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A Brief History of Corn: Looking Back to Move Forward

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By

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ABSTRACT

Maize was domesticated from teosinte in Mexico some 7,000 to 10,000 years ago and quickly spread through the Americas. It has become one of the most important crops at a local and global level. Two types, Northern Flint corn and Southern Dent corns provided the basis of the genetic background of modern maize hybrids. The development of hybrids, first double-cross and later single-cross hybrids, along with a transition to high input farming provided huge yield increases, which have continued to improve with improving technology.

Increase in maize production also caused a rise in Western corn Rootworm (*Diabrotica virgifera virgifera* LeConte). As maize cultivation increased it spread from Eastern Colorado into Nebraska in the 50's, Indiana by the 70's and the East coast by the 90's, and even Europe in 1992. A broadcast soil application of organochlorine insecticides was a common control tactic beginning in the late 40s. By 1959 control failures were noted and resistance spread with the concurrent corn rootworm range expansion. Resistance spread into areas where organochlorine insecticides had never been used. New modes of action were adopted and, more importantly, new management practices reducing selective pressure. In 2003 Bt traits for rootworm control were released, but by 2009 resistance was documented. The Western corn rootworm has proven highly adaptable to control measures, including rotation.

Many challenges face agriculture in the future including water use, soil degradation, pest and disease control issues, and stagnant yield potentials. Despite these challenges, a great deal of technological advances such as precision agriculture, improved molecular techniques, and better adoption and implementation of Integrated Pest Management will provide effective tools for addressing these challenges.

Addressing the challenges of the future is not an issue of technology. Maize is more than a commodity; it has been and continues to be an essential part of our culture. The objective of this work is to illustrate that addressing the human dimension of these challenges will be crucial to addressing the current and future issues in agricultural production. Two separate examples of how this is being addressed are discussed.

Introductory Note

This work is influenced to a great extent by a number of past experiences. The first was an internship during the 2014 growing season at Midwest Research, Inc. in York, Nebraska. A great deal of research is conducted there on numerous crops, practices, and emerging technologies. However, one area of research where they devote a great deal of resources is in the area of corn rootworm research. Midwest Research was formed in response to growing concerns about corn rootworm. It was one of the first contract research organizations. It was a pioneer in private research in many ways. They started, and continue today, with corn rootworm research in response to the need for more research on corn rootworms. It also played an important role in developing protocols for transgenic research and meeting regulatory compliance requirements while getting valuable data and keeping studies practical and manageable.

This experience at Midwest Research was instrumental in the next important opportunity, the development of educational modules directed at educating producers about the causes and perils of resistance. Focusing on teaching best management practices for delaying resistance. This project is explained in greater detail in chapter 4 of this document.

During the 2015 growing season I had the opportunity to work at the Gothenburg Water Utilization Learning Center in Gothenburg, Nebraska. Greater detail is also given in chapter 4 of this document about the role and mission of the Gothenburg Learning Center. These opportunities impressed upon me the importance of recognizing and understanding the human dimension of the challenges we face as a society. Addressing the human dimension and the resulting social factors will be crucial to moving forward. These social factors are a result of historical, economic, and cultural experiences. Understanding these and adequately addressing them will be crucial to addressing the challenges of the future.

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CHAPTER 1: Domestication and Improvement

In 2014, 36 million hectares were planted to corn in the United States; 3.7 million of those were in Nebraska (USDA-NASS, 2015). More tonnage of corn is produced worldwide each year than any other major crop. From 2005 to 2007, corn production was 736 million metric tons, surpassing wheat and rice by 122 million and 92 million metric tons respectively. That gap is projected to continue growing into the future (Alexandratos & Bruinsma, 2012). Corn production is significant to agricultural markets at a local level as well as internationally.

With corn playing an ever-increasing role in agriculture it will be important to understand how corn best fits into the agricultural systems of the future. This will require a greater level of cooperation among the players involved, as well as, a better understanding of the components of agricultural systems. Over the past 100 years corn yields have increased fivefold. Worldwide increases in yield have been documented for many other crops, including wheat, rice, and soybean. However, there are indications that many these crops are reaching a plateau in production (Egli, 2008). With each increase in production coming at a greater cost and with a lower payoff, it will be important to optimize resource use.

Often, the best way to look forward is to first look back. Luther Burbank was a well-known botanist, horticulturalist, and pioneer in agricultural sciences. He is widely known for the Burbank potato, though he made a large number of important contributions in the area of plant breeding. "To really understand a plant, one has to look into its history. It became what it is now through its whole course of development." Stated Burbank (Bacon, 1960). This is an attempt to look back into the history of corn or maize in order to identify the best options moving forward.

Domestication

Modern corn or maize was likely domesticated from a Mexican wild grass somewhere around 7,000 to 10,000 years ago (Smith, 1989). The Mexican wild grass has been identified as Balsa teosinte, *Zea mays* spp. *Parviglumis* (Wang, Stec, Hey, Lukens, & Doebley, 1999). The Balsa teosinte was native to the Balsa River Valley of Mexico. Domestication happened as ancient farmers noticed that not all plants were the same. They would save seeds from the best plants and use them for seed the next year. This selection process was essentially the beginning of plant breeding.

Up to this point, teosinte grains would have been difficult to consume and yielded little nutritive value to humans (Kempton, 1937). The well-known geneticist George Beadle (1939) demonstrated that teosinte grains could be heated to make them pop, like popcorn today. This separated the grains from the hard hulls and released the grains from the joints of the rachis. This made teosinte inefficient as a food source. However, teosinte was an excellent grain for storage. Mice and insects would not eat stored teosinte grain. Even birds, though they would eat it, did not prefer it and they would eat it only when all other food sources are exhausted (Smith & Betrán, 2004).

One important source of variation came, though unknown to early farmers, from a change in the *teosinte branched1* (*tb1*) gene. This variation limited tillers or organ proliferation on the plant. The *tb*1 gene controls apical dominance in maize plants by producing mRNAs that repress organ growth (Clark, Linton, Messing, & Doebley, 2004). The mutation in *tb1* changed plant architecture to give domesticated corn one relatively strong stalk while teosinte has numerous relatively weak stalks. Limiting the plant to produce a single stalk, forced a large amount of resources into the stalk, including the grains in that stalk. This was a significant development in the domestication of maize.

Although little is known about the specifics of maize domestication it presents a unique case in that maize is just as diverse if not more diverse than its wild ancestor (Doebley, Goodman, & Stuber, 1984). Shortly after domestication in most plants, there is generally a period of intense selection for agronomic traits. This, coupled with a generally small initial population, creates a population bottleneck that significantly limits genetic diversity (Tanksley & McCouch, 1997). That is why in many crops breeders use wild ancestors as a source of genetic variation. However, in the case of maize, the genetic variation is still quite large, even today, after thousands of years of selection. Eyre-Walker et al., (1998) found that this was likely due, in part, to a small initial population with high genetic diversity.

Shortly after maize domestication, it spread throughout North and South America, likely spreading along trade networks. As it moved, early maize growers utilized the genetic variation to adapt maize to new environments. By the time Europeans arrived there were about 300 distinct races of corn in the Americas, spanning from Chile to Southern Canada (Hallauer, 1987). Races of maize are characterized by morphological characteristics and ecogeographic adaptations (Tracy, 1999). Even within these races there can still be a distinct amount of variation. Maize originated in a tropical climate, but over thousands of years, genetic diversity was harnessed to provide a staple crop that was a high producer in a wide variety of environments.

As maize spread it became an important part of many cultures, allowing societies to grow and flourish. Evidence of maize in the Southwestern United States indicates that it was being grown there by 2100 BC at the latest (Merrill et al., 2009). Two different types of corn were being grown; one adapted to high elevations and one adapted to low elevations. These were types of flint corn. Characteristics of flint corn include long slender cylindrical ears with 8 to 10 rows, thick shanks, and proportionally larger cobs; kernels are wide, undented and not pointed (Troyer, 2006). The undented kernels are due to a hard starch, and this is where the name flint corn originated, as seeds were "hard as flint." This particular flint corn was a type of maize thought to originate in the highlands of Guatemala, but not common to Mexico (Anderson & Brown, 1952). This would have made the maize more adapted to the environment of latitudes further north, especially those at higher altitudes.

Flint corn was the predominant type of corn grown in the Eastern United States. Corn didn't arrive there until around 200 CE, but was not a staple crop until the period from 800 to 900 CE (Smith, 1989). Flint corn was often grown in conjunction with beans and squash. This was important because the beans and corn together provided a complete protein, or supplied all of the essential amino acids necessary in the human diet (Landon, 2008). Seeds from all three plants were planted at the same time in a mound. The corn provided a pole for the beans, and the squash provided ground cover for weed control. The beans also provided some nitrogen for the other plants.

Though the change to using corn as a staple crop was a societal phenomenon, it was likely heavily influenced by the development of a type of corn with earlier maturity and greater cold hardiness. This was known as Northern Flint corn (Hart & Lovis, 2012). Northern Flint corn descended from the flint corn introduced into the southwestern United States 4100 years ago and provides a substantial portion of the genetic background of modern corn hybrids (Troyer, 1999).

Development of New Open-Pollinated Varieties

U.S. Corn belt dent corn was the product of two important types of corn. The first was Northern Flint corn, introduced from Central America some 4,000 years earlier. The second was southern dent corn, which arrived shortly after Europeans arrived (Hallauer, 2000). The first reference to southern dent corn came in 1705 as reported in Robert Beverly's *History of and Present State of Virginia.* In his description, he describes it as having a dent on the back, "as if it had never come to perfection." The dent on back was due to a higher amount of soft starch compared to the flint corn. Southern dent ears had 14 to 22 rows with large, deep kernels and a white endosperm (Troyer, 2006). Dent corn was noted for its height and ripening later, but it was far more productive than the predominant Northern flint corn. Another distinguishing characteristic was that the corn kernels were always white (Lorain, 1825). Southern dent corn provided high yield while the Northern flint corn provided genetic variation for earlier maturity and greater cold hardiness (Troyer, 1999).

Lorain (1813) was the first to describe the effect of crossing dent and flint corns. He also elaborated on techniques for crossing the two types of corn and saw the potential for these types of seeds for farmers. By 1835 newspaper articles explained how to cross varieties and gave directions for detasseling to produce hybrids (Anderson & Brown, 1952). Southern Dent and Northern Flint corn were purposefully crossed through much of the United States for quite some time to produce new varieties of corn. Corn producers tried to mix the favorable traits of the two corn types to increase yield.

By crossing the two types of corn, farmers were able to select new types of corn more suited to their local environments. Originally, the Corn Belt was further south. In 1838, Tennessee led the nation in corn production followed by Kentucky and Virginia. However, by 1878 Iowa led the nation in corn production followed by Illinois and Missouri (Troyer, 2006).

This shift in corn production was a result of the crosses being made by corn farmers at the time. New cultivars being produced were earlier flowering and more tolerant to droughts. This was because they were being grown further north where seasons were shorter and further west where climates were more arid (Montgomery, 1913). Many open-pollinated varieties existed, but all were not equal. Over time, farmers and later plant breeders tested the open-pollinated varieties to find the best traits that provided adaptability to the environment as well as increased yield.

Perhaps the best known and successful such cross was conducted by Robert Reid, by accident, in 1847. Reid had moved from Ohio to Illinois in 1846 and brought some "Gordon Hopkins" seed. "Gordon Hopkins" was a semi-gourd dent seed. He had planted it in late spring and then saved the best ears for seed. However, he did not check germination on them, so the next spring when he planted he had a poor stand. He replanted the missing hills with “Little Yellow,” a native Indian flint corn with earlier germination (Troyer, 1999). The two corns pollinated at the same time and cross-pollinated. These seeds were then used for seed in subsequent years. Reid continued to work with the corn and developed a new cultivar. This cultivar became known as Reid’s Yellow Dent.

Robert’s son James Reid continued to cultivate Reid’s Yellow Dent, even giving seeds to the neighbors to prevent cross-pollination with other varieties. It was even rumored that the best ears overwintered under his mattress (Shamel, 1907). James won a blue ribbon with his Yellow Dent at the Illinois state fair in 1891 and then a gold medal at the Chicago World’s Fair in 1893 (Anderson & Brown, 1952). Reid’s Yellow Dent was commonly called World’s Fair corn for quite some time after that. It sold at a significant premium and was the dominant corn in the US Corn Belt for 50 years (Troyer, 1999). Today it continues to provide a significant portion of the genetic background of many modern hybrids.

The Indiana and Wisconsin Experiment Stations ran dry-lot feeding trials with swine from 1916 to 1920. In these trials they advocated that yellow corn was better for feed than white corn because of the higher vitamin A content. Before these trials, the amount of white and yellow corn produced was equal. By the early 1940’s the percentage of white corn produced had dropped to 17% and was 1% by 1970 (Poneleit, 1994). These studies are the primary reason for the prevalence of yellow over white field corn today.

Commercial Corn Hybrids

From 1865 to 1935, average corn yield in the United States had essentially no change. The national average yield exceeded 30 bu/acre in only four of those years (Hallauer, 2008). During the early part of the twentieth century there was growing interest in using corn as a livestock feed, especially in the Corn Belt. Native Americans favored large ears for harvest and storage. However, with westward expansion land was becoming a limited resource for American corn growers. As a result, more of an emphasis was placed on increased yield per unit area (Troyer, 1999). In an effort to improve yield, extension workers used corn shows as way to help farmers identify the best ears to save for seed (Egli, 2008). This ultimately did not improve yield, but did help the important shift to using replicated yield tests to compare lines.

The potential for using hybrid crosses for seed production were being studied by the late 1800s. Dr. W.J. Beal conducted experiments with hybrids at Michigan State in 1878. He called his hybrid mule corn since the corn was the result of a cross just as mules are the result of a cross. George Morrow confirmed his results at the University of Illinois in 1892 and 1893. He proposed production methods similar to those used today (Morrow & Gardner, 1893).

Though the benefits of making crosses were known, no commercial hybrids were produced. All corn were still open-pollinated. In 1908, G.H. Shull proposed that corn could be improved by selfing plants to develop inbred lines, making hybrids or crosses between the inbred lines and making that seed available for farmers (Hallauer, 2008). In 1908 and 1909, Edward M. East worked with hybrids that yielded higher than 200 bu/acre (Troyer, 2006). Thus, the obvious benefits of hybrid corn were known by the early 1900s, but to claim that yield would require a significant increase in inputs.

The problem with using inbred lines to produce hybrids was that inbred lines had poor vigor and very low yield. They were also very susceptible to corn pests and easily outcompeted by weeds. This made the cost of producing hybrid seed greater than the value that could be obtained from them (Hallauer, 2008). D.F. Jones overcame this obstacle when he produced the Burr-Leaming double cross hybrid in 1917 and it was first produced commercially in 1921 (Jones, 1927). Double cross hybrids were cheaper to produce, making it feasible for farmers to adopt the new technology. This was a major turning point in hybrid seed corn production.

A double cross hybrid is essentially a cross between two hybrids. The first generation hybrids do not have the same weaknesses as inbred corn lines and they yield significantly more (Hallauer, 2008). With fewer disease and weed issues and increased yield it was possible to make double cross hybrid seed production commercially viable. The first nationally popular double cross hybrid was U.S.13, and it was used in breeding nurseries into the 1960s (Smith & Betrán, 2004).

At the same time that double cross hybrids were produced, a number of other technological advances were adopted in corn production. One significant factor was the use of inorganic nitrogen (N) fertilizer, which increased significantly starting in 1945 (Gardner, 2009). Also during the first part of the twentieth century mechanization started to play a significant role in agriculture. Hybrids provided stand uniformity with ears at the same height on the plant and this made hybrids much easier to combine (Crow, 1998). Double cross hybrid seed was part of the important shift in corn production in the United States to a high-input agricultural production system. Hybrid corn both contributed to and benefited from this shift.

With the shift to a high-input agricultural production system came significant improvements in management practices. Mechanization of much of the farm labor allowed for more management operations such as cultivating, planting, harvest, etc. to be conducted in a timely manner (Egli, 2008). Increasing plant population was another management practice that contributed significantly to increased yields (Troyer, 2003). The increase in plant populations was made possible in by other technological advances such as N fertilizer use and, in more arid climates, irrigation. Hybrids that maintained high yield at high densities were a significant component of increased yield and this development remains important to this day. Increased planting densities provide greater yields on a per hectare basis. Most corn hybrids do not produce more corn than they used to, but the increase in the number of plants per acre provides increased yield.

Once it caught on, the shift to planting hybrid seed was a rapid one. Iowa farmers went from 10 to 90 percent of their corn acres being planted with hybrid seed in only four years (Griliches, 1957). In 1940 about 50% of corn production area was planted with hybrid seeds and by 1950 that number was up to 90%. The adoption of hybrid corn seed proceeded quicker in high-yielding areas while low-yielding areas adopted at a much slower rate since corn was not the primary crop and economic advantages were fewer (Egli, 2008). During the double cross hybrid era, national corn production averages increased by an average of 1 bu/acre each year (Crow, 1998). Another important reason for the adoption of hybrids in some parts of the US was that during the dust bowl years of 1934-36 hybrid strains had been significantly more resistant to drought than open-pollinated varieties (Crabb, 1947). This provided convincing evidence of the benefits of hybrid maize, especially for those who experienced the devastating effects of the dust bowl years.

Another important component of the transition to high-input production systems was the increased use of herbicides. During World War II, 2,4-D was developed; this provided producers with their first opportunity to use selective weed control (Naylor, 1996). As more herbicides were developed herbicide use continued to increase significantly (Evans, 1996). Perhaps the most important group of herbicides for maize production was the triazine herbicides, introduced in the late 1950s. Atrazine was registered in 1958 and significantly changed weed management in maize. Atrazine was significant in that it did not injure corn. Thus it could be used to control numerous annual weeds, without ill effects for the corn. Within two years of being released, Atrazine was quickly becoming an important part of corn production (Bridges, LeBaron, McFarland, & Burnside, 2008).

The use of effective herbicides was significant for corn producers, but it also had implications for those producing hybrid seed. One major constraint to producing single cross hybrids was weed control (Hallauer, 2008). With effective, selective herbicides it suddenly became much more manageable to control weeds in inbred corn. During the era of double cross hybrids many of the inbred lines had been improved significantly to yield higher. In fact, some of inbred lines yielded as high as previous hybrids (Crow, 1998). With more vigorous, higher yielding inbred lines and more effective weed control, it became feasible to produce single cross hybrid seed. These became more common in the 1960s and by around 1980 they were the standard (Troyer, 2006). Single cross hybrids were higher yielding and the annual national yield increased by an average of 1.71 bu/acre each year during the single cross hybrid era (Crow, 1998).

In 1963, DeKalb XL45, a single cross hybrid with a relative maturity of 110 days was first grown commercially. It was the first early, popular hybrid released in the northern U.S. Corn Belt (Troyer, 1996). It was widely adapted, growing as far north as Minnesota and as far south as Texas. It was also grown from Colorado to Delaware. It was a small hybrid that flowered early, lengthening out the grain fill period. The early flowering combined with more hard starch reduced the amount of damage to kernels when combined. The smaller size made it more adapted to higher plant densities and narrower rows, allowing for greater yield per unit area. Due to the high yield it was highly popular. However, due to small seed size, it was sold in 80,000-kernel bags and sold by seed count rather than weight (Troyer, 2004). The seed industry eventually followed their lead, which is why seed is now sold in bags of 80,000 seeds.

With the transition to single cross hybrids came other significant changes for the seed corn industry as well. During the 1950s, many public breeding programs were downsized, eliminated or restructured. At the same time, the commercial breeding industry saw a period of rapid growth, in terms of size, number and their role in hybrid seed corn production (Hallauer, 2008). This shift has left much of the development of inbred lines to commercial companies as they seek to provide more competitive hybrids.

The Biotechnology Era

For thousands of years, humans altered plant genetics to develop crops more suited for food, fiber, feed and energy. Much of this was done through phenotypic selection. It wasn't until Gregor Mendel's discoveries that we started to understand the causes for the phenotypic variation, but even then it was just the start (Barrows, Sexton, & Zilberman, 2014). Though Mendel's breakthroughs were very important and served as a catalyst to many of the discoveries to come, it was merely the beginning of what we are coming to understand.

The twentieth century brought new light and understanding to genetics that has proven invaluable in crop breeding. This genetic technology provided the tools necessary for understanding phenotypic variation at the molecular level. Tools such as marker assisted selection and Targeting Induced Local Lesions in Genomes (TILLING), allow for more targeted breeding approaches (Kaeppler, 2004). This has the potential to significantly reduce the time necessary to develop and improve both inbred corn lines and the hybrids. It can also reduce the amount of labor associated with traditional breeding.

Plant breeders attempt to harness the natural variation in crops to develop useful combinations of phenotypic traits. This is a long process and numerous methods have been used to introduce variation into crops to improve them. One common method is to use wild ancestors and cross the two to increase genetic diversity. This isn't as useful in corn since it is already quite diverse. Also, with corn it has been shown that adaptedness to different environments, as was the case with Northern Flint corn, is more important than diversity for increasing yield (Troyer, 1999). Thus, it would not likely be useful to use a plant adapted to a tropical climate as a source for variation in a temperate crop. US corn breeders have focused primarily on corn adapted to North America. In fact they use less than 3% of the corn germplasm in the world because much of it does not provide beneficial genetic variation (Hallauer, 2008).

Another method for increasing genetic variation in traditional plant breeding was the use of chemicals, or more commonly, radiation to induce mutations. Since 1927, with the discovery of X-ray induced mutations, over 2,250 plant varieties have been developed with this technique (Schouten & Jacobsen, 2007). Though this has produced many useful mutations, one of the most targeted and efficient methods for introducing genetic variation, has been through the use of genetic engineering.

In 1972, restriction enzymes were used to create the first recombinant DNA (Jackson, Symons, & Berg, 1972). In 1973 Cohen et al., (1973) produced the first genetically modified organism, a bacteria. The first genetically modified plant came in 1983 when Bevan et al., (1983) introduced a gene for antibiotic resistance to tobacco plants using the bacterium *Agrobacterium* *tumefaciens* in a process known as *Agrobacterium*-mediated transformation. In 1994, the FDA approved the FLAVR SAVR™ tomato; the first genetically modified whole food to be sold commercially. It was made more resistant to post harvest fungal infections by using antisense RNA that regulates the expression of polygalacturonase, the enzyme associated with softening in ripe tomatoes. By slowing the softening process, the tomatoes became more resistant to fungal infections and had a longer shelf life (Kramer & Redenbaugh, 1994). Despite these advantages, the FLAVR SAVR™ was not a commercial success in part due to a lack of public support.

Genetically engineered crops met with mixed results initially. Attempts at releasing both genetically modified tomatoes and potatoes had been unsuccessful. Padgette et al. (1995) demonstrated that effective resistance to the herbicide glyphosate could be transformed into soybean lines and stably perpetuated through traditional breeding. Scientists isolated a gene from *Agrobacterium* sp. that coded for a form of the 5-enolpyruvylshikimate-3-phsophate synthase (EPSPS) enzyme that enabled glyphosate tolerance. The EPSPS enzyme is crucial for aromatic amino acid synthesis (Della-Cioppa et al., 1986). That gene was then introduced into the chloroplast and found to confer glyphosate resistance. This was significant because it addressed an important need that farmers had; it provided effective weed control. It also avoided previous controversies because soybeans were not used for direct human consumption.

Glyphosate, sold as Roundup at the time was relatively inexpensive, yet effective, and it was considered to have a low environmental toxicity. Monsanto released the glyphosate resistant soybeans under the name Roundup Ready Soybeans in 1996 (Carpenter & Gianessi, 1999). The adoption of glyphosate resistant crops happened at an unprecedented rate, 80% adoption within 10 years in the U.S. (Green, 2012). The improved weed control allowed producers to increase yield as well as quality by allowing for better weed control. The potential for other crops to express the same gene did not go unnoticed, as glyphosate resistance was subsequently conferred to other crops.

Glyphosate was not the only herbicide used in developing herbicide tolerance. In 1997, corn resistant to glufosinate, another broad-spectrum, non-selective herbicide was released as Liberty Link corn by AgrEvo, now Bayer (Singh, Batish, & Kohli, 2006). Glufosinate acts on the enzyme glutamine synthase, an important enzyme in nitrogen metabolism, but like glyphosate, it has very low human toxicity (Kataoka, Ryu, Sakiyama, & Makita, 1996). The era of genetically modified crops was just beginning.

The introduction of hybrids with plant-incorporated protectants was a significant development in that plants now produced insecticidal proteins. This provided better protection and eliminated the cost, both financial and ecological, of insecticide applications. The financial cost was not eliminated, but was transferred to the seed. This was accomplished by using the gene for an insecticidal protein produced by the soil bacterium *Bacillus thuringiensis* Berliner (Bt). The Bt protein is toxic to insect pests such as the European corn borer, *Ostrinia nubilalis* Hübner, but not to humans (Barrows, Sexton, & Zilberman, 2014). It is also relatively benign in the environment and eliminated the need for numerous chemical applications. Bt proteins had been used for insect control for nearly a century. Now the plants could produce the protein. The first Bt traits used were for control of the European corn borer, a serious pest of corn, especially in the US Corn Belt.

In 1996 Mycogen Seeds released the first commercial Bt-corn hybrids in partnership with Ciba Seeds, now part of Syngenta (Andow, 2001). Numerous other Bt traits were characterized, transformed into corn germplasm, and commercialized. Due to their effectiveness they have been widely popular.

Roundup Ready corn received FDA approval in 1997 and commercial release in 1998. It took advantage of the same technology used in soybeans. However, the release of Roundup Ready Corn was significant in that it also provided the first stacked trait combination in corn. Not only was it glyphosate tolerant, but also had insect protection in the form of a Bt protein. Corn with a Bt trait had been released commercially the year earlier in 1997 under the brand name YieldGard® (Shelton, Zhao, & Roush, 2002). By this point it was not uncommon to have a plant with DNA introduced from another source. However, this was the first commercial release containing two separate transgenic events.

The original Bt trait introduced in 1997 stacked with glyphosate tolerance is still found in more than 85% of the Bt corn planted worldwide (Shelton, Zhao, & Roush, 2002). The durability of this trait has been impressive for a number of reasons. One reason has to do with its effectiveness at controlling European corn borer. Expression levels in the plant were achieved that resulted in toxicity to all susceptible insects. This is known as high dose toxin expression. This, coupled with an effective refuge strategy has done an exceptional job of delaying resistance and maintaining the durability of the trait (Gassmann et al., 2014).

Over time, new Bt traits were developed. Some of which were also found to control various other pests, such as the Southwestern corn borer, *Diatraea grandiosella,* Dyar, Western bean cutworm, *Striacosta albicosta*, Smith, and corn rootworm *Diabrotica* spp. (Shelton, Zhao, & Roush, 2002). Control for each has been variable, and not all are at a high dose. Now many of the traits are stacked to provide a greater range of protection. Though all were effective tools for pest control their levels of efficacy varied greatly. However, the impact they had on pest control cannot be ignored. Marra et al. (2003) found that early Bt corn provided a small, yet significant yield increase in most years. In high yielding areas such as the U.S. Corn Belt the yield increase could be substantial with significant increases in profit due to the Bt trait alone. This is one of the reasons why there was such rapid adoption of Bt technology. Increases in yield did not initially lead to increases in profitability however, especially outside of high-yielding areas.

Another significant event was the development of the Bt trait, Cry 3Bb, was developed for control of corn rootworms. Corn rootworm was more damaging than the European corn borer. Estimates of yield loss and treatments costs to producers were around $1 billion annually in the late 1990s (Payne, Fernandez-Cornejo, & Daberkow, 2003). The development of Bt traits for corn rootworm control had significant impacts for corn producers, especially with the challenges they faced in controlling rootworms.

Genetically engineered plant technology has become one of the most rapidly adopted agricultural technologies in history. By 2010, genetically engineered crops were planted on 140 million hectares in 29 different countries (Barrows, Sexton, & Zilberman, 2014). In the United States, corn with stacked Bt traits went from 1% of total acreage in 2000 to 71% in 2013. It also led to increased average yields by mitigating yield loss due to insects, and resulted in higher net returns when pest pressure is high. The yield advantage of Bt corn over conventional seed has grown over the years and continues to be more profitable when considering net returns, averaging a 2.3% increase in net returns on average with considerable net returns when pest pressure is high because of the yield stabilization it provides (Fernandez-Cornejo, Wechsler, Livingston, & Mitchell, 2014). Bt corn is slightly more profitable than conventional under normal conditions, but provides the greatest benefit when pest pressure is high. Hybrids with stacked Bt traits were especially popular among growers because of the added advantages, e.g., the decrease in insecticide use. The clear advantages of Bt hybrids to producers have been a huge part of their widespread adoption.

The advantages of glyphosate tolerant corn were clear as well. The adoption of glyphosate tolerant crops revolutionized weed management. By using a strong, broad-spectrum herbicide that controlled weeds without harming crops farmers were able to effectively control weeds. This also led to a decrease in the use of other herbicides such as the acetamides, but obviously led to an increase in glyphosate use. There were also significant yield gains; however, much of that was offset by the increased seed cost (Fernandez-Cornejo, Wechsler, Livingston, & Mitchell, 2014). Herbicide tolerant crops have become an integral part of weed management systems. Herbicide tolerant crops, when used properly, can be a very effective tool in weed management plans.

Though many new Bt traits were developed, relatively few new herbicide tolerance traits were developed. Rather, focus was placed on improving the current herbicide tolerance traits. Initially, herbicide tolerance in corn wasn't adopted as readily because it had lower levels of tolerance to glyphosate and herbicide resistant hybrids didn't provide the desired yield. As a result, companies focused on eliminating yield drag and allowing for more glyphosate applications (Owen, 2000). As these issues improved, it was more readily adopted. However, significant problems developed with herbicide resistant weeds and now there is a greater importance placed on developing new weed management strategies to delay the development of resistance (Green, 2012). With new weed management tools available it will be important to use them wisely, in a way that will maintain the durability of those technologies.

Another significant trait introduced was one that conferred drought tolerance. Drought tolerant corn was approved by the USDA in 2011 and commercialized in 2013 as DroughtGard (Waltz, 2014). This was significant because drought stress is a major cause of yield loss throughout the world, and corn is especially susceptible to water stress. The trait produces bacterial cold shock proteins (CSPs) that allow cellular machinery to remain functioning properly during periods of stress such as drought (Castiglioni et al., 2008). Another significant advantage with this trait was that it is activated in response to stress. With herbicide tolerance and Bt proteins, the gene or trait is expressed regardless, which can result in a yield drag. However, in this case, the proteins were expressed only when the plant was stressed, so there was no yield loss.

The transgenic era brought another restructuring in the seed business. Previously, much of the cost of production was in the management and purchasing chemicals was a significant cost of production. Most companies made their money selling these inputs. During the transgenic era, the cost of pesticides went down, but the cost of seeds went up significantly. There is a cost associated with the development of new technology and the new technology was now going into the seeds. The result was a merging of chemical and seed businesses as large chemical companies bought up the seed businesses to get the best genetics to go with new traits (Mittra, Tait, & Wield, 2011). As agricultural companies adjusted to this disruption, there has been a consolidation of companies and capital. As the cost of inputs get higher, the cost of providing inputs that provide a benefit increase as well. This requires large pools of capital provided by larger companies.

It is also important to note that not all of the advances in maize yields have been strictly a result of genetics. Duvick (2005) found that about 50% of yield increases since the introduction of commercial hybrids in the 1920s to today have been the result of breeding while the other half have come from improved agronomic practices. Moving forward it will be important to focus on improving agronomic practices as well as genetics.

One aspect of the transgenic era and the advances made is that none of these genetically modified crops had a trait for increased yield potential. All of the increases in yield associated with genetically modified corn come in the form of yield protection or stability, not actual increases in yield potential. Current traits that have been incorporated protect or stabilize yield rather than increase the potential for it. The same has been true of traditional breeding methods as well. They have done an excellent job of protecting or stabilizing yield, but yield potential has not increased since the 1970s (Duvick & Cassman, 1999). This is significant because this eventually puts a limit on the amount of yield increase possible (Edgerton, 2009). Future traits will need to look at enhancing yield potential rather than just protecting it.

Conclusion

Maize is an important crop, historically as well as today. From its initial domestication in the Balsas River Valley of Mexico to its role in the world economy, maize has had a storied past. Many historical societies have been built on maize production. European explorers came to the new world looking for treasure, but in maize they found something that would become much more important. Today, it is the most important crop in terms of volume produced in the world.

The unique characteristics of maize have made it a valued crop throughout history. As ancient agriculturalists harnessed its genetic variation to adapt new varieties of maize to new environments they were laying the groundwork for the agricultural revolutions in maize of the 20th Century. Northern Flints provided environmental adaptability that allowed farmers to move corn production north and west and Southern Dent corn provided increased yield. These two types came together to form the genetic backbone of modern corn hybrids.

Early in the 1900s, double cross hybrids were developed that started an upward trajectory of yields that has not stopped. This coincided with a transition to a high-input agricultural system that leveraged the power of agronomic practices such as mechanized farm machinery, nitrogen fertilizers, and more effective herbicides. These in turn helped make possible single cross hybrids and single cross hybrids have increased yields that much more.

The transgenic era has increased the transition to high input corn production. New sources of genetic variation have been introduced to maize germplasm, further increasing its adaptedness and yields. Changes in maize production have been significant throughout its history, but especially in the past 100 years. However, it just may be that the next 100 years could see even greater changes.

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CHAPTER 2: Corn Rootworm – A History of Adaptation

The western corn rootworm *Diabrotica virgifera virgifera* LeConte (Coleoptera: Chrysomelidae) is considered the most important pest of maize (*Zea mays* L.) in United States corn production, particularly in the U.S. Corn Belt (Spencer, Hibbard, Moeser, & Onstad, 2009). Due to its impact on corn production it is often referred to as a "billion-dollar bug." However, estimates of the economic impact of the western corn rootworm exceed $2 billion annually in the United States alone (Frank, Zukoff, Barry, Higdon, & Hibbard, 2013). Western corn rootworm traditionally posed problems to the maize producers and will continue to do so in the future. To successfully manage western corn rootworms it is essential to understand western corn rootworm biology as well as its history.

Biology

The western corn rootworm is a univoltine pest of maize. An adult female corn rootworm will oviposit between 200 and 1,000 eggs in the soil. In the fall, corn rootworm egg densities can range from 0 eggs per acre up to 50 million or more eggs per acre. Most rootworm egg populations in maize producing areas range from 10 million to 20 million eggs per acre (Gray & Luckmann, 1994). This can be highly variable over time and space due to environment and management. Hibbard et al. (2004) found that in field conditions only 5-10% of eggs laid in the fall hatch the following spring. Eggs that survive until spring hatch in response to favorable environmental conditions, based largely on temperature.

Once the larvae emerge, neonate larvae are attracted to carbon dioxide, but not corn seedling volatiles. However, by the time they are second instar larvae, corn seedling volatiles serve as a stronger attractant than carbon dioxide (Hibbard & Bjostad, 1988). Gustin and Schumacker (1989) found that movement through the soil by first instar larvae is limited. They are unable to burrow, so they are limited to movement through interconnected air-filled pores in the soil. This limits movement under wet conditions as soil becomes saturated and reduces available air-filled pore spaces (Spencer, et al., 2009). Heavy spring rains and saturated soils can contribute a great deal to larval mortality.

Larvae feeding on roots, which interferes with water and nutrient uptake, compromises the structural integrity of the plant, and makes it more susceptible to lodging and pathogens (Levine & Oloumi-Sadeghi, 1991). Since larval development rates vary based on diet and soil conditions. Due to this, rootworm populations have prolonged egg hatch, and larvae will be at different life stages. Young larvae feed on fine root hairs and larger larvae invade the root core (Chiang, 1973). Western corn rootworms go through three larval stages that each last from 7 to 10 days. After the third instar the larvae will pupate in the soil.

The duration of pupation can ranges from 2 to 3 weeks (George & Hintz, 1966). Western corn rootworm pupae can be found throughout the soil, but most are in the top 5 cm of soil (Chiang, 1973). After pupation adult corn rootworms emerge from the soil and begin feeding on aboveground plant parts.

Western corn rootworms are protandrous; males will emerge approximately 5 days before females. This is because male larval development of males is faster than that of females (Branson, 1987). There is still a significant overlap in the emergence period of males and females. Quiring and Timmins (1990) found a 97.8% overlap in emergence period between the two despite the difference in development. This is likely due to prolonged egg hatch and varied developmental rates as well. After males emerge they still require an additional 5-7 days of post emergence development before they reach sexual maturity, or respond to female sex pheromones (Guss, 1976). The female, on the other hand, is sexually mature upon emergence (Hammack, 1995) and they will often mate within hours of emergence (Ball, 1957).

Western corn rootworm mating behavior is influenced by numerous factors. Ball and Chaudhury (1973) were the first to provide evidence of a female sex-pheromone when they demonstrated elevated levels of males attracted to sticky traps baited with sex pheromones extracted from females. Guss et al. (1982) later discovered the sex pheromone to be 8R-methyl-2Rdecenyl-propanoate, which is also the sex pheromone of the northern corn rootworm, *D. barberi* Smith and Lawrence and the southern corn rootworm *D. undecimpunctata howardi* Barber (Spencer, et al., 2009). Due to this, it is possible to see hybrid pairings in the field. However, other factors such as the viability of eggs produced from these pairings limit the amount of hybrid organisms in the field (Krysan & Guss, 1978). The rickettsial bacterium *Wolbachia* is thought to play a role in keeping some of these species isolated as well. *Wolbachia* causes cytoplasmic incompatibility, preventing hybridization (Kim & Sappington, 2005). Western corn rootworms are *Wolbachia* infected while southern corn rootworms are *Wolbachia* free (Giordano, Jackson, & Robertson, 1997). The role of *Wolbachia* in northern corn rootworms is not clearly understood.

After females emerge they will exhibit a calling posture. Hammack (1995) described this calling posture as females having the tip of the abdomen everted to expose the dorsal and ventral intersegmental membranes between the seventh and eight abdominal segments. Females in this pose were much more likely to be sexually receptive to males. The exposed abdominal area was also identified as the site where epithelial cells secreted the sex pheromone described earlier (Lew & Ball, 1978). Almost all females exhibit calling behavior within two days after emergence, though the calling behavior is not necessary for mating (Spencer, et al., 2009). Females do not need to be calling to be approached by a male, as they will usually mate shortly after emerging.

Western corn rootworm males will attempt to jump onto the back of the female, grabbing her elytra with the first two pairs of legs. Unreceptive females will attempt to dislodge the male by kicking him or simply walking away. The female may also simply turn the tip of her abdomen downward to discourage the male (Lew & Ball, 1979). If the male is not rejected, courtship behavior will continue for up to an hour. It usually takes 3-4 hours before the male is able to completely deposit the spermatophore (Spencer, et al., 2009).

The deposition of the spermatophore involves transferring 5-9% of the male's mass; males can mate twice a day (Quiring & Timmins, 1990). After mating, males will often remain on the female in a guarding position until he is dislodged. One mating is sufficient to support a high rate of egg production for 4 to 5 weeks after mating (Sherwood & Levine, 1993). Females will generally mate only once, though in rare cases a second, later, mating can prolong the egg-laying period.

Females will go through a 13-day preovipositional period during which time the female continues to feed and the eggs develop. (Bayar, Komaromi, & Kiss, 2002). Females can lay between 200 and 1,000 eggs. The percentage of of the eggs that hatch decreases from approximately 80% at first to 30% by the eighth week (Fisher, Sutter, & Branson, 1991). Branson and Krysan (1981) found that females lay eggs wherever they are as long as conditions are suitable and since adults feed on maize most oviposition occurs in maize fields. Maize silks are a preferred source of food, but maize leaves and pollen are food sources as well. After silks brown, many adult rootworms will leave the field in search of younger corn or alternative food sources (Spencer, et al., 2009). Studies in Europe have indicated that flowering weeds outside of the field become a more attractive food source late in the season (Moeser & Vidal, 2004).

Western corn rootworm females do not dig or burrow in the soil, but rely on natural openings into the soil such as drought cracks, cracks around cornstalks and earworm burrows to find suitable soil moisture content to lay eggs (Kirk, 1979). Most eggs are found in the top 10 cm of the soil, though it can vary depending on soil type and environmental conditions (Pierce & Gray, 2006). In rare cases, after oviposition stops, a second mating can occur, but they often remain in a nonovipositing state until they are die in the fall (Branson, Guss, & Jackson, 1977). The eggs overwinter in the soil and hatch in the spring when conditions become favorable again.

A History of Range Expansion

Western corn rootworm origins can be traced back nearly 5,000 years to Central America, Guatemala specifically, where they were pests of maize (Melhus, Painter, & Smith, 1954). Maize was commonly grown in conjunction with other grasses (*Setaria* spp.) and sometimes with a leguminous plant (family *Fabaceae*) and a cucurbit (*Cucurbita* spp.). With the introduction of the European system of large tracts of monoculture, the western corn rootworm likely became a more challenging pest (Smith & Lawrence, 1967). Further intensification of maize cultivation has favored the western corn rootworm and it will likely provide even greater challenges in the future.

The western corn rootworm was first collected in 1867 (LeConte, 1868) while surveying for a railroad extension from Kansas to Fort Craig. The line would have gone into Colorado and then in a South-Southwest direction towards Fort Craig. It was later identified as a pest near Fort Collins, Colorado in 1909 (Gillette, 1912). There it was identified as a pest of sweet corn and originally referred to as the Colorado corn rootworm. Native grasses were likely able to support low populations of the beetle when maize was not cultivated (Clark & Hibbard, 2004). By 1929 evidence of root injury from the western corn rootworm was found in southwestern Nebraska. By the mid 1940's corn rootworm populations produced severe root damage further east in central Nebraska (Tate & Bare, 1946). The western corn rootworm was slowly moving eastward, but the landscape was about to make a drastic change.

The period after World War II was characterized by a significant shift in agriculture. With new technology available such as inorganic fertilizers, irrigation, machines, pesticides, etc., there was a shift to a high input approach to maize cultivation (Egli, 2008). This allowed for not only more maize production, but perhaps more importantly, non-rotated maize. Increased irrigation and increased nitrogen fertilizer use allowed for more land to come under maize cultivation and more frequently. This was especially true in Nebraska. The increase in maize cultivation in the western plains favored an increase in western corn rootworm populations and led to a significant range expansion (Gray, Sappington, Miller, Moeser, & Bohn, 2009).

This period after World War II was marked by rapid range expansion of the western corn rootworm. The new habitat gained during this range expansion was significantly larger that its original range in Colorado. By 1970, it had moved as far west as Indiana (Chiang, 1973). By the 1980s it had even expanded to Virginia as well (Youngman & Day, 1993). The western corn rootworm had quickly moved across North America, seemingly stopped only by the Atlantic Ocean.

However, the Atlantic did not prove to be an insurmountable hurdle for the western corn rootworm. In 1992, a population of western corn rootworms was found in Serbia, (Yugolsavia at that time), near the Belgrade airport (Baca, 1994). The population was likely a result of corn rootworm adults being accidentally transported by commercial aircraft flying in from an area of large maize production (Gray, et al., 2009). Genetic analysis of European populations, Miller et al. (2005) showed that since then, the western corn rootworm had been introduced into Europe at least three separate times with future introductions highly possible. As of 2007, the western corn rootworm has been reported in 20 separate European countries, with the most severe problems in the south, especially in the countries surrounding Belgrade where it was first detected (Kiss et al., 2005). As western corn rootworm spreads through Europe it will be important to monitor its spread as it has potential to severely impact maize growing regions throughout Europe and also maize growing areas of Asia and Africa.

History of Resistance

The western corn rootworm has shown a remarkable ability to adapt, to control measures of producers. As maize production increased after World War II, and western corn rootworm populations increased, newly developed insecticides were used to control corn rootworms. A group of organochlorine insecticides were the first synthetic insecticide class to be used for larval control of corn rootworm in the late 1940s (Hill, Hixson, & Muma, 1948). They were broadcast applied just prior to planting or at first cultivation (Mayo & Peters, 1978). The primary chemical insecticides recommended for control of corn rootworms were: benzene hexachloride or lindane (Muma, Hill, & Hixson, 1949) aldrin, chlordane (Ball & Hill, 1953), and heptachlor (Ball & Roselle, 1954). By about 1954 the use of these insecticides for larval control was common practice in Nebraska (Metcalf, 1986). However, control failures for these insecticides were first noted in 1959 (Roselle, Anderson, Simpson, & Webb, 1959). High levels of resistance were confirmed in central and eastern Nebraska by 1963 (Ball & Weekman, 1963).

Western corn rootworms resistant to organochlorine insecticides spread rapidly as the western corn rootworm expanded its range during this same time period. By 1980, resistant western corn rootworms could be found throughout the U.S. Corn Belt (Metcalf, 1986). High levels of chlorinated hydrocarbon resistance have persisted in western corn rootworm populations despite the fact that these insecticides have not been used since the 1970s. Also, resistance has been found in western corn rootworm populations never exposed to chlorinated hydrocarbon insecticides at all (Siegfried & Mullin, 1989). It is generally expected that resistance would come with a fitness cost, and in the absence of selection pressure it would slowly be lost over time. However, the persistence of this resistance indicates that the fitness advantages associated with resistance in this case were very minor (Parimi, Meinke, French, Chandler, & Siegfried, 2006).

After development of resistance to organochlorines, a new approach was necessary. One control tactic was to reduce the amount of eggs laid by controlling adults through aerial applications of an organophosphate or carbamate insecticide (Pruess, Witkowski, & Raun, 1974). This was adopted in areas of the Platte River Valley of south central Nebraska where resistance to organochlorine insecticides first developed. The most commonly used insecticide was an encapsulated methyl-parathion sold as Penncap-M. This organophosphate insecticide was preferred because of its low price and longer residual activity compared to other available options (Meinke, Siegfried, Wright, & Chandler, 1998). Another popular insecticide used for adult control was the carbamate, Carbaryl.

Soil applications of organophosphates and carbamates at planting time or the first cultivation also became popular during this period (Mayo & Peters, 1978). The carbamate and organophosphate insecticides were heavily relied in the 1960 and the four following decades for both larval and adult control of western corn rootworm (Scharf, Meinke, Siegfried, Wright, & Chandler, 1999). Instead of a broadcast application, as was the case with the organochlorines, there was also a shift to applying insecticides in-furrow or with T-band applications (Meinke, et al., 1998). This change had significant implications on the development of resistance.

The practice of band applications essentially created an untreated refuge, although it was not intentional. Outside the treated area susceptible individuals could survive and maintain the genes for susceptibility in the population. A study by Gray, Felsot, Steffey, & Levine, (1992) however, found that though soil insecticides often provide root protection under certain situations, when judged based on reducing rootworm populations their usefulness as a management tool was questionable. Corn rootworms experience population-dependent mortality. This means that at high populations, many of the young larvae will die due to intraspecific competition. With soil-applied insecticides the populations were lowered enough initially that there was reduced larval mortality. This coupled with the root protection provided by the insecticide allowed for a greater proliferation of roots and greater food supplies for corn rootworm larvae. Often fields treated with soil-applied insecticides could produce as many or, commonly, more corn rootworm adults.

These new management strategies of banded applications, coupled with the fact that the organophosphate and carbamate insecticides are less persistent, led to lower levels of selection pressure. This is likely why these insecticides remained effective for quite some time (Parimi, et al., 2006). However, by 1996, reports of control failures for adult corn rootworms were reported (Wright, Meinke, & Siegfried, 1996) and resistance confirmed for both carbaryl and methyl parathion (Meinke, et al., 1998). This was significant because at the time a new bait formulation known as SLAM was being used as part of an areawide management program for western corn rootworm. SLAM used adult arrestants, feeding stimulants such as cucurbitacins, and carbaryl as the toxin (Siegfried et al., 2004). An areawide management program that relied on an insecticide to which corn rootworms had developed resistance would not work very well, and would likely spread resistance.

Interestingly, resistance to carbaryl and methyl-parathion developed in the same area where resistance to the organochlorine insecticides developed (Ball & Weekman, 1963; Meinke, et al., 1998). Control failures and the subsequent confirmation of resistance were found in York and Phelps counties of south-central Nebraska. York county, and especially Phelps county, Nebraska had a long history of continuous corn and had been using been using adult management strategies since the development of organochlorine resistance and subsequent control failures in the early 1960s (Meinke, et al., 1998).

Crop rotation and soil insecticides largely replaced adult management after the development of resistance to methyl parathion in south central Nebraska. This was largely a local phenomenon; most of the U.S. Corn Belt did not use adult control. Since then, other soil insecticides, e.g. pyrethroids as well as new chemistries, are much more commonly used (Parimi, et al., 2006). More recently, insecticidal seed treatments have increased in use for corn rootworm control.

In 2003, a significant new tool was made available to producers with the introduction of maize expressing the Cry3Bb1 protein. Cry3Bb1 maize expresses a protein derived from the bacterium *Bacillus thuringiensis* (Bt) that is toxic to corn rootworms. The development of Bt traits for corn rootworm control was significant because it could reduce reliance on insecticide sprays (Sanahuja, Banakar, Twyman, Capell, & Christou, 2011).

It also reduced applicator exposure and environmental toxicity. Corn rootworm control through the use of Bt hybrids provided a valuable new tool for producers trying to control western corn rootworm, and this technology was widely adopted.

Other Bt proteins for western corn rootworm control were developed as well. Cry34/35Ab1 was registered for commercial sale in 2005 and mCry3A in 2006. In 2013, eCry3A was also released pyramided with mCry3A (Frank, et al., 2013). Despite other Bt proteins being release, Cry3Bb1 has been used disproportionately more than the others (Tabashnik & Gould, 2012), increasing selective pressure.

Bt hybrids that expressed the insecticidal Bt proteins were widely adopted throughout the U.S. Cornbelt. Maize expressing the Cry3Bb1 protein went from being planted on 0.2 million ha in 2003 to 12 million ha in 2008 (Tabashnik & Gould, 2012). The more it is used, the more selection events there are and the more likely western corn rootworms are to develop resistance. These were not high dose events, a high dose event is defined as one that has a level of toxicity 25 times the toxin concentration needed to kill susceptible larvae (Horowitz & Ishaaya, 2013). With none of the corn rootworm traits being high dose the potential for resistance to develop was recognized from the start (Siegfried, Vaughn, & Spencer, 2005).

Unfortunately, their concerns were not unfounded. In 2009, field-evolved resistance to Cry3Bb1 maize was found in Iowa (Gassmann, Petzold-

Maxwell, Keweshan, & Dunbar, 2011). Cry3Bb1 resistant rootworms were found in maize fields where Cry3Bb1 maize had been grown for at least 3 consecutive years. This was the first example of field-evolved resistance to a corn rootworm Bt trait. Cry3Bb1 was released in 2003, and resistance developed in the space of only 6 years. The fact that resistance developed in a situation of continuous corn, and particularly continuous Cry3Bb1 maize, underlies the role of cultural practices and the need to adopt multiple tactics for successful management of western corn rootworm.

In 2011, field resistance to Cry3Bb1 had persisted, however, Gassmann et al., (2014) demonstrated that not only were corn rootworms resistant to the Cry3Bb1 protein, but Cry3Bb1 resistance conferred cross-resistance to the mCry3A protein as well. As resistant populations spread and/or develop the efficacy of Bt proteins for rootworm control will be compromised even more. In an effort to delay resistance, many have advocated for the pyramiding of traits, or using more than one distinct mode of action. This is based on modeling that shows that resistance development to pyramided Bt maize can be delayed considerably (Carroll, Head, Caprio, & Stork, 2013). However, if high levels of resistance to one mode of action are already present, then a pyramid is the same as using a single mode of action. Thus, selection will occur for resistance to both modes of action.

Rotation Resistance

Western corn rootworms have not only shown a marked ability to adapt to chemical control measures, but they have adapted to cultural control measures as well. This is exemplified by the rotation-resistant western corn rootworms. Rotation-resistant western corn rootworms were originally found in east-central Illinois, in Ford County (Levine & Oloumi-Sadeghi, 1996). Ford County was an area where approximately 89% of the land is agricultural and 98% of the agricultural land is in a corn-soybean rotation (Onstad et al., 1999). Rotation-resistant western corn rootworm has spread from that area and it can now be found in Michigan, Indiana, Iowa, Missouri, Wisconsin and Ohio (Gray, et al., 2009).

Due to their reliance on maize as a host, western corn rootworm females exhibited a fidelity to maize when ovipositing eggs. This would be expected since their offspring rely on maize roots for food. Damage to rotated maize has traditionally been attributed to northern corn rootworm or an alternate food source such as volunteer corn or pigweeds (*Amaranthus* spp.) that attracted gravid females (Shaw, Paullus, & Luckmann, 1978). However, starting in the mid 1990s there were more and more incidences of severe corn rootworm injury to rotated maize fields due to western corn rootworm. Levine et al. (2002) found that they had become rotation resistant by loosing their maize fidelity in terms of oviposition. It wasn't that they had gained a new host, or gained fidelity to a new crop, but their ovipostional fidelity had been relaxed. Pierce and Gray (2006) found gravid females in numerous crops besides maize, such as soybean (*Glycine max*), oat (*Avena sativa*) stubble and alfalfa (*Medicago sativa*). Rotation-resistant western corn rootworm females will oviposit in all crops, not just soybeans and can be found in Illinois, Indiana, and parts of Ohio, Wisconsin, Michigan, Iowa and the province of Ontario in Canada. However, they continue to spread across the U.S. Corn Belt (Gray, et al., 2009).

The mechanisms behind this were largely unknown for some time. Since control had been obtained through a maize-soybean rotation, a trait was selected for that enabled high mobility (Mabry, Spencer, Levine, & Isard, 2004). The same study also found that females lay significantly more eggs on days when their diet consists entirely of soybean. Curzi, Zavala, Spencer, & Seufferheld (2012) later found that rotation-resistant western corn rootworms had elevated levels of proteases that allowed them to tolerant plant defense proteins and feed on soybean leaves for a longer period of time. This allowed adults to remain in soybean fields longer and lay more eggs. Chu, Spencer, Curzi, Zavala, & Seufferheld, (2013) also found significant differences in the gut microbiota between rotation resistant and wild type or non-rotation-resistant western corn rootworms. Rotation-resistant corn rootworms had higher levels of bacteria that produce extra-cellular proteases and regulate host gene expression in the gut. This allows rotation-resistant corn rootworms to survive longer on non-maize hosts. They found that antibiotics could reduce tolerance to soybean feeding in rotation-resistant individuals to the level seen in wild type individuals. The mechanisms behind rotation resistance are being elucidated and will shed further light on the biology and effective control options for western corn rootworm.

Conclusion

Historically, the western corn rootworm has shown a remarkable ability to adapt, from the highlands of Guatemala to the modern day U.S. Corn Belt and even into Europe. Whether adapting to new environments as maize spread to new environments, or to control tactics, the western corn rootworm has proven highly capable of adapting to new environments. This ability has served it well as it has become the most important pest of maize. Despite our efforts it remains a significant pest to this day.

The western corn rootworm was first described in Colorado in 1867, and identified as a pest in 1909. By 1929, it was found in Nebraska. However, with the expansion and intensification of maize cultivation that came after World War II, the conditions were perfect for the western corn rootworm to expand its range. By the 1990s it had moved all the way to the Atlantic. It had crossed the Atlantic by 1992 and it continues to expand its range in Europe today.

As the western corn rootworm spread through the U.S. Corn Belt, new tactics were used for control. In the late 1940s organochlorine insecticides were used as a broadcast soil insecticide at planting or the first cultivation. By 1959, resistance had already developed to these insecticides in some populations and quickly spread. Organophosphate and carbamate insecticides were then used for control. Besides an insecticide with a new mode of action, they also adopted new management techniques that reduced selective pressure. The soil insecticide was applied either in-furrow or T-banded. Since not all of the soil was treated this method allowed a number of susceptible individuals to survive and reproduce. It was an inadvertent refuge that helped maintain the durability of the insecticides. However, another practice adopted around that time was to use aerial applications for adult control. This provided more selection pressure on the population and by 1996 populations of western corn rootworm were found to be resistant to carbamates and organophosphates.

New modes of action for control of western corn rootworm were needed. Pyrethroids and the phenylpyrazole fipronil were added as soil insecticides. However, the most significant development came in 2003 when maize plants expressing the Cry3Bb1 protein, an insect toxin specific to corn rootworms, were released commercially. This too did not last, as by 2009, there were confirmed cases of resistance to the Cry3Bb1 protein.

Western corn rootworms have even adapted to crop rotation by loosening their ovipositional fideltity to maize. Crop rotation was, and still is, in most cases, the most effective option for managing western corn rootworm. This just further demonstrates the remarkable ability of western corn rootworms to adapt.

The western corn rootworm has an incredible ability to adapt. Many factors play into this ability. However, in all cases, the development of resistance was also associated with management tactics such as continuous corn and repeated use of the same mode of action. Management tactics have helped provide conditions conducive to the development of resistance. In most cases, resistance could have been delayed significantly with better management.

Because of the ability of western corn rootworm to adapt to control measures, it is essential to realize that with rootworms, it is not *if* resistance will develop, but *when*. Many control measures are no longer effective due to overreliance on single measures. Moving forward it will be important to remember the lessons of the past and utilize the management tools available with a long-term approach that maintains the durability of those tools and allows for effective management well into the future.

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Chapter 3 – Looking Forward: Current and Future Challenges

The benefits of agriculture revolutionized societies throughout history and continue to do so today. It is estimated that the hunter-gather lifestyle supported about 4 million people globally (Cohen, 1995). The current world population is now over 7 billion and continues to grow. Improvements in agriculture played an integral role in this growth in numerous different ways. As discussed in the first chapter, maize yields increased significantly; improving from 24.2 bushels per acre the 1930s (Troyer, 2006) to 148 bushels per acre in 2005 (USDA-NASS, 2006). Global average wheat yields increased 250% in the latter half of the 20th century (Calderini & Slafer, 1998) despite remaining stagnant for the first half of the century (Slafer, Satorre, & Andrade, 1993). Rice yields in the past century have also experienced a 2.5-fold increase (Evans, 1993).

Yield increases over this time period have resulted from modification of the plant itself, through plant breeding, and modifying the plant environment through improvements in crop management (Egli, 2008). Improvements in plant genetics and crop management are often required in conjunction to achieve significant yield increases (Duvick & Cassman, 1999).

Despite these gains, there is a rising demand for crop production. This demand stems from three key forces: rising population, increasing meat and dairy consumption from portions of the population with a higher socioeconomic status, and increased reliance on biofuel (Foley et al., 2011).

By 2050, global crop production may need to increase by 60-100% in order to meet these needs (Tilman, Balzer, Hill, & Befort, 2011). These increases will come at a cost. Increased agricultural production that require increasing productivity on the currently used land or converting more land to agricultural land. Of the two, increasing agricultural productivity is the preferable option (Edgerton, 2009). It avoids excess greenhouse gas emissions and large scale disruptions that happen when new land is brought under cultivation.

In addition, increases in agricultural productivity provide an added benefit to producers, especially in developing countries as small-scale farmers constitute the vast majority of the poor and undernourished. (Pingali, 2012). Increased agricultural productivity has the potential to meet the needs of a changing world as well as benefit those who need it most. Increases in agricultural productivity will be essential for global stability of political and social systems (Tilman, Cassman, Matson, Naylor, & Polasky, 2002).

Agricultural intensification often brings with it numerous detrimental environmental impacts that often go unmeasured. Environmental impacts often do not directly influence producers' choices about production methods (Tilman et al, 2002). It will be important to maximize the benefits while limiting the costs of agricultural intensification. Producing more at the expense of the environment and losing ecosystem services will not be a long-term solution; rather it will be trading one set of challenges for another, and likely, more difficult set of challenges. Foley et al., (2011) expressed concern that current agricultural practices may be trading short-term increases in food production for long-term losses in ecosystem services. Many of those services are important to agriculture as well. Both agricultural production and ecosystem services are essential for life, as well as quality of life. Balancing the needs of both will be essential.

The past century has been characterized by unprecedented yield increases among many agricultural crops throughout the world. The amount of growth has been astounding in many cases. Wheat, rice and maize account for 60% of human food (Tilman et al, 2002). However, several studies indicate that yields may no longer be increasing in different regions of the globe (Pingali, 2012). Potential plateaus in yield have been noted for wheat (Calderini & Slafer, 1998), rice (Cassman, Dobermann, Walters, & Yang, 2003), and soybeans (Nafziger, 2004). A recent study found that yield increases continue in many areas, but in 24-39% of maize, rice, wheat and soybean producing areas throughout the world, yields are no longer improving (Ray, Ramankutty, Mueller, West, & Foley, 2012). This does not bode well for attempts to double production. One study found average yield improvements for maize, wheat, rice and soybean production to have growth rates of between 0.9 and 1.6 percent per year. This is well below the estimated 2.4% growth rate required to double production (Ray, Mueller, West, & Foley, 2013). They also found that many of the highest producing nations were experiencing the lowest growth rates for many crops as well. Thus, the current and future challenges are great.

Water-usage

Worldwide, agriculture accounts for 70% of water consumption (Pimentel et al., 2004). Forty percent of crop production comes from irrigated land. However, this land only accounts for 16% of the total land that is used for agricultural purposes (Postel, Daily, & Ehrlich, 1996). Irrigated land is often highly productive and provides a substantial proportion of yield, and it accounted for a substantial portion of increased yields obtained during the Green Revolution (Tilman, et al., 2002). Water used for agriculture is essential for maintaining an adequate food supply and providing food security.

In the United States, 65% of irrigation water is pumped from groundwater (Pimentel et al., 2004) and an estimated 20% of the water comes from aquifers that are being pumped faster than they are recharging. This is also a significant issue in other countries such as China, India and Bangladesh (Tilman, et al., 2002), as well as Iran and Mexico (Pimentel et al., 2004). Water is being mined in many areas faster than it is replenished. This poses a serious threat to the long-term availability of water for food production, ecosystem health and other essential needs.

Another issue of significance is that irrigation return-flows often carry more salts, nutrients, minerals and pesticides. These can then contaminate areas downstream, such as agricultural fields, natural ecosystems, or even drinking water (Tilman, et al., 2002). It is estimated that worldwide, half of all irrigated soils are negatively impacted by salinization (Hinrichsen, Robey, & Upadhyay, 1998). Groundwater can have high salt content. Adding 10 million L of irrigation water per hectare each year can result in the addition of 5 t of salt being added to the soil (Bouwer, 2002). Salinization of irrigated lands is estimated to cause the loss of 1.5 million hectares per year throughout the world, as well as $11 billion due to lost production (Wood, Sebastian, & Scherr, 2000). This can obviously depend a great deal on the quality of the water source being used for irrigation.

Soil Fertility

Soil degradation poses a serious threat to current agricultural productivity as well as future productivity. Soil degradation is a human-induced phenomenon that lowers the current and future capacity of a soil to support life (Bridges and Oldeman, 1999). It is caused by overexploitation of the soil. Worldwide, 16-40% of the land used for agricultural purposes is already light to severely degraded (Chappell & LaValle, 2009). Wood et al. (2000) reported that 40% of global cropland is experiencing some type of soil degradation. Bridges and Olderman (1999) reported that 1,965 million hectares of vegetated land have already undergone some type of human-induced soil degradation.

Soil degradation can come in the form of water erosion, wind erosion, chemical degradation, or physical degradation (Olderman, 1992). Water erosion is the loss of topsoil displaced by water and occurs almost everywhere. Wind erosion is the displacement of soil by wind. This is almost always associated with a decrease in surface vegetative cover of the soil (Wolfe & Nickling, 1993). Chemical degradation is a loss of nutrients and/or organic matter, salinization, acidification or pollution of the soils. All of these can be important in agricultural systems. Physical degradation occurs from compaction, crusting, sealing, waterlogging and subsidence of organic soils. These processes decrease the current or future capacity of the soil to support life (Bridges and Oldeman, 1999).

High input agricultural systems rely on fertilizer inputs to maintain or increase yields. The amount of nitrogen fertilizer used increased sevenfold between 1960 and 1995 in the United States, and it will likely increase another 3-fold by 2050 (Tilman et al., 2001). However, only 30-50% of nitrogen fertilizer applied to the soil is actually taken up by crops (Smil, 1999). Phosphorus use in that same time period (1960-1995) increased 3.5-fold (Tilman et al., 2001); only about 45% of the phosphorus applied as a chemical fertilizer is taken up by crops (Smil, 2000). This is an inefficient process that can lead to resource depletion as well as environmental contamination if not managed properly.

The overexploitation of soils is often linked to poverty, ignorance and an inability to adopt a sustainable system of agriculture. At the heart of it, this is a social problem since most would not intentionally limit their own ability to survive. It is driven by a number of social factors, such as the increased desire for better living conditions, a higher standard of living, or simply a struggle to meet basic survival needs (Olderman, 1992). This happens in all areas of the world, but it is especially troublesome in developing countries. It can often be compensated for with agronomic practices, such as fertilization, irrigation and pest control; however all of these require inputs, driving up production costs (Naylor, 1996).

Pest and Disease Control Issues

As agricultural systems have become more intensive they have also created conditions that are highly favorable to different pests. As plant populations increase, a proportional increase of pest and disease incidence would be expected as well (Tilman, et al., 2002). Plant breeders have done an excellent job of breeding for stress resistance. The goal of most breeding programs, especially in maize breeding, is to increase yields and provide greater yield stability (Cassman, et al., 2003). This approach develops hybrids that are resistant to the biotic and abiotic stresses encountered in the field and adapted to high input management tactics. For the current level of intensification, most major breeding programs have been very effective at providing resistance to biotic and abiotic stresses. However, many challenges still remain, especially if intensification is to increase.

Despite the success of most breeding efforts, there have still been substantial pest issues. This is also a result of higher inputs. The amount of pesticides used worldwide from 1960 to 2003 increased 15-20 fold (Oerke, 2006). Increases in fertilizer use, pesticide use, and plant breeding programs have been the major drivers in yield increase during the past century. Even today, 10% of global food production is lost to plant disease (Strange & Scott, 2005). The estimated global average loss in yield in maize due to weeds is 10%, though losses are greatly reduced under intensive production systems used in the United States. This doesn't account for the yield that is protected due to weed management practices. This is estimated at about 33% of attainable yield (Oerke & Dehne, 2004). The average global yield loss in maize due to insect pests is estimated to be around 10% (Oerke, 2006). It is reported that a minimum of 10% of cereals are lost after harvest due to pests and pathogens (Boxall, Brice, Taylor, & Bancroft R.D., 2008). However, global averages do not tell the whole story. Variation in yield loss is great depending on the local environmental conditions, pests, cultural practices, resources (technology, information, training, etc.) available as well as the socioeconomic conditions of the farmers (Alexandratos, 1999). All of these factors influence the severity of yield losses due to different plant pests.

Significant losses are still seen due to pests and diseases, but this is one area where progress has been significant. With the amount of land being used for agriculture and the level of intensification on much of that land, the pest and disease problems would be expected to be worse. This has been due in large part to breeding for tolerance to these stresses (Cassman, et al., 2003) and the extensive use of pesticides (Oerke, 2006). However, this comes at a cost. With the focus on yield stability, or tolerance to stress, yield potential has largely been overlooked (Tilman, et al., 2002). Increased pesticide use has had significant environmental and public health consequences as well. These consequences are especially seen in developing countries where farmers often have a lack of knowledge and training on proper use and personal protection necessary when applying pesticides (Oerke & Dehne, 2004). In some areas, the excessive use of pesticides has led to increased pest outbreaks and yield losses due to the destruction of natural biological control agents, secondary pests and pesticide resistance. Though yield has been protected, the absolute value of crop losses and overall proportion of crop losses has increased despite the increased use of pesticides (Oerke, 2006). Much of this is due to not adopting integrated pest management practices (IPM) and the control failures associated with improper use of the pesticides.

Pesticide resistance is a growing concern in agriculture. As discussed in the previous chapter, issues of resistance can have significant consequences for producers and the options available for controlling pests. When corn rootworm beetles became resistant to encapsulated methyl-parathion (Penncap-M), producers lost a valuable tool for controlling western corn rootworms and most had no option but to use rotation (Parimi, Meinke, French, Chandler, & Siegfried, 2006). Rotation is a very effective control option, but that too can lead to resistance if not coupled with other control tactics. This was the case with the rotation resistant western corn rootworm that developed in an area where 98% of the agricultural land was on a corn-soybean rotation (Gray, Sappington, Miller, Moeser, & Bohn, 2009). Pesticides are best used as part of an effective IPM program.

Pesticide resistance is an ongoing problem with significant immediate, as well as long-term consequences. According to the International Survey of Herbicide Resistant Weeds (2016) there are currently 466 unique cases of herbicide resistant weeds to 22 of the 25 known herbicide sites of action. This includes 249 different species resistant to 160 different herbicides. Herbicide resistance has also been reported in 86 crops in 66 countries. According the Insecticide Resistance Action Committee (IRAC), commonly referred to as IRAC, more than 500 arthropod pests worldwide have developed resistance to insecticides (IRAC, 2007). According to the Fungicide Resistance Action Committee (FRAC) there are around 300 different cases of known plant pathogenic organisms resistant to disease control agents FRAC, 2013). Adequately addressing the issues of pesticide resistance will be crucial to increasing agricultural production.

Yield Potentials

One issue with increasing yields is that of yield potential. This is the yield of a crop cultivar when grown in environments to which it is adapted, with nutrients and water nonlimiting and pests and diseases effectively controlled (Evans, 1993). Yield potential is determined by incident solar radiation, temperature and plant density (Cassman et al., 2003). Most producers do not reach yield potential, as it is not economical. Typically, yield stagnation occurs when actual yield is about 80% of the yield potential (Cassman, 1999). The difference between the yield potential and actual yield is called the yield gap. It is important to maintain an exploitable yield gap, or a gap greater than the difference between 80% and 100%, because this is where yield increases can be exploited. If actual yield is already at 80% of yield potential there is no exploitable yield gap and yield stagnation occurs (Cassman et al., 2003). Maintaining an exploitable yield gap is essential if yields are to continue to increase.

Maize yields have increased steadily since the commercial introduction of double-cross hybrids in 1921. For a significant period, there were increases in maize yield potential due primarily to genetic improvement. However, since the mid 1970's, there has been little evidence of increases in yield potential for corn (Duvick & Cassman, 1999). Cassman et al., (2003) stated that average maize yields were at about 50% of potential yield. That is a significant exploitable yield gap. They estimate that it is enough to sustain yield growth for the next 20 to 25 years, but not beyond that. With the fast rate of genetic improvement in maize, it will become increasingly important to increase not only yield, but yield potential.

Less research on yield potential in soybeans has been done, however, Egli (2005) concluded that there is sufficient genetic variation to provide for increases in yield for the near future. As the exploitable yield gap closes in soybeans it will be increasingly important to increase yield potential in soybeans as well.

In some of the world's top rice-producing regions, yield stagnation is occurring due to shrinking exploitable yield gaps (Cassman et al., 2003). In fact the last time there was a detectable yield increase was in 1966 when the inbred rice variety IR8 was released (Peng & Khush, 2003). This presents a significant challenge in increasing rice yields in the future.

Wheat shows evidence of increasing yield potential. Global wheat production since the early 1900s has increased significantly. During the first half of the century most of the increased production came from cultivating new lands. However, since the early 1960s global wheat yields have increased noticeably due to increased productivity (Slafer & Satorre, 1999).

These increases in productivity are attributed to improved agronomic practices and genetic improvements in yield potential (Reynolds et al., 2009). Average global wheat yields increased from 1.0 t/hectare (0.446 U.S. tons per acre) in the 1960s to 2.6 t/hectare (1.186 U.S. tons per acre) in 2005. This rate of increase was 14% less than the 15-year period beforehand (Miralles & Slafer, 2007). This decrease is attributed to the fact that though the yield potential is increasing, yields are increasing faster, reducing the exploitable yield gap (Fischer, 2007). Thus current trends do not bode well for sufficient increases in wheat production.

Maintaining exploitable yield gaps will be essential to increasing yields into the future. An active effort to increase the yield potential of staple food crops will be key to doing this.

Addressing the Challenges – Moving Forward

Though the current and future challenges facing agriculture are great, so are the possibilities. The tools available to producers and researchers are great and continue to improve. Understanding the basis of past increases is fundamental to finding the best strategy to achieve higher yields in the future (Egli, 2008). Historical increases have largely been the result of improved plant genetics through breeding and/or modifying the plants environment through improved management practices. Often, both will be needed together (Duvick & Cassman, 1999). It is highly likely that future yield increases will come from those same areas. However, with a better understanding of the mechanisms that drive the process it will be possible to more effectively utilize them to our advantage.

Management practices will play a vital role in addressing many of the challenges we face. One area where management is changing significantly is precision agriculture. Precision agriculture is considered one of the top ten revolutions in agriculture (Crookston, 2006). Precision agriculture involves numerous aspects of remote sensing, crop protection, field sampling, precision planting, precision tilling, precision fertilizer placement, precision irrigation, and on-the-go yield monitoring (Sadler, Evans, Stone, & Camp, 2005). It can reduce environmental loading through reducing inputs, specifically pesticides and fertilizers that can lead to environmental contamination. It offers to improve crop productivity and farm profitability through more efficient input management. (Zhang, Wang, & Wang, 2002). Besides increasing yields, precision agriculture will play a crucial role in making agriculture more environmentally friendly, sustainable, and profitable (Bongiovanni & Lowenberg-Deboer, 2004). Precision agriculture already provides many benefits to producers, but it is still relatively young. As it is improved and developed it will continue to improve management practices.

Precision agriculture can address challenges of water use. Variable rate irrigation technology can significantly improve water-use efficiency. This allows producers to account for variation within the field and only irrigate those areas where water is needed. This allows producers to use management zones that account for variations within the field to more effectively manage the rate at which the water infiltrates the root zone (Feinerman & Voet, 2000). This leads to greater efficiency and requires less water. Sadler et al., (2005) found that variable rate irrigation could save 10-15% of the water used compared to conventional irrigation practices. It also provided the added benefit of decreased incidence of disease and even a reduced risk of leaching in some cases. Though this was an isolated study, it serves to demonstrate that the tools are available and many producers are using them effectively.

Variable rate technology (VRT) has applications in the use of pesticides and fertilizers as well. Bongiovanni and Lowenberg-Deboer (2004) demonstrated that the use of VRT in Argentina allowed N fertilizer application rates to be cut in half, and the reduced N application rates were accompanied by a modest gain in profitability. This benefited the ecosystem by reducing the amount of nitrogen lost into the ecosystem (Tilman, et al., 2002). Precision agriculture also allows for nitrogen to be delivered more directly to the plant at a time when it can be more effectively used. This increases the nitrogen use efficiency, reduces fertilizer costs and environmental impact (Shanahan, Kitchen, Raun, & Schepers, 2008).

High costs associated with precision agriculture often limit it to high input farming systems. However, it can be used at any scale and any situation as long as the producer has the proper tools (Cassman, 1999). As technology improves and costs go down, this technology could play an important role in increasing yields in developing countries.

Another area of precision agriculture that shows great promise is remote sensing. Remote sensing data have been used for crop classification and mapping (Erol & Akdeniz, 1996), crop condition (Blackmer, Schepers, & Varvel, 1994), crop forecasting and yield predictions (Tucker, Holben, Elgin, & Mcmurtrey, 1980), crop disease (Malthus & Madeira, 1993) and micronutrient deficiencies (Adams, Norvell, Philpot, & Peverly, 2000). It is also increasingly used for predicting chlorophyll content (Haboudane, Miller, Tremblay, Zarco-Tejada, & Dextraze, 2002), which is a good indicator of N levels. Remote sensing data are also being used to study the use of evapotranspiration in making water management decisions (Bastiaanssen, Molden, & Makin, 2000).

Other management practices, such as conservation tillage, can provide numerous added benefits as well. The practices prevent soil degradation from wind and water erosion (Singh, Sharratt, & Schillinger, 2012). They also reduce erosion by increasing water infiltration, leading to reduced runoff (Palm, Blanco-Canqui, DeClerck, Gatere, & Grace, 2014). Conservation tillage also has the added benefit of increasing the water holding capacity of soils (Shipitalo, Dick, & Edwards, 2000). This can be especially important in water-limiting environments. Conservation tillage practices are a valuable tool, but do not come without challenges. Increased incidences of diseases such as Gray leaf spot (*Cercospora zeae-maydis*) (Ward, Stromberg, Nowell, & Nutter, 1999) and Goss's bacterial wilt (*Clavibacter michiganensis* subsp. *nebraskensis*) (Schlund, 2015) under conservation tillage can provide a new set of challenges.

Cover-crops provide numerous benefits to the soil as well as the ecosystem. Benefits include pest suppression, improvements in soil and water quality, and greater efficiency in nutrient cycling; reducing the need for fertilizer inputs (Snapp et al., 2005). They reduce soil erosion and nitrate leaching (Creamer, Bennett, & Stinner, 1997) and improve soil quality by building soil organic matter. This enhances the yield potential of the soil by increasing the soil water holding capacity, nutrient supply capacity and aeration. These benefits to soil provide an added benefit of greater yield stability as well (Letter, Seidel, & Liebhardt, 2003). The benefits to the soil make it more resistant to extremes such as drought. This makes those soils capable of supporting higher yields under adverse conditions.

These are just a few of the agronomic practices that are being used to improve yields. Improved management practices have increased yields historically, but they have not completely closed the exploitable yield gap (Cassman, et al., 2003). Continuing improvements in existing agronomic practices and development of new ones as new technologies become available will be essential for increasing yields.

Improved plant genetics will be a key factor in increasing agricultural productivity. Egli (2008) found no evidence for yield reductions in maize due to genetic limitations in the near future. Cassman, et al., (2003) speculated that current yield potentials will suffice for 20 to 25 years before it starts to become a limitation. However, this is not the case for yield potential in other crops, e.g. rice and wheat.

Rice yield potentials have not increased since the IR8 line was released in 1966. However, hybrid rice has been developed and it has an advantage in yield potential of 9% over non-hybrid varieties (Peng & Khush, 2003). This represents an important first step in increasing yield potential in rice.

Wheat is in a similar situation: yield potential is increasing, but not at a rate sufficient to keep ahead of actual yield, thus the exploitable yield gap is shrinking (Fischer, 2007). Hybrid wheat varieties have been developed and grown in some areas and many of these hybrids have increased yield potential (Bruns & Peterson, 1997). Though they do not provide added yield stability (Morgan et al., 2004). Rice and wheat are in a situation similar to corn when all varieties were open pollinated. Many knew of the benefits of hybrid seed corn, but the technology to produce large amounts to hybrid seed was not there to make it commercially feasible (Hallauer, 2008). However, as the technology becomes available to produce wheat and rice hybrids it may become feasible to take advantage of heterosis.

Another important tool in addressing the challenge of increasing yield potential is that of the genetic techniques that are now available. The rice genome was sequenced in 2002 (Goff et al., 2002), the corn genome was sequenced in 2009 (Schnable et al., 2009), and the wheat genome was sequenced in 2012 (Brenchley et al., 2012). This information will help identify genetic variation and accelerate gene discovery. This will focus the efforts of plant breeders and speed up the process of plant modification through use of marker-assisted selection (Edgerton, 2009). Eventually, with continued improvements in technology, marker-assisted breeding can evolve into genomics-assisted breeding to become even more targeted (Varshney, Graner, & Sorrells, 2005). Improvements in molecular technology allow plant breeders to more effectively improve crops to provide both yield stability and yield potential.

Biotechnology has already played an important role in agriculture and will continue to do so well in to the future. Herbicide resistance traits allowed for improved weed control; after a producer adopted glyphosate tolerant technology they were much more likely to adopt conservation tillage practices as well, if they hadn't already (Givens et al., 2009). This illustrates how both genetic improvement and improved management practices often work together.

Insect protection traits have also been important for increasing yields in both developing countries as well as developed countries where they are used (Ruttan, 2002). However, there is disparity in their economic profitability in developing countries due to research and regulatory limitations of some nations (Raney, 2006). Ensuring access to technology, both in the form of products as well as training on how to use them, will be essential for increasing productivity in developing countries.

Biotechnology traits that provide increased tolerance to environmental stress will continue to be important. The first of these traits was commercialized as DroughtGard in 2013 (Waltz, 2014). Other traits that increase tolerance to abiotic stresses will be important as well, especially if soil degradation continues. These types of traits allow for increased yields under suboptimal conditions and can potentially decrease the reliance on inputs (Edgerton, 2009).

Other biotechnology such as RNAi technology has the potential to become a powerful tool for producers in managing pests. RNAi uses RNA molecules to inhibit gene expression; it can be very targeted to specific pests. It is being developed for control of pests such as corn rootworms and potato beetles. In addition, it is being explored as a tool for control of tospoviruses, a group of viral plant pathogens (Hoemann, 2015). No RNAi traits are on the market, but they are being actively researched and developed as tools for management.

One concern with biotechnology traits is that many have focused on yield stability, but have not increased yield potential. Biotechnology traits that increase nitrogen use efficiency, grain fill, or other physiological factors that increase yield potential will be crucial (Edgerton, 2009). Though current levels of maize yield potential are sufficient for the next 20-25 years, long-term sustainability will only be possible if yield potential is increased (Cassman, et al., 2003). Biotechnology traits could potentially provide significant increases in yield potential for many crops.

Genetic improvement of crops will be vital moving forward. Many plant-breeding programs have been very effective at increasing yields. This has been crucial to the growth in production experienced in recent history. Maize has benefitted because many commercial breeding programs have the resources available to drive breeding efforts. This is not the case for other crops such as wheat and rice (Edgerton, 2009). The lack of funding for plant breeding at public institutions could be a serious detriment to the development of useful biotechnology traits for producers of crops other than maize and soybean (Gepts & Hancock, 2006). It will be important for public and private institutions to support the continued genetic improvement of important food crops.

Integrated Pest Management represents one of the more powerful tools to successfully integrate available options to effectively manage and minimize adverse effects. IPM can be defined as “a comprehensive approach to pest control that uses combined means to reduce the status of pests to tolerable levels while maintaining a quality environment” (Pedigo & Rice, 2014). With its comprehensive approach that uses multiple options and accounts for pest ecology it provides a robust framework for effective, economic, and environmentally friendly pest management. For these reasons it is considered one of the most robust constructs to arise in the agricultural sciences during the second half of the twentieth century (Kogan, 1998). Future challenges will rely on the robust framework provided by IPM to find effective solutions that maximize benefits while minimizing costs.

The basic principles of IPM were proposed more than 50 years ago (Stern, Smith, van den Bosch, & Hagen, 1959). Despite the time it has been around and the potential for providing effective control while reducing the negative effects, widespread adoption of IPM remains elusive (Naranjo & Ellsworth, 2009). This is often attributed to the lack of sound ecological information about pests and their crop environment (Kogan, 1998). More research is needed in the areas of applied ecology and pest behavior in field situations (Way & van Emden, 2000). Issues will arise, but most can be overcome by ensuring that IPM implementation plans start with the goal of meeting the needs of the local producer in all possible respects and continuing with that goal (Wearing, 1988). Environmental conditions can vary greatly from one situation to another. The principles of IPM, if applied correctly, can account for that and provide solutions. In the future, IPM will require higher levels of integration of all aspects of agricultural systems. This will require a greater understanding of agroecosystem structure and dynamics (Kogan, 1998). The challenges of IPM are great, but the possibilities and potential are even greater.

The Solution?

Will it be possible to meet the growing needs of a dynamic and diverse planet? Though the challenges are great, they are not insurmountable. Many areas of easy yield increases exist, particularly in developing nations where yield increases are needed most. Raising maize yields in the 10 largest maize-producing countries, but with below-average yields to just the world average would result in an additional 100 million tonnes of corn (Edgerton, 2009). This accounts for just under one third of the roughly 310 million tonnes of maize production in the US in 2014 (USDA-NASS, 2015). Brazil, India and Romania still plant significant amounts of open-pollinated varieties (Edgerton, 2009). This represents a portion of the increases needed, but serves to illustrate that current yields could improve significantly without additional technology. Simple changes can provide significant results. Identifying areas where better technology is needed and aiding producers to understand and effectively implement that technology is essential.

In the end, it will be crucial to realize that even with all of the technology available and being produced; technology will not be the solution. Rather, it will provide tools necessary to address future challenges. Using the right tool for the right job will be essential. This is why IPM can be such a powerful tool. With the proper information, the right tools can be identified and used in each situation. The current paradigm of science being developed and disseminated to producers will need to be replaced with one that fosters active participation and an exchange of ideas and information between producers and researchers (Tilman et al., 2002). Real solutions will require cooperation between all parties and relationships that foster trust between groups.

Rachel Carson stated, "the aim of science is to discover and illuminate truth (Lear, 2009)." More specifically, the aim of science is to discover truth about the natural or physical world and the laws that govern their function. Technology comes from our understanding and operating within the laws that govern the natural world. Knowledge truly is power. We can fly not because we overcame the laws of the natural world, but because we understand and operate within those laws.

Failing to understand how to properly wield the power this knowledge provides this has led to numerous problems throughout history. Pesticides were a technological innovation that completely altered agriculture. However, they were used improperly in many instances and resistance developed in numerous organisms. Proper understanding of the laws that govern the natural world, and in this case agricultural ecosystems will be essential.

In addressing the challenges of the future, success will depend on operating within those laws. As our understanding of those laws improves, we are able to create more powerful technology. That will allow us to more efficiently exploit resources. For example, irrigation technology has the potential to conserve water, but if its use results in more water intensive crops grown so there is no real change in water use, it doesn't help solve the problem. The same holds true for pest management. If new technology allows for more effective control of corn rootworms, then it should be used as a tool within the framework of IPM. If used in a way that selects for resistance, such as a continuous corn with repeated use of one mode of action for control, it will not last. We are not able to operate outside of natural laws indefinitely. However, the opposite is true. Organisms such as the western corn rootworm must operate within those laws as well, but without the benefit of science to help it understand them. We have or can get the tools we need, but how we use those tools will determine our success.

Conclusion

Looking forward, the challenges of the future will be significant. Dwindling freshwater supplies could significantly limit agricultural production with pronounced effects in areas that are already unstable. Soil degradation is already diminishing the capacity to produce food for many soils. As intensification of agriculture increases, so will the potential for soil degradation.

Pest and disease issues already account for a great deal of crop loss and will likely continue to cause significant losses well into the future. As producers adapt to the challenges of diseases and pests, they too adapt; resulting in widespread resistance to control tactics. Resistance issues can severely limit control options and negate the benefits of previous technological advancements. Managing resistance will be an essential component of addressing future challenges.

Despite the historic yield gains in recent history, many crops, and especially maize still have an exploitable yield gap, though it is dwindling. Recent yield increases have come primarily through yield stabilization, or increased tolerance to biotic and abiotic stresses. This is an important component of yield, but future research into increasing yield potential to maintain an exploitable yield gap is a must. Increasing the yield potential of maize and other crops presents one of the greatest challenges.

Despite all of these challenges, we are not without hope. Just as crop yields have experienced an historic rise, so have science and technology. The challenges are greater now than at any other time in history, but the tools available are greater as well. Precision agriculture has the potential to provide greater accuracy at a rate faster than ever before. This will increase resource use efficiency for nutrients and water. It can be used to make better management decisions regarding pests and diseases as well. As the technology driving precision agriculture advances even greater tools will be available.

Agronomic practices such as conservation tillage and cover cropping provide useful tools for better managing water and making soils more productive. As they are adapted to and implemented in local environments they will be valuable tools in the hands of producers.

Continued efforts of traditional breeding coupled with molecular techniques will be crucial in providing increases in yield potential and stability. Just as hybrid varieties of maize provided significant increases in yield, hybrid varieties of other crops have the potential to do the same. Wheat and rice hybrids have been shown to have higher yields, as the technology for hybrid seed production and breeding improves significant yield gains can be realized.

Molecular techniques such as marker-assisted breeding have already helped to speed the process of plant breeding. The genomes of major crops such as rice, wheat and maize are powerful tools as well. As the genomes are better understood and sequencing capacity improves, plant breeding will not only be faster, but more focused.

Traits introduced through biotechnology have already had a significant impact on stabilizing yield. Future traits will need to continue to stabilize yield and provide for increases in yield potential through processes such as increased nitrogen use efficiency and grain fill. These types of traits will be essential in maintaining an exploitable yield gap.

Sustainable agriculture into the future will rely heavily on IPM. IPM provides the basic framework for maintaining good management practices as well as maintaining the durability of control tactics. Though there are numerous tools available, proper use of and maintaining the durability of those tools will be crucial. IPM is uniquely suited to address many of the current and future challenges. Adoption of the principles of IPM will be essential.

Science has provided and continues to provide a great deal of knowledge about the world, and this knowledge provides power. With that power comes the ability to address the various challenges of the future. Proper use of that knowledge and learning from the past, in large part, will determine if we are able to successfully address the challenges of the future.

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Chapter 4: The Culture of Corn

When attempting to solve problems it can be useful to look to the example of the corn rootworms. By attacking the root, the rootworm interferes with water and nutrient uptake, compromises the structural integrity of the plant, and makes the plant more susceptible to pathogens (Levine & Oloumi-Sadeghi, 1991). Attacking at the root of the maize weakens the plant by interfering a number of vital processes. The same is true of attacking problems in general; it is essential to attack the root of the problem. To understand how to attack at the root, you must first have a correct understanding of the root of the problem.

Maize is a commodity; it even has its own ticker symbol (C). Historically, maize cultivation was a major economic force in establishing complex societies such as the Maya (Leyden, Brenner, & Dahlin, 1998) and the Anasazi or Ancestral Pueblo in the American Southwest (El-Najjar, Ryan, Turner, & Lozoff, 1976). Economies of great societies were and are today closely linked to corn production. In 2015, the value of maize production alone was over $49 billion in the United States (USDA-NASS, 2016). States in the U.S. Corn Belt have economies very tightly linked with maize production.

Maize played an important cultural role in ancient societies. Early societies of eastern North America cultivated maize, but it was primarily a high status or ceremonial crop (Smith, 1989); the Maya had maize deities

(Estrada-Belli, 2006). Throughout the New World, maize was an important part of native mythology. Maize played an important role in the culture and the economy.

As it has in times past, maize continues to play an important cultural role today. Though, there are no maize deities are not prevalent today, the evidence of the cultural impact of maize and agriculture in general are clear. At the University of Nebraska they are Cornhuskers. The Seneca foods plant in Rochester, Minnesota has an ear of corn water tower. In 1892, the Corn Palace was built in Mitchell, South Dakota with corn murals as a way to prove to the world that South Dakota had a healthy agricultural climate (Dunham, 1914). The Corn Palace hosts 500,000 tourists from around the nation each year and a Corn Palace Festival each fall to celebrate the harvest. Throughout the country, corn mazes are an essential part of fall festivities. Just as in times past, maize is an integral part of our cultural identity.

Though maize is a commodity, it is important to realize that it is much more than a commodity. This is also evidenced by the concern when evidence that transgenic DNA had been found to be introgressed into traditional maize landraces in Mexico (Quist & Chapela, 2001). There is a cultural component to maize and agriculture in general that cannot be ignored. Dealing with current and future problems in agriculture will require attacking at the root of the problem, and that involves social and cultural factors as well.

Addressing the social and cultural components of agriculture will be essential to moving forward.

Addressing Social Factors

Looking back to the case of hybrid corn, developing the new technology was merely the first step of the process. Yields only increased after the technology was adopted and this was determined by economic considerations (Griliches, 1957). Stacking more traits or developing pyramided traits so that multiple modes of action can be used will not get at the root of the problem. At best, it will delay the consequences, but more likely it will exacerbate the problem by ignoring the root causes and neglecting to address them (Ervin & Jussaume, 2014). This is not to say that the technology will not be important or useful, but it will not be a silver bullet. Technology will be crucial, but it is not the solution.

Challenges such as herbicide resistance cannot be mitigated without addressing the human dimension of the problem (Ervin & Jussaume, 2014). The human dimension includes the social, economic, political and cultural aspects. The decision by cotton farmers in India to adopt or not adopt Bt technology was not only driven by their own experience, but by the experiences of other farmers with whom they interacted (Roy, Herring, & Geister, 2007). It is essential to recognize that human decision making is not only made by individuals, but those individuals are highly influenced by social structures and conditions (Ervin & Jussaume, 2014).

The human dimension of decision-making is heavily influenced by social capital. The four central features of social capital are: relations of trust, reciprocity and exchanges, common rules, norms and sanctions, and connectedness in networks and groups (Pretty & Ward, 2001). Social capital implies that the social structure and organization can serve as a resource to individuals, allowing them to realize their personal aims and interests (Pretty & Smith, 2004). Social capital engenders trust and facilitates cooperation. It also decreases the likelihood of groups engaging in unrestrained actions with negative consequences such as resource degradation.

Social networks are often more effective for enforcement and compliance of regulations than formal institutions. Additionally, social networks can alter those formal institutions to make them more effective (Scholz & Wang, 2006). Although this approach does not guarantee success, it is highly unlikely that any approach will achieve success without incorporating the human dimension of that specific problem (Ervin & Jussaume, 2014). Policy makers and practitioners tend to focus on changing the behavior of individuals rather than groups or communities (Pretty & Smith, 2004). Regulations and incentives play a role in encouraging changes in behavior (Nayar & Ong, 1996), but without social changes people often revert to old ways when incentives or regulations end (Pimbert & Pretty, 1995).

Developing sustainable management strategies will require the integration of social and economic science with biophysical science and technological innovation. Developing new "silver bullet" technologies will not solve the problem (Ervin & Jussaume, 2014). Previous paradigms focused on science being developed by scientists and then disseminated to others. This is not a healthy social structure. It will need to be exchanged for a paradigm that encourages an active exchange of ideas and information between scientists and producers (Tilman, Cassman, Matson, Naylor, & Polasky, 2002). Having an active exchange between the two strengthens the social capital of the group. It also accounts for complexity; the heterogeneity of farms and farmers provides the resources necessary to adjust best management practices to individual farms and operator situations (Ervin & Jussaume, 2014). Though the tools and resources are great, each situation can vary greatly and management strategies need to be adjusted based on individual situations. Having social capital in social networks allows for these adjustments.

Accounting for the human dimension and building social capital will be essential to providing changes in behavior that lead to lasting solutions. Without social change, there will be no meaningful change for the better. To get at the roots of the problem, the human dimension needs to be further explored, understood, and cultivated.

Gothenburg Water Utilization Learning Center

The Gothenburg Water Utilization Learning Center located in Gothenburg, Nebraska is a state-of-the-art facility dedicated to understanding and communicating the role of water and its place in agricultural production. It is one of four learning centers owned and operated by Monsanto as part of their commitment to sustainable yield (Monsanto, 2015). The Learning Center has 324 acres dedicated to research with over 100 different trials. Since 2009 the Learning Center has hosted 29,000 visitors from over 50 countries (B. Olson, personal communication, March 2, 2016). An important component of the mission of the Gothenburg Learning Center is demonstration of that research as well. The results of research experiments conducted at the site are published each year in a booklet. A hard copy of the booklet is available onsite, but the summaries are available on the company website as well.

One interesting component of the Gothenburg Learning Center is what is referred to as a rainout shelter. The learning center was opened in 2009 with the mission to better understand how water can be used more efficiently. However, the next two years were uncharacteristically wet, which severely hampered drought research. As a result a rainout shelter was constructed.

The rainout shelter is a building that moves on a track. It is 80 feet wide by 180 feet deep and houses 36 separate research plots. A weather sensor next to the building will instruct the building to close when it senses rain and the building will move over research plots to protect. This allows for control of water conditions within the rainout shelter. When no rain has been detected for a period of time the rainout shelter will automatically open back up.

The rainout shelter accounts for movement of water through the soil as well. Each plot has a membrane trenched around it to prevent water movement through the soil from plot to plot; one plot could potentially have excessive water content and the water would not move to surrounding plots. Soil moisture content is measured in each plot with a neutron probe down to six feet (M. Reiman, personal communication, June 24, 2015). This setup provides a high level of control of soil moisture conditions and detailed information about water movement and use in the soil.

Though a great deal of research is conducted onsite, it is a learning center. Demonstrations are set up to illustrate critical components of agriculture with an emphasis on management of the entire agricultural system, as opposed to control of certain aspects. Areas of research and demonstration include herbicide resistance, proper irrigation management, different crop rotation systems, disease management, etc. These serve as valuable learning tools, as well as a starting point for discussion between individuals about the issues they face and potential solutions.

A critical component of the center is that each summer visitors are able to take tours out in the field to see what type of research is being conducted. These tours are an important source of dialog that helps bridge the gap between producers and researchers. As results from the research are shared, input is sought from producers to see if it is representative of what they are seeing in the field. This dialogue helps guide the direction of future research. Many trials are the direct result of concerns expressed by producers. The learning center will also bring together a wide variety of individuals. It is open to all and hosts diverse groups e.g. retirement communities, school groups, and the chamber of commerce. In some ways, it is industry's version of a research and extension farm.

Work at the Gothenburg Water Utilization Learning Center is merely one example of attempts to address social issues. It serves as a place where producers are brought together to discuss what changes need to be made. Perhaps more importantly it helps foster new relationships and builds social capital. Social capital is essential to creating meaningful change (Pretty & Smith, 2004). The Gothenburg Water Utilization Learning Center is one example of getting at the root of the problem to address the social factors of the challenges to agriculture.

Corn Rootworm Resistance Management Educational Modules

In response to corn rootworm resistance to Bt and recognition of the importance of the human component of resistance management, new approaches are being developed. One example is the development of online educational modules to present information, but also help stimulate dialogue and build social capital. The goal of this project is to create research-based educational modules teaching corn rootworm resistance strategies for use by growers, consultants and students. This employs both modern technology-enhanced (website, Mini-Online Open Courses, Mobile Applications) and traditional instructional techniques (factsheets, whitepapers, etc.). The educational modules provide tools to help educate growers and professionals that consult with growers to make more informed management decisions. These tools easily shared across multiple digital platforms to facilitate their use.

The educational modules present high-level information on best management practices, but it is written to be understandable to someone with a high school education. This is critical, the most important reason for adoption of herbicide resistant technology was that it was simple and flexible (Duke & Powles, 2009). Though the solutions will not be simple, communicating the tools necessary needs to be simple and understandable.

These modules also leverage the social capital of existing communities. These modules will be used for continuing education credits (CEUs) for certification as a Certified Crop Adviser (CCA) or Certified Professional Agronomist (CPAg) within the American Society of Agronomy (ASA). The American Society of Agronomy was established in 1907 and has provided a strong foundation for agriculture in the past century (Egli, 2008). By leveraging the power of existing communities the information can reach a broader audience more quickly.

While leveraging existing communities of individuals this project will also seek to create new communities of influence through social media. The learning modules have numerous learning objects, activities, videos, and quizzes that can be shared across multiple platforms, e.g. Websites, Facebook, Twitter. A Facebook account for the educational modules is already posting educational resources to stimulate discussion and build communities where resistance management can be more effectively addressed. Allowing members of a community to use these tools to educate each other is an essential component of building strong communities. Social learning involves building the capacity of communities to learn about and understand the physical and ecological complexity within their ecosystems and collectively come to the decision to change their behavior (Pretty & Smith, 2004).

Communities of individuals tend to group based on shared values or ideas. Not everyone is technologically savvy or has a desire to be. That is why traditional methods of disseminating the information will be used as well. Adopting multiple strategies and reaching out to different communities broadens the reach of the information. At the same time, it bridges the divide between different communities. This provides opportunities for group members to make connections with others that have different views, yet share a common goal in addressing the issue of corn rootworm resistance management.

The last and final module of this project will directly address the social and economic factors of corn rootworm resistance. It will explore the importance of resistance from a different perspective. The module will move from discussing how resistance happens and how it can be prevented to why it is important. The importance of preventing resistance is clear to some, but everyone has a different perspective. Until individuals clearly see the consequences of their actions and the ability they have to influence their own future they are not likely to act.

Conclusion

Maize serves an important role as a commodity, but it represents so much more. Societies have risen and fallen with maize production, but through it all maize has been as much a part of their culture as their economy. Maize as a high status crop or ceremonial object has been replaced in modern societies with Cornhusker mascots, maize water towers, corn mazes and corn palaces. Though society has changed drastically over time, the fact that maize and agriculture in general are an integral part of culture has not.

Social factors lie at the root of overcoming agricultural challenges, current and future. To get at the root of the problem will require a better understanding of social factors and the best way to work effectively within communities to provide lasting change for the better. Though technology will play a vital role, it will not be the solution. Communities of people working together will provide solutions with the tools technology provides.

The Gothenburg Water Utilization Learning Center in Gothenburg, Nebraska is one example of working to build social capital. Producers and all members of the community are able to come in and exchange ideas and opinions to discuss challenges and solutions. This helps strengthen social networks and provides the necessary social capital to adequately address problems in a way that brings lasting change.

Corn rootworm resistance education modules seek to provide relevant information to producers in a way that resonates with them. It leverages the power of current communities, such as ASA, and creates new ones. Shareable educational tools are an important component of these modules.

They allow members of a community to teach each other, further strengthening the bonds that tie them together.

The future is full of challenges, but none are insurmountable. Technological advances over the past century have allowed for incomprehensible increases in agricultural productivity. They have the potential to do the same in the next century, but their effectiveness will be determined by their use. Improper use of technology will severely hamper agricultural productivity by ushering in more and greater challenges. How they are used is a social phenomenon and needs to be addressed as such. Recognition of the social factors and seeking to understand them will be essential to overcoming the current and future challenges in agriculture. Already, great strides are being made as communities come together to address these challenges. The future depends on working together to find meaningful solutions that provide the tools or technology necessary, but more importantly, the social capital to ensure that the technology is used in a socially responsible manner to ensure durability.

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