field. Immediately following silage harvest, a cereal rye (*Secale cereale* L.) cover crop was planted. On 22 November 2019 soil testing was conducted and found that the pH was 6.9 and the soil contained 3.3% organic matter (Table A.1). The soil test also reflected that the amount of P within the soil was 250 lb ac⁻¹ and the amount of K was 971 lb ac⁻¹. All nutrients tested were at sufficient levels. Soil N is not commonly tested, but based on the cropping history soil N levels should have been low. The soil types within the experimental space were Andres silt loam and Drummer and Elpaso silty clay loam (Web Soil Survey).

On 10 May 2020 the cereal rye was cut (Figure 3.1) and the following day it was harvested for rye silage, again leaving little biomass from the grass crop on the surface of the experimental space. On 12 May 2020 a preemergent herbicide was applied consisting of Boundary (*S*-metolachlor and Metribuzin) and RoundUp PowerMax (Glyphosate, N-(phosphonomethyl)glycine) herbicide which was mixed with Class Act (Ammonium sulfate, corn syrup, alkyl polyglucoside) liquid tank additive. This mix was applied to terminate the cereal rye and any grass or broadleaf weeds that might have emerged or would have emerged within the residual timeframe. The experimental site had no prior history of the application of any source of fertilizer since before the 2019 growing season. We can assume that after two grass crops that excess N should be depleted and other nutrients are sufficient (Figure A.1).

Layout for Corn-Soybean Intercropping

A row intercropping system was used to allow the use of existing planting machinery and to most benefit both the corn and soybean in this cropping system. Every row in this cropping system is 38-cm apart to utilize common machinery in the Corn Belt. Each row of corn has its own neighboring rows of soybean plants on either side of it (Figure 3.2 and B.1). Within the intercropping system, the soybean plants were planted at the same intra-row spacing as the 38-cm soybean and the corn is planted at the same intra-row spacing as the 38-cm (15-inch) corn. The corn in the intercropping treatment, however, has 114.3-cm (45-inch) between corn rows which inspired a second intercropping treatment with the same intra-row spacing as the 76-cm (30-inch) corn. At 114.3-cm between rows of corn at a (comparatively) low population, the corn canopy will not completely close and for most of the growing season the soybean plants will grow in lower light intensities provided by the taller corn plants. Figure 3.2 also highlights the move toward equidistant spacing between plants as the row spacing becomes narrower. Corn shows this concept the clearest as 76-cm corn rows at 83,980 plants ha⁻¹ (34,000 plants/acre) have only 15.5-cm (6.1-inches) between plants, whereas this same population in 38-cm rows have (12.3-inches) 31.2-cm between plants (Figure 3.3 and 3.4).

Experimental Design

This experiment was set up as a Completely Randomized Design. Many studies detail results of monoculture treatments; this study was interested in observing the effect of intercropping corn and soybean. Therefore, to expand resources on the treatment level of most interest the experimental design that was constructed contained unequal replications (Figure B.1). There was one treatment factor of cropping system that contained six different levels of cropping systems: monoculture corn with 38-cm row spacing (narrow-spaced corn), monoculture

corn with 76-cm row spacing (wide-spaced corn), monoculture soybean with 38-cm row spacing (narrow-spaced soybean), monoculture soybean with 76-cm row spacing (wide-spaced soybean), intercropped corn/soybean with a corn population of 27,993 plants ha⁻¹ (11,333 plants per acre), and intercropped corn and soybean with a corn population of 55,985 plants ha⁻¹ (22,666 plants per acre). An experimental unit (eu) was 12, 38-cm rows with the outer 3 rows on either side functioning as a border and data was only collected from the middle 6 rows of each eu. The intercropping plot consisted of four rows of soybean plants and two rows of corn plants. Each row of plants within the plot were spaced 38-cm apart, the corn rows were 114-cm from one another with two rows of 38-cm spaced soybean rows between the corn rows and a row of soybean plants on each side of the corn rows to make up the area grown for data collection. This planting sequence allowed each row of corn to have two rows of soybean, one on each side.

There were two experimental fields, one planted in an EW orientation and the other planted in an NS orientation. Both planting orientations were identically replicated, each containing 25 eu (Figure 3.3). Each eu was 610 cm in length and 457 cm in width, collecting data only from the middle 229 cm (either six 38-cm rows or three 76-cm rows wide). The soybean variety planted was Golden Harvest 3582E3 and they were planted on 12 May 2020 at a population of 345,000 plants ha⁻¹ (140,000 plants per acre) for monoculture treatments and 230,533 plants ha⁻¹ (93,333 plants per acre) for the intercropping treatments (Figure B.2). The variety of corn that was used was AgriGold A639-70STX and was planted on 21 May and 22 May 2020 at 83,980 plants per hectare (34,000 plants per acre) for the monoculture treatments, 27,993 plants per hectare (11,333 plants per acre) for the intercropping treatment, and two intercropping plots having doubled corn populations of 55,985 plants per hectare (22,666 plants per acre). Soybean planting was completed by a 38-cm (15-inch) Kinze row planter and a John

Deere tractor. The wide soybean rows had to have extra soybean seeds hand planted with the jab planter to account for the difference in population. All other soybean seeds were planted with the planter which was immediately followed by rain. In 10 days, after the soil dried, the corn was hand-planted with a jab planter. Once all the seeds had germinated and emerged, the soybean plants that did not belong in certain rows and plots were removed by hand to overcome machinery limitations that would have otherwise limited randomization.

Following planting, plot maintenance took place throughout the growing season and until harvest which included hand weeding (Figures B.3 – B.7). The experiment was walked on a weekly basis in order to reduce the potential weed pressure and to monitor crop growth and development. Soil tests were performed before planting to monitor nutrient status within the field. On 06 July 2020 the experimental site was hand-watered due to a mid-season drought. Corn plants were still in mid-vegetative state at the V10 growth stage.

In mid-August 2020, a visual difference in tissue color between the intercropping corn and the monoculture corn treatments was observed. The monoculture corn appeared to be a lighter color green than the corn in the intercropping plots. On 25 August 2020, leaf tissue samples were collected for nutrient analysis, specifically N concentration in the leaf. Corn leaves were sampled from each of corn treatment level (narrow, wide, or intercrop). Each sample was a pool of three leaves, and three samples were collected for each treatment level. The leaf samples were dried in the laboratory oven at a temperature of 40°C for three days until fully dried, then ground using a 1-mm diameter screen, and sent to United Soils Inc. in Chenoa, IL for analysis.

Grain harvest took place between 12 October and 19 October 2020. On 12 October and 13 October 2020, all corn plants within the corn plots and intercropping plots were hand-harvested and the ears were placed in mesh bags (Figures B.8, B.9, and B.12). From 14 October

and 19 October 2020 all soybean plants within the soybean plots and intercropping plots were hand-harvested and threshed in the field. When hand-harvesting the soybean plants, all the plants were cut off approximately 3-cm above the soil surface with hedge shears, essentially mimicking the action of a combine (Figures B.10 and B.11). The plants were then collected and carried to an ALMACO belt thresher, where one plant was sent through at a time and threshed two-to-three times (Figure 3.4). Soybean seeds were collected and placed in mesh bags. The corn was shelled using an ALMACO Ear Corn Sheller on 22 October 2020 (Figure 3.5).

Data Collection

Once the corn was shelled, each plot was then weighed to receive a total seed weight per plot. A subsample of grain was analyzed by a Seedburo GMA 128 Grain Moisture Meter to get a moisture percentage and test weight for each plot. A similar process was utilized for soybean on 23 October 2020.

Statistical Analysis

The first analysis that was performed was a MANOVA to test the overall statistical significance of the entire experiment. The factors that were taken into account for this analysis were all the dependent variables, the six treatment factor levels, the two different planting directions, and the treatment replications. To perform a Multivariate analysis in SAS a statistical model was constructed:

$$y_{ijk} = \mu + \tau_i + \alpha_j + \tau\alpha_{ij} + \varepsilon_{ijk}$$

$$\text{Degrees of freedom } 50 = 1 + 5 + 1 + 5 + 38$$

Where y_{ijk} is the observed phenotypes of this experiment,

i = narrow-spaced corn, wide-spaced corn, narrow-spaced soybean, wide-spaced soybean, intercropping treatment, intercropping treatment with doubled corn population

$j = \text{NS, EW}$

$k = 1, 2, \dots, 11$

μ is the grand mean,

τ_i is the fixed effect of i^{th} cropping system, NID $(0, \sigma_\tau^2)$,

α_j is the fixed effect of j^{th} direction, NID $(0, \sigma_\alpha^2)$,

$\tau\alpha_{ij}$ is the fixed interaction between treatment and direction, NID $(0, \sigma_{\tau\alpha}^2)$ and,

ε_{ijk} is the error term for the entire model, including treatment, direction, and replication,

NID $(0, \sigma_\varepsilon^2)$

Leaf Nitrogen Analysis

In this (part of the study) the experimental units were 76-cm corn, 38-cm corn, and intercropped corn. Utilizing PROC GLM in SAS with a Tukey-Kramer adjustment, an ANOVA was performed including a multiple comparison of all three of the treatments to be compared, testing the null hypothesis that all treatment means of N concentration were equal. This analysis was performed at a significance level of $\alpha = 0.05$.

Soybean Productivity – Row Spacing

In the context of this part of the study, row spacing was utilized to compare the different monoculture soybean treatments, 76-cm and 38-cm soybean. Estimate statements in PROC GLM in SAS were constructed to test the null hypothesis that there was no difference in the two row spacing treatments. Three different estimate statements were constructed. One was used to observe the overall difference in row spacing not accounting for the different directions. Then two other estimate statements were constructed, one for NS and one for EW, observing if row direction had an impact on row spacing. This analysis was performed at the significance level $\alpha = 0.05$.

Soybean Productivity – Monoculture vs. Intercropped

Comparing monoculture soybean productivity to the intercropped soybean was also tested within this study, via seed weight per plant (g). This was done because there were a different number of soybean seeds that were planted within each eu between the monoculture and intercropped plots. The intercropped treatments contained two-thirds of the soybean plants than the monoculture treatments had, due to every third row being a row of corn in the intercropped treatments. The total weight of the seeds per plant was calculated by taking the total weight of the seeds per plot and dividing it by the total number of plants within the plot. Estimate statements in PROC GLM were utilized to compare the monoculture treatments to the intercropping treatments. Three different estimate statements were constructed to test the null hypothesis that there is no difference in seed weight per plant between the monoculture treatments when compared to the intercropped treatment. One statement was constructed to analyze the overall difference between the monoculture treatments and the intercropped treatments including both directions, averaging all eu regardless the row orientation. Two other estimate statements were constructed to observe if row orientation had an impact on the different treatments, one for NS and one for EW orientation. There was a separate comparison performed utilizing an estimate statement to compare the two different intercropping treatments. The two intercropping treatments that were present within the study differed in corn plant population, but not soybean population. This analysis was also performed at a significance level of $\alpha = 0.05$.

Corn Productivity – Row Spacing

In the context of this study, we tested for different phenotypic traits isolating the effects of the different row spacings, 78-cm and 36-cm corn. Utilizing estimate statements in PROC GLM in SAS to test the null hypothesis that there was no difference in productivity between the

corn planted in different row spacings. Three different estimate statements were constructed. One was used to observe the overall difference in row spacing not accounting for the different orientations. Then two other estimate statements were constructed, one for NS and one for EW, observing if row orientation had an impact on row spacing. This analysis was also performed at a significance level of $\alpha = 0.05$.

Corn Productivity – Monoculture vs. Intercropped

Monoculture corn treatments and intercropped treatments were also compared throughout this study via kernels per plant (g). The total weight of the kernels per plant was calculated by taking the total amount of weighed grain per plot and dividing it by the total number of plants within each plot. The null hypothesis that was tested was that there is no difference in kernel weight per plant within the monoculture treatments when compared to the intercropped treatment. Estimate statements utilizing the PROC GLM command in SAS were again utilized to compare the monoculture treatments to the intercropping treatment. Three different estimate statements were constructed. One statement was constructed to analyze the overall difference between the monoculture corn treatments and intercropped corn treatment excluding the effect of the different row orientations. Two other estimate statements were constructed including the effect of row orientation to observe if row direction had an impact on the different treatments, one for NS and one for EW. We also wanted to compare the two different intercropping treatments that were present within the study, the two intercropping treatments with different corn populations. These two intercropping treatments were tested by utilizing an estimate statement that compared the overall difference. This analysis was also performed at a significance level that was determined at a level of $\alpha = 0.05$.

Corn Productivity – Extra Ears

Monoculture and intercropped corn treatments were also compared to one another looking at the amount of second ears that were produced by the different treatments. A nonparametric alternative to ANOVA, the Kruskal-Wallis test, was used because the residuals were not normally distributed.

Profitability – Cash Transaction on 19 October 2020

Comparing the different treatments to one another had to be completed on a scale that was easily comparable and one that did not allow some treatments to be at an advantage to others. The scale that was appropriate for this comparison was profitability, which considered seed costs, cash bid price or selling price, and overall yield. To be able to complete this analysis seed costs were obtained by collaborating with six different seed representatives to obtain a representative unit price for both soybean and corn. The prices were based on average costs that a typical farmer that operated on 1,000 acres would pay per unit in McLean county, IL area. The prices that were obtained were \$56 per unit for an Enlist soybean variety and \$292 per unit for a triple-stacked corn variety. The cost of seed was the only expense that varied based on treatment throughout the study. The seed cost was calculated by taking the total cost of seed per unit and dividing it by the total amount of seeds in one unit to get the cost per seed within a unit (Table 3.1). This seed cost calculation was used for cost of seeds for all corn, soybean, and intercrop treatments. The market price that was utilized was the cash bid or selling price on 19 October 2020, the day that the grain was taken to Prairie Central Coop in Lexington, IL. The market value for soybean was \$10.24 bu⁻¹ while corn was \$3.79 bu⁻¹. This comparison was performed by utilizing PROC GLM in SAS and including a pairwise comparison by performing a Tukey comparison to group the different treatments based on profitability. This procedure in SAS was

utilized to generate a box plot for a visual and a Tukey table that groups the different treatments in like groups according to their mean profit.

Profitability – Interval pricing

Due to the fluctuation in market value, not all Midwest grain producers are going to sell their harvested grain for the same prices used above. Therefore, a range of different prices for both soybean and corn had to be established. The historical price range from the past 10 years was established as approximately \$8.00 to \$14.00 for soybean and \$3.00 to \$6.00 for corn. These different price ranges were established to assist in the visualization of the different prices at different times and what the potential profitability would be. Again, the cost of seed was the only expense that varied based on the different treatments (Table 3.1). Utilizing RStudio, a dot plot was generated that compared the profitability of the different cropping systems. The treatments that were included within the graph were narrow-spaced monoculture corn, wide-spaced monoculture corn, narrow-spaced monoculture soybean, wide-spaced monoculture soybean, and intercropping (the double corn intercropping had a similar slope to the intercropping treatment and thus was left off the plot for simplicity). For this study, all plots were treated equally except what species seeds were planted and how many seeds were planted. Thus, the ‘profit’ of a plot is determined by subtracting the seed cost to plant that plot from the cash value of the grain produced on that plot.

To compare the five treatments, all possible combinations of market values for the intercropping treatments were made. The soybean market price has no bearing on the profit of a corn plot, which is influenced by the corn market price only. The intercropping treatments have multiple values indicating the dependence on both corn and soybean price. Therefore, the intercropping treatments can have different pricing combinations based on the different market

prices that were distinguished within the price ranges. A “conventional corn” treatment was added in recognition that many Illinois corn producers apply N fertilizer. Neighboring plots on the Farm this year averaged 200 bu ac⁻¹ corn yields with this management. The profit for this treatment is the cost of seed and N fertilizer (200 units N per acre) subtracted from the monetary grain value.

Figure 3.1. Cutting/conditioning of rye. On 10 May 2020 the rye had to be cut and conditioned for it to be harvested for ryelage.

Figure 3.2. Plant spacing and row intercropping planting scheme. This plant spacing and intercropping scheme portrays the different planting schemes in the 2020 study that took place in Lexington, IL. The spacing between plants in each treatment and the layout of each treatment is shown in a. 76-cm soybean, b. 76-cm corn, c. 38-cm soybean, d. 38-cm corn, e. intercropping corn and soybean, f. higher population corn intercropping.

Figure 3.3. Ariel image of the entire experimental site. Ariel image of the entire experimental site. The use an unmanned aerial vehicle (UAV) was utilized to capture this image to showcase the two planting orientations, EW and NS, within the experimental site during the 2020 growing season in Lexington, IL.

Figure 3.4. Aerial image of the EW oriented plot. The same UAV from Figure 3.3 that took the picture in part a, took a close up of the EW oriented plot to show a visual of the plants in the 2020 study in Lexington, IL.

Figure 3.5. Soybean Harvest. Soybean plots were hand-harvested during the dates of 14 October through 19 October 2020. During the harvest process, an eu was cut with pruners and taken to the small plot thresher for removal of the seeds from the plant material.

Figure 3.6. Shelling corn. On 22 October 2020 all of the corn ears were hand fed into an ALMACO ear corn sheller to be shelled. As the corn is being hand fed into the sheller the machine is separating the cobs and the kernels, retaining the kernels into a bucket.

Table 3.1. Seed Expense Table. This table is highlighting the seed cost expenses for the different treatments during the 2020 study that took place in Lexington, IL. The different costs of seeds for the treatments was generated based on the number of seeds of corn or soybean that were planted within the ac.

Plot	Corn plants ac⁻¹	Corn cost ac⁻¹	Soybean plants ac⁻¹	Soybean cost ac⁻¹	Cost ac⁻¹
Narrow corn ^a	34,000	\$124.10	0	0	\$124.10
Wide corn ^a	34,000	\$124.10	0	0	\$124.10
Intercrop ^{a, b}	11,333	\$41.37	93,333	\$37.33	\$78.67
Narrow soybean ^b	0	0	140,000	\$56.00	\$56.00
Wide soybean ^b	0	0	140,000	\$56.00	\$56.00

^a Purchase price of the corn was \$292 per bag of 80,000 seeds of AgriGold A639-70STX.

^b Purchase price of the soybean was \$56 per bag of 140,000 seeds of Golden Harvest 3582E3.

CHAPTER IV: RESULTS AND DISCUSSIONS

Leaf Nitrogen Analysis

The N concentration with the leaf tissue of all the corn treatments was evaluated due the visual difference that was noticed during the 2020 growing season. Table B.1 shows there was a significant increase in the amount of N within the corn leaf tissue from the intercropped treatment compared to the monoculture corn treatment ($p = 0.0006$). The mean N concentration from the intercropped corn tissue was 2.7% compared to 1.9% from the wide spaced corn and 1.8% from the narrow-spaced corn (Table 4.1). These finding agree with the findings of Searle et al., who found that the cereal within the intercropping system scavenged enough N from the legume crop in order to efficiently make up their need of available N within the soil (1981). Similarly, Fan et al. found corn tissue had a greater N concentration when intercropped with soybean plants when compared to monoculture treatments (2020). In these studies and in the current study, intercropped corn had a higher N concentration in the leaves than the monoculture corn.

Comparing monoculture to intercropping, there is a difference in N concentration. This could be due to the presence of a legume within the intercropping treatment because the corn plants within this treatment have more N available to them and can scavenge more N than the monoculture treatments. The corn tissue from the intercropped treatments had a greater N concentration and greater production per plant was likely due to the presence of the legume and a lower corn population. Soybean seeds are commonly inoculated with *Bradyrhizobium* which infect soybean roots as the plant grows. The infection is a symbiotic relationship between the bacteria and host plant. In the association, the plant provides sugars from photosynthesis that provide energy for the bacteria, which in turn convert atmospheric N_2 into ammonia, which is

converted to amino acids and proteins in the plant. In production systems, legumes are often not fertilized with N because the rate of symbiotic N₂-fixation will meet the plant need. Thus, corn intercropped with a legume could have more soil N available, especially in soils with greater rates of N mineralization from soil organic matter, which can result in greater grain yields compared to unfertilized monoculture corn (Fan et al., 2020). Therefore, the intercrop corn had more plant available N to utilize resulting in a significantly greater N concentration within the leaf tissue.

MANOVA – All dependent variables

A MANOVA was used to test the overall significance of all of the dependent variables in this study (cropping system Wilk's Lambda $F = 136,189$, $p < 0.0001$). Further ANOVAs can be utilized to test each dependent variable for the different treatment effects.

Soybean Productivity – Row Spacing

The level of productivity in soybean production was observed by assessing the effect of row spacing and row direction. Soybean row spacing is two levels of the cropping system effect in the ANOVA model (Table B.2). The cropping system was significant therefore, row spacing was further analyzed. When excluding the effect of row orientation, it did not appear that there was an influence by row orientation and row spacing that occurred on soybean yield ($p = 0.0624$). Table 4.2 illustrates when including row orientation into the analysis, NS orientation ($p = 0.1206$) was not different than the EW orientation ($p = 0.2669$) but overall, the difference was not significant and did not have a significant influence on yield. We can conclude that at alpha of 0.05, row spacings, even in different orientations, did not have a significant influence on the overall soybean productivity.

A drought during the growing season of this experiment may have confounded the effects of row spacing. Previous studies conducted by De Bruin and Pedersen (2008) and Cox and Cherney (2011) found that narrow spaced rows (38-cm) had greater yield than wider spaced rows (76-cm). However, under drought conditions, Walker et al. found yield was not affected by row spacings (2007). These results may be explained using the Law of the Minimum. In this study water may have limited yield. Therefore, adjusting other factors like row spacing did not increase yield. However, when water was not limiting, Walker et al. found that the row spacing was identified as a subsequent limiting factor (2007). Therefore, due to the lack of soil moisture during the growing season it could have hindered the results of this portion of the study.

Along with the drought that occurred, the results could have also been caused by the low statistical power for this test. The power of this test was 0.50 and was limited by the small sample sizes of the different monocropping treatments. To increase the power of the test, the number of replications could have been increased; however, row spacing was not the primary focus of this study, rather the focus was on the effect of intercropping. Including the different row spacings within the experiment functioned as a direct comparison for the intercropping treatments to monoculture systems commonly used today.

Soybean Productivity – Monoculture vs. Intercropped

Soybean productivity within monoculture treatments and intercropped treatments were measured by utilizing the total weight of the seeds (g) produced per plant. Soybean intercrop treatment is two levels of the cropping system effect in the ANOVA model (Table B.3). The cropping system was significant therefore, intercropped soybean treatments were further analyzed. The data reveal that productivity per plant was significantly greater (Table 4.3, $p < 0.0001$) from the intercropped treatment, regardless of row orientation.

Zhi-dan et al., found that when intercropping soybean plants with corn, the soybean biomass yield increased by 25.5% when compared to monoculture soybean systems (2019). Even though the soybean biomass was not measured in this study, the soybean plants in the intercropped system produced a significantly greater seed weight per plant than soybean plants in monoculture systems.

In addition to yield, this study evaluated the difference in the return on investment to compare these cropping systems. Since the intercropped soybean plants produced more seed weight per plant, it can be assumed that intercropped soybean with corn may have a better return on investment. The intercropping system is more cost effective because it costs less (fewer seeds were purchased) to produce more grain, therefore the intercropping treatment resulted in a greater return on investment for soybean.

The symbiotic interaction between the corn and soybean plants in an intercropping system may be responsible for some of the increased yield in those plots. The corn plants use C4 photosynthesis and continue to increase their photosynthetic rate to high light intensities, so the corn plants benefit from extra space next to the shorter soybean plants. The corn plants provide more shade for the intercropped soybean plants which are C3 plants that are light-saturated at a lower light level than corn plants. The shade could aid in reducing the temperature for the soybean plants. Since the (approximate) optimum temperature for C3 photosynthesis is 25°C, soybean plants partially-shaded by corn could undergo greater photosynthesis during hot, dry periods of the growing season without extensive photorespiration because of the cooling effects of the shade from the corn. This in turn could increase seed productivity per plant compared to monoculture soybean plants which are not able to convert carbon dioxide and water into energy. Under hot and dry conditions soybean will undergo photorespiration instead of photosynthesis,

which is a very wasteful process that could displace up to 30% to 50% of total photosynthesis that would have occurred within the plant.

Corn Productivity – Row Spacing

The productivity of corn was evaluated by comparing yield from the different monoculture corn treatments. Corn row spacing is two levels of the cropping system effect in the ANOVA model (Table B.4). The cropping system was significant therefore, row spacing was further analyzed. Results from this study did not find a significant difference ($p = 0.1468$) in corn yield between the two row spacings of 38-cm and 76-cm (Table 4.4). Further evaluation comparing row orientation on yield found there was no difference in yield between the 38-cm and 76-cm row spacings between the different orientations of NS ($p = 0.4587$) or EW ($p = 0.1863$).

Contrary to this study, Bernhard and Below found that narrower rows increased yield significantly compared to wider row spacing (2020). They attributed the increased yield in part to an increase in plant population associated with the narrower rows, which differs from this study where the total plant population is kept constant. They further concluded that the positive increase in yield, may have been from a decrease in stress due to the increased plant-to-plant spacing within the narrower-planted corn rows (Figure 4.2 and Bernhard and Below, 2020). For instance, when planting at a population of 83,980 plants ha^{-1} (34,000 plants ac^{-1}) on 38-cm rows, plants within rows are 30.5-cm apart while in 76-cm rows the plants are much closer, only 15.25-cm apart within the row. Narrowing row spacing can result in a more even distribution of plants when population stays consistent. There is no more space available to the plants, the plants are just more evenly spaced out and better utilizing the available land. The findings within this study support the results that Barr et al. found that there was no difference in yield between 38-cm corn

and 76-cm corn grown in east-central Nebraska (2013). As studies have found varying results of row spacing on corn yields, it may be partially controlled by environmental conditions. Plants in this study experienced a drought during the growing season that may have limited yield from both row spacing treatments. Further, the statistical power of the analysis was 0.32; therefore, the results could have benefited from more replications to improve the low statistical power of the analysis.

Corn Productivity – Monoculture vs. Intercropped

Corn production within monoculture and intercropping systems were evaluated by measuring the total weight of the kernels (g) produced per plant. Intercropped corn is two levels of the cropping system effect in the ANOVA model (Table B.5). The cropping system was significant therefore, intercropped corn treatments were further analyzed. Table 4.5 shows a comparison of yield between monoculture corn and intercropped corn, when excluding the effect of row orientation. The kernel weight per plant was significantly greater in the intercrop plants when excluding the effect of row orientation (Table 4.5, $p < 0.0001$). When testing if the different monoculture and intercropping treatments were the same when including the effect of row orientation, intercropped plots produced a greater kernel weight per plant than monoculture corn, for both EW orientation ($p = 0.0001$) and NS orientation ($p = 0.0001$).

The effect of two corn populations in an intercropped system were further evaluated. Corn grain yield from the intercropped treatment with 27,993 plants ha^{-1} yielded 160 g of kernels per plant, which was significantly greater than the yield of 90 g of kernels per plant from the treatment with 55,985 plants ha^{-1} ($p = 0.0001$). This may be due to the different plant spacings in these treatments. While the row spacing was the same for both treatments (114-cm), within a row, plants seeded at 27,993 seeds ha^{-1} were 30.5-cm apart, while plants seeded at

55,985 seeds ha⁻¹ were 15.25-cm apart. Thus, with less competition from neighboring plants, corn from the treatment seeded at 27,993 seeds ha⁻¹ may have had access to more sunlight, soil water, and essential nutrients, contributing to approximately 175% more kernel yield per plant.

Monoculture corn yields are enhanced from N fertilizer applications (Jun-bo et al., 2018). In the presence of legumes, corn may scavenge some N that is being fixed by symbiotic N₂-fixing bacteria. With the soybean being supplied with most of its N requirements, and utilizing little soil N, then corn intercropped with soybean may have access to more soil N than monoculture corn. Further, there is a difference in root architecture between the two plants. Corn roots are fibrous while soybean plants have a taproot with smaller roots that branch out laterally. Underground, the roots of the corn plant tend to move towards the source of the N and may have taken up N in the proximity of the soybean roots. Therefore, this additional N could have contributed to increasing the kernel weight and/or the kernel number when compared to the monoculture corn.

Corn Productivity – Extra Ears

Corn plants are currently being bred to produce a single ear because it takes more energy to produce two ears. Through a nonparametric analysis this study found that intercropping systems showed a greater propensity of producing a second ear (Table 4.6, Figure 4.1). No second ears were observed from the monoculture corn. However, intercropped corn had a median of almost two extra ears per the 40 plants from the treatment, with one of the replications producing seven second ears. While it is unclear what caused the modest increase in second ears produced, it may have been a result of less competition or more available resources, such as sunlight, water, and plant essential nutrients, triggering this phenotypic change in the treatment with the lower population density (27,993 plants ha⁻¹). To further analyze the distribution of

second ears, differences in row orientation were evaluated and it appears that row orientation was not as influential as the cropping system.

Since developing a second ear of corn is not desired by producers, these results may aid in determining optimal corn populations for intercropped systems. Because the population of 27,993 plants ha^{-1} more frequently produced two extra ears and the population of 55,985 plants ha^{-1} did not produce any second ears, further research testing seeding rates between 27,993 and 55,985 should be evaluated. The 27,993 corn plants ha^{-1} was selected because it had the same intra-row spacing as the 38-cm monocrop corn treatment and the 55,985 corn plants ha^{-1} in intercropping had the same intra-row spacing as the 76-cm monocrop corn treatment. Identifying the optimal combination of row spacing and seeding rate could help increase the utilization of resources like sunlight, water, and nutrients to maximize yield and profit.

Profitability – Cash Transaction on 19 October 2020

An objective of this experiment was to compare monoculture crops to intercropped treatments and determine if there were any advantages or differences between the systems in terms of profitability. Corn and soybean profitability were considered at all levels of the cropping system effects in the ANOVA model (Table B.6). The cropping system was significant; therefore, profitability was further analyzed. Monocropped corn yielded 10,693 kg ha^{-1} (159 bu ac^{-1}), monocrop soybean yielded 4,300 kg ha^{-1} (64 bu ac^{-1}), and intercropping yielded 4,842 kg ha^{-1} (72 bu ac^{-1}) corn and 3,292 kg ha^{-1} (49 bu ac^{-1}) soybean.

To calculate the profitability of these systems, multiple prices of corn and soybean were analyzed. For this analysis, the price of corn and soybean from Prairie Central Coop (Lexington, IL) on harvest date was used. The response variable was converted from the amount of grain to the value of the grain. A Tukey test was used to identify significant differences between the

treatments (Figure 4.2 and Table 4.6). Figure 4.2 and Table 4.6 show that values of grain produced from the treatments of 19 October 2020.

When comparing monoculture and intercropped treatments a difference in profitability was observed. Profit from the intercropped treatment planted at 27,993 corn seeds ha^{-1} (11,333 seeds ac^{-1}) was significantly greater than all of the monoculture treatments (Table 4.6). However, profit from the intercropped treatment planted at 55,985 corn seeds ha^{-1} (22,666 seeds ac^{-1}) was \$604.54 ac^{-1} , which was not significantly different than the intercropped treatment seeded at the lower corn seeding rate which generated \$694.24 ac^{-1} .

The monoculture corn treatments were the least profitable from this study, with the narrow-spaced corn profiting \$474.78 ac^{-1} and the wide-spaced corn profiting \$436.64 ac^{-1} . Monocropped soybean profits tended to be greater than monocropped corn. For example, the narrow-spaced soybean showed a profit of \$599.33 bu^{-1} , which was significantly greater than both monoculture corn treatments. Profit from the intercropped treatment seeded at 27,993 corn seeds ha^{-1} was significantly greater profit than both monocropped corn and soybean treatments.

Results from this study supports those of Raseduzzaman and Jensen who found when intercropping a cereal with a legume, the intercropped treatments increased yield compared to monoculture cereal and legume treatments (2017). These findings are also supported by those of Kithan and Longumer, who found that the sole crops of corn and soybean performed better within the intercropping system than when compared to planting them separately (2017). These studies attribute the increase to the presence of a legume in the system and its ability to fix atmospheric N for itself, leaving more available N within the soil for the corn plants (Raseduzzaman and Jensen, 2017; Kithan and Longumer, 2017). Therefore, intercropping corn and soybean crops can not only have environmental benefits, but it can also have parallel

benefits for producers. Cereal and legume intercropping systems can produce profitable commodities without the application of added nutrients (N), reducing the production cost and increasing the profit margin.

Profitability – Interval pricing

In a given year, determining whether monocropped corn or soybean will be more profitable is a function of many factors with the selling price of the two commodities being one of the major factors. Since the selling price of corn used for this study was relatively low, a range of corn and soybean selling prices was evaluated to show a wider range of selling prices on profit. Corn grain and soybean seeds are sold as commodities and their prices are subject to volatility. To make a profit, marketing strategies identify breakeven commodity prices. When planning for a season, a farmer might consider a range of possible prices that would entice them to sell their grain. Figure 4.3 shows how incremental changes of \$0.25 bu⁻¹ for corn and \$0.50 bu⁻¹ for soybean affects profit. Comparing the different scenarios that were evaluated, the intercropped treatments are the most profitable except for a very narrow range of values when corn prices are high and soybean prices are low.

Although N is frequently one of the most limiting nutrients for corn production, no N-fertilizer was applied to corn in this study. This management decision was made to reduce N-movement between plots and determine if N-fixed by the soybean plants improved the yield of the intercropped corn. N was also not added to the soybean treatments, because fertilizing soybean plants with N can reduce N₂-fixation. Further, by not applying N-fertilizer, cost analysis is not confounded by added N. Finally, if synthetic fertilizer use becomes limited because of regulations in the near future, this study provides data and guidance for this more holistic agricultural production of the future.

Narrow-spaced and wide-spaced corn treatments showed the lowest profit when corn commodity prices are low. Figure 4.3 shows that as the price of corn increases to \$5.00 bu⁻¹ and \$8.00 bu⁻¹ for soybean, narrow-spaced monoculture corn profit approaches the intercropped treatment. The wide-row monoculture corn does not near an intercropping profit until the corn price reaches \$5.75 bu⁻¹, and the soybean price is \$8.00 bu⁻¹. Therefore, the wide-spaced monoculture corn is not as profitable as the intercropped treatment when corn prices are low to moderately high. Also, when observing the slopes of the two treatments the narrow-spaced corn has a greater slope of 158.83 while the wide-spaced corn has a slope of 148.77. The slopes project that the corn price for the narrow-spaced corn profit will increase by \$158.83 ac⁻¹ with every 1 increase in the market value of corn, while the wide-spaced corn profit will increase by \$148.77 ac⁻¹. These results indicate that the narrow-row spaced monoculture corn without the application of N will always be more profitable than the wide-row spaced monoculture corn, but narrow-row corn is not statistically different than wide row corn.

Monoculture soybean plants were also produced without the addition of fertilizer or chemicals (Figure 4.3). When the soybean prices are low (\$8.00 bu⁻¹), the monoculture soybean treatment is not as profitable as the intercropped treatment. As the price of soybean increased to \$9.50 bu⁻¹ and corn was \$3.00 bu⁻¹, narrow-spaced monoculture soybean treatment profit approached that of the intercropped treatment, but narrow-spaced soybean is not different than the intercropped treatment. The wide-spaced monoculture soybean treatment is not as profitable as intercropped treatment until the soybean price reaches \$10.00 bu⁻¹ with the corn price at \$3.00 bu⁻¹. The narrow-spaced soybean treatment has a greater slope of 63.97, while the wide-spaced soybean treatments slope was 60.10 indicating that with every 1 increase in market value the profit will increase by \$63.97 ac⁻¹ for the narrow-spaced soybean and \$60.10 ac⁻¹ for the

wide-spaced soybean. Overall, the narrow-spaced monoculture soybean treatment will have a similar profit compared to wide-spaced soybean treatment. Therefore, narrow-row soybean and wide-row soybean are not statistically different in terms of profitability.

Figure 4.3 shows 169 different intercropping profit points with many combinations of soybean and corn prices (169 different combinations total, 13 different corn prices and 13 soybean prices). At low corn prices and low soybean prices intercropping is the most profitable treatment. At higher corn prices ($\$5.25 \text{ bu}^{-1}$ - $\$6.00 \text{ bu}^{-1}$) and lower soybean prices ($\$8.00 \text{ bu}^{-1}$ - $\$9.00 \text{ bu}^{-1}$) narrow-spaced corn is more profitable and wide-spaced, but corn is very comparable to the intercropping treatment when soybean prices are on the lower end being $\$8.00 \text{ bu}^{-1}$ or $\$8.50 \text{ bu}^{-1}$. When the prices are inversed, and corn prices are low and soybean prices are high the intercropping treatment is more profitable than both monoculture corn treatments and wide-spaced monoculture soybean treatments. But the narrow-spaced monoculture soybean treatment is slightly more profitable when the price is at $\$14.00 \text{ bu}^{-1}$. Additionally, when the markets are favorable and both corn and soybean prices are relatively high, corn is $\$5.25 \text{ bu}^{-1}$ or greater and soybean are $\$10.50 \text{ bu}^{-1}$ or greater, the intercropped treatment was the most profitable.

Comparing the intercropping treatment to the conventional corn treatment, the intercropping is more profitable when corn prices are low with any soybean price. The intercropping treatment is more profitable until corn prices exceed $\$4.00 \text{ bu}^{-1}$ and when soybean prices are $\$9.00 \text{ bu}^{-1}$ or less. As the price of corn increases, the profitability of conventional corn exceeds intercropped treatments because as the price of corn increases and soybean price stays relatively low conventional corn is more profitable. But as the corn and soybean prices increase together the intercropping treatment was more profitable than monoculture corn.

Overall, the intercropped treatment is the most profitable treatment, especially when prices are low.

Table 4.1. Plant tissue nitrogen analysis. Plant Tissue Nitrogen Analysis conducted on the corn treatments during the 2020 study that took place in Lexington, IL. Tissue samples were taken from each of the three treatments and compared to observe the N concentration that was within corn leaves in each treatment. The standard error for this analysis was 0.086 and the minimum significant difference is 0.37.

Tukey Grouping	Mean (N concentration, %)	Treatment
A	2.7	Intercropped Corn
B	1.9	Wide-Spaced Corn
B	1.8	Narrow-Spaced Corn

Table 4.2. Effect of row spacing on soybean monoculture production. The effect of row spacing and row orientation on soybean monoculture production in the 2020 study that was conducted in Lexington, IL.

Linear Function	Estimate (kg)	Standard Error	t Value	p	Grouping
Soybean Overall: Narrow vs Wide	106	54	1.92	0.0624	A
Soybean NS: Narrow vs Wide	122	79	1.59	0.1206	A
Soybean EW: Narrow vs Wide	87	79	1.13	0.2669	A

Table 4.3. Monoculture soybean vs intercropped soybean. Comparison between monoculture soybean production and intercropping soybean production was analyzed, accounting for the effect of row direction based on the amount of seeds produced per plant in the 2020 study that took place in Lexington, IL.

Treatment	Estimate (g of seeds per plant)	Standard Error	t Value	p
Soybean Overall: Intercrop vs Monocrop	4.5	0.62	7.16	< 0.0001
Soybean NS: Intercrop vs Monocrop	4.2	0.88	4.18	< 0.0001
Soybean EW: Intercrop vs Monocrop	4.7	0.88	5.31	< 0.0001

Table 4.4. Effect of row spacing on monoculture corn production. The effect of row spacing and row orientation on monoculture corn production in the 2020 study that took place in Lexington, IL.

Treatment	Estimate (kg)	Standard Error	t Value	p	Groupin g
Corn Overall: Narrow vs Wide	257	172	1.48	0.1468	A
Corn NS: Narrow vs Wide	183	244	0.75	0.4587	A
Corn EW: Narrow vs Wide	328	244	1.35	0.1863	A

Table 4.5. Monoculture corn vs intercropped corn. Comparison between monoculture corn production and intercropping corn production was analyzed, accounting for the effect of row direction based on the number of kernels produced per plant within the 2020 study that took place in Lexington, IL.

Treatment	Estimate (g of kernels per plant)	Standard Error	t Value	p
Corn Overall: Intercrop vs Monocrop	85.2	8.26	10.32	< 0.0001
Corn NS: Intercrop vs Monocrop	97.2	11.67	8.31	< 0.0001
Corn EW: Intercrop vs Monocrop	73.4	11.67	6.28	< 0.0001
Normal Intercrop Corn vs Doubled Intercrop Corn	74.5	6.53	11.41	< 0.0001

Table 4.6. Cash transaction on 19 October 2020. Corn and soybean commodities were sold at Prairie Central Co-operative in Lexington, IL. Profitability comparison between all the treatments if the grain was sold on the day of harvest 19 October 2020.

Tukey Grouping		Mean profit ^a (\$/bu)	N	Treatment
A		694.24	22	Normal Intercrop
A	B	604.54	4	Double Corn Populated Intercrop
	B	599.32	6	Narrow-Spaced Soybean
C	B	559.65	4	Wide-Spaced Soybean
C	D	474.78	8	Narrow-Spaced Corn
	D	436.64	6	Wide-Spaced Corn

^a Profit was calculated by subtracting cost of the seed for planting from the income from selling harvested grain. Commodity prices are from the date of harvest, 19 October 2020.

Figure 4.1. Distribution of amount of second corn ears produced. On 12 October 2020 all corn plots that were used for data collection for the study in Lexington, IL were harvested. Some plants within the different treatments produced a viable second corn ear. This figure is highlighting the distribution of second ears that were produced in the different corn treatments.

Figure 4.2. Cash transaction on 19 October 2020. Cash transaction on 19 October 2020 for the grain that was produced within the 2020 study in Lexington, IL. Corn and soybean were sold on 19 October 2020. This figure is highlighting the distribution of the profits based on the market values on that day.

Figure 4.3. Cash transaction interval pricing. Cash transaction based on interval pricing for the grain that was produced in the 2020 study in Lexington, IL. The LSmean for yield of each treatment was multiplied by the market price and the seed cost was subtracted. Different potential profits were generated from a range of corn and soybean market prices. In addition to the regular interval of prices, the selling price from 19 October 2020 is also shown.

CHAPTER V: CONCLUSION AND IMPLICATIONS

The goal of this study was to compare different treatments of intercropped corn and soybean to monoculture corn or monoculture soybean. Corn and soybean planted within an intercropping system have an increased productivity and profitability when compared to monoculture corn or soybean setting without the application of N at most market prices. These results reflect that intercropping could in fact be a future production practice within agronomic/commercial agriculture. Current mechanical limitations at harvest could be overcome through engineering ingenuity making this cropping system feasible for producers.

Producing corn and soybean within an intercropping setting provides benefits that can directly impact the producer. One benefit that producers could receive is a substantial increased profit potential. The intercropping system is the most profitable treatment when compared to all the monoculture treatments that were tested at most market values. In years of drought, the supplemental support of intercropped soybean within corn plants can aid to an increased yield due to the absence of excess moisture available within the soil. Within the intercropped treatment there is less corn seeds planted, reducing planting costs and there is also a reduced number of soybean plants planted when compared to the monoculture treatments. Both corn and soybean produced more yield per plant in the intercropping treatment.

Utilizing this type of production practice can add an additional amount of stability because there are two crops being produced, instead of one crop. When one crop fails to produce a reasonable yield, there is a supplemental crop that may replace for the lost profit. For example, if the market price for corn was low and the price of soybean was moderately high, the production of soybean plants within this given system could account for the lost corn profit. The cost to produce both corn and soybean in an intercropping system will be less than the cost of

production with a ‘conventional farming’ operation. Soybean plants can produce enough N for themselves, without utilizing any of the N within the soil leaving larger amounts of N within the soil for the corn plants to utilize. Therefore, the requirement or need for added fertilizers to be applied is reduced which can reduce the overall cost of production. Overall, intercropping corn and soybean can provide producers with benefits that include increasing profit and additional stability.

The state of the environment is often overlooked when producing crops for a profit. Intercropping could be an essential asset to the economy and the future of the agriculture industry to reduce the amount of synthetic inputs that are currently being applied. A reduction in the use of those types of inputs is possibly due to the diversity of plant species that is present. Through the implementation of intercropping, corn can take up significant amounts of N when compared to monoculture corn. Therefore, by utilizing this cropping system the cost of added inputs can be reduced. This would in turn reduce the amount of nutrients that could be lost to the environment. Therefore, by reducing the negative effects on both the environment and the producer’s profit, this cropping system could be mutually beneficial for the producer and the environment.

Intercropping can be essential to the future of Midwest farming. Commonly, agronomic crop production is being done in a conventional manner to increase yield and often ignores environmental considerations. Integrating intercropping systems into production systems within the Midwest can bring benefits to both the producer and the environment. Mutual benefits include the presence of diversity in crop species, yield stability, increased profit, and reduced impacts on the environment. Increasing the crop diversity that is present withing agricultural land that results in an increased profit in the Corn Belt can be driving force to intercropped systems

being practiced. By integrating intercropping systems into production it increases both production and profit on operations. Intercropping corn and soybean can be an essential cropping system, implementing change and diversity into the agriculture industry.

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APPENDIX A: SOIL TEST RESULTS

Table A.1. Soil Test. On 22 November 2019 a soil test was conducted by Brandt on the experimental space in Lexington, IL. pH is water pH, CEC is Cation Exchange Capacity (reported in ME/100g, ME is milli-equivalent), and OM is organic matter concentration in the soil. P is Phosphorous measured by Bray test, K is Potassium, Ca is Calcium, and Mg is Magnesium all measured by Mehlich III Extractable test.

ID	pH	CEC	OM (%)	P (lb/ac)	K (lb/ac)	Ca (lb/ac)	Mg (lb/ac)
1	7.0	22.4	3.5	250	964	6616	1111
2	6.9	17.9	3.0	250	920	5208	797
3	6.8	19.4	3.5	250	1000	5544	845
Avg.	6.9	19.7	3.3	250	971	5776	906

APPENDIX B: SUPPLEMENTAL TABLES & FIGURES

Table B.1. ANOVA table for N Leaf Analysis. In this analysis three levels of cropping system (narrow-row corn, wide-row corn, and intercropped corn) are being considered.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1.40	0.70	31.64	0.0006
Error	6	0.13	0.02		
Corrected Total	8	1.53			

Table B.2. ANOVA table for row spacing analysis in soybean production. In this analysis two levels of cropping system, narrow-row soybean and wide-row soybean, are being considered from the six total levels of cropping systems.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Cropping system	5	28991.64	5778.33	590.96	< 0.0001
Row orientation	1	58.88	58.88	6.02	0.0188
Interaction	5	36.41	7.28	0.74	0.5950
Error	38	371.56	9.78		
Corrected Total	49	29361.88			

Table B.3. ANOVA table for monoculture soybean vs intercropped soybean analysis. In this analysis four levels of cropping systems (narrow-row soybean, wide-row soybean, intercropped soybean, and intercropped soybean with the doubled corn population) are being considered.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Cropping system	5	1878.43	375.69	579.34	< 0.0001
Row orientation	1	3.29	3.29	5.07	< 0.0001
Interaction	5	1.93	0.39	0.60	< 0.0001
Error	38	24.64	0.65		
Corrected Total	49	1908.99			

Table B.4. ANOVA table for row spacing analysis in corn production. In this analysis two levels of cropping system, narrow-row corn and wide-row corn, are being considered from the six total levels of cropping systems.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Cropping system	5	143471.00	28694.20	181.32	< 0.0001
Row orientation	1	17.66	17.66	0.11	0.7402
Interaction	5	156.30	31.26	0.20	0.1863
Error	38	6013.42	158.25		
Corrected Total	49	149646.20			

Table B.5. ANOVA table for monoculture corn vs intercropped corn analysis. In this analysis four levels of cropping systems (narrow-row corn, wide-row corn, intercropped corn, and intercropped corn with the doubled corn population) are being considered.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Cropping system	5	190015.32	38003.06	263.53	<0.0001
Row orientation	1	0.0359	0.0359	0.00	0.9875
Interaction	5	528.61	105.72	0.73	0.60
Error	38	5479.97	144.21		
Corrected Total	49	196035.13			

Table B.6. ANOVA table for corn and soybean profits on 19 October 2020. In this analysis all levels of the cropping system (narrow-row soybean, narrow-row corn, wide-row soybean, wide-row corn, intercrop, and intercropped treatment with the doubled corn population) are being considered.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Cropping system	5	487489.13	97497.83	35.24	< 0.0001
Row orientation	1	3925.08	3925.09	1.42	0.2410
Interaction	5	9424.38	1884.88	0.68	0.6403
Error	38	105124.55	2766.44		
Corrected Total	49	607213.37			

c		c	30 in corn	c	c	s	s	c	s	Intercrop	Intercrop	Intercrop	s	c	s					
c	c	c	15 in corn	c	c	c	s		s	30 in soybeans	s	s	c	c	30 in corn	c				
s	c	s	intercrop	s	c	s	s	s	s	15 in soybeans	s	s	s	c	c	15 in corn	c	c	c	
s	c	s	Intercrop	Intercrop*						Intercrop	Intercrop*						Intercrop	s	c	s
s	s	s	15 in soybeans	s	s	s	c	c	c	15 in corn	c	c	c	s	s	s	15 in soybeans	s	s	s
s		s	30 in soybeans	s		s	s		c	30 in corn		c	c	s	c	s	Intercrop	s	c	s
s	c	s	Intercrop	Intercrop						Intercrop	s	c	s	c	c	c	15 in corn	c	c	c

Figure B.1. Experimental Design. The experimental layout for the 2020 study that took place in Lexington, IL. This layout was planted in two different orientations, North-South and East-West.

Figure B.2. Hand planting corn. On 21 May and 22 May 2020 all corn plots in the study that took place in Lexington, IL were hand planted using a jab planter.

Figure B.3. Intercropped treatment in early vegetative stage. Intercropped corn and soybean on 24 June 2020. This picture captures a corn and soybean intercropping treatment planted in an NS orientation in Lexington, IL. During this time of the growing season the corn plants were at V5 growth stage and the soybean plants were between V2 and V3 growth stages.

Figure B.4. Intercropped treatment at full canopy closure. Intercropped corn and soybean on 21 July 2020. This picture captures a corn and soybean treatment planted with an NS orientation in Lexington, IL. During this time in the growing season the corn plants around V16 growth stage and the soybean plants were around R4 (full pod) stage.

Figure B.5. Monoculture soybean treatments highlighting canopy closure. Monoculture soybean on 06 July 2020. This picture is capturing both monoculture soybean treatments, wide row (front half of picture) and narrow row (back half of picture), that were planted in an EW orientation in Lexington, IL. During this time in the growing season the soybean plants were beginning to bloom (R1).

Figure B.6. EW plot at physiological maturity. EW plot at physiological maturity on 21 September 2020. This picture is capturing all the treatments within the EW oriented plots in Lexington, IL. During this time in the growing season the corn plants are reaching R6 stage (black layer) and the soybean plants are at R8 stage (full maturity).

Figure B.7. Intercropped treatment at physiological maturity. Intercropping treatment at physiological maturity on 21 September 2020. This picture is capturing four rows of the intercropping treatment (two soybean rows between the two rows of corn) in Lexington, IL. During this time in the growing season the corn plants are at R6 (black layer) growth stage and the soybean plants are at R8 (full maturity) growth stage.

Figure B.8. intercropped treatment at harvest. Intercropped corn and soybean treatment during the time of harvest on 13 October 2020. This picture is of an intercropping treatment in the NS orientation in Lexington, IL right before both corn and soybean plants would be hand-harvested.

Figure B.9. Narrow-row corn plot at harvest. Narrow-row corn fully matured at harvest time on 13 October 2020. This picture is capturing the narrow row corn treatment (38 cm) on the day of harvest in Lexington, IL. During this time in the fall, the ears on the plants were fully dried and ready to be hand harvested.

Figure B.10. Intercropped soybean plant at harvest. Soybean plant in the intercropped treatment during harvest on 17 October 2020 in Lexington, IL. In this picture the soybean plants are being cut using hedge trimmers right below the first branch (approximately 3 cm above the soil surface).

Figure B.11. Harvested soybean plot. On 15 October 2020 some of the soybean plots were hand-harvested. This picture shows a narrow-row soybean (38-cm) treatment after it was harvested in Lexington, IL.

Figure B.12. On 17 October 2020 soybean harvest took place in Lexington, IL. This picture captures a NS-oriented intercrop plot that is partially harvested, the corn ears have been hand harvested and the soybean plants are still standing waiting to be harvested.