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# Rye, triticale, and intermediate wheatgrass: Recent updates in research, plant breeding, and their common uses

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**Rye, triticale, and intermediate wheatgrass: Recent updates in research, plant breeding, and their common uses**

by

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# DEDICATION

This creative component is dedicated to my wife, Danielle Menefee. Thank you for putting up with me!

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# ABSTRACT

This creative component (CC) provides a brief snapshot into three alternative small grain crops that provide viable alternatives to fill niche roles on farms looking for additional crops to include in their production system. These include, an ancient grain rye (*Secale cereale* L.), a man-made species Triticale (×*Triticosecale* Wittm. ex A. Camus*)* and a crop just beginning to be commercialized intermediate wheatgrass (*Thiopyrium intermedium*), with the first commercialized cultivar, Kernza™. The major areas covered in this CC includes the most recent updates on research, breeding and common uses for these three crops. These three crops rye, triticale and intermediate wheatgrass have multipurpose roles to fill on the farm including forage, fodder, grain and cover crop. On-going research is expanding and improving their economic viability along with their ability to excel on marginal soil and in unproductive areas on a farm.

# CHAPTER I
## INTRODUCTION: Three Alternative Small Grains

The definition and classification of commodities for the Food and Agriculture Organization of the United Nations lists 17 crops as cereals, and includes maize (*Zea may* L.*s*), rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.) and some lesser grown crops such as quinoa (*Chenopodium quinoa*) (which is not a true cereal), triticale (×*Triticosecale* Wittm. ex A. Camus) and rye (*Secale cereale* L.). Many of these cereal species, such as green cut maize, sweet sorghum (*Sorghum bicolor* (L.) Moench) and rye, have alternate uses and can be classified as a fodder crop, but the harvest of dry grains traditionally garners more attention. In the United States, corn and wheat are the top cereal grain producers. The early spring estimated total acreage of corn in the United States for 2019 was 92.8 million acres while the total wheat acreage was at 45.8 million acres(*Prospective Plantings USDA*, 2019). The planned wheat and corn acreage are at a historic low and can be compared with the 1919 growing season acreage(*Prospective Plantings USDA*, 2019). These lower numbers demonstrate an opportunity for non-mainstream and lesser utilized cereal crops to fill in acreage and to increase their market share as viable alternatives to traditional crops. The three less common small grains under review in this paper are rye, triticale, and intermediate wheatgrass, more specifically, Kernza™ (*Thinopyrum intermedium*). Rye and intermediate wheat grass are cross pollinating crops whereas Triticale is a self-pollinating crop species. Conventional plant breeding for rye, triticale, and Kernza™ can take over 10 years to develop and release new varieties but technology such as double haploids, genomic selection and marker assisted selection speed up the process and propel the genetic gains to a new level when compared to conventional breeding alone. A good example is the domestication utilized in breeding program for intermediate wheatgrass by the Land Institute. Plants were first sown in 2001 and in 2015, the 6th cycle of selection was planted(DeHaan et al., 2018).

Triticale was developed by crossing wheat (*Triticum* spp.) and rye with the hope of harnessing wheat's yield potential and rye's ability to grow under various stresses. Triticale crossing can be traced back to Wilson in 1876(Zillinsky, 1974). Some modern triticale cultivars are able to compete with wheat when there has been a concerted effort to sustain research (Mergoum et al, 2004). Tests on certain types of marginal soils show that triticale can outperform the best wheat cultivars (Mergoum et al., 2004).

In addition to triticale, rye is also an important and versatile cereal species. In the United States, it is primarily grown as a cover crop but can be used for grain or hay. Rye has a strong history of cultivation in Europe and was the main cereal in Germany until 1960 when it was surpassed by wheat (Laidig 2016). With the commercial success in Europe, we have a proven model that we can use and modify and improve upon in the United States to make this crop more viable. Rye acreage and yield were up in the United States significantly in 2019 compared to 2018. Rye acreage increased 41% with an increase in grain yield of 3.5 bushels an acre. 310,000 acres of rye were harvested in the United States in 2019 (*United States Department of Agriculture National Agricultural Statistics Service*, 2019). Although, triticale and rye offer several advantages and have a history of cultivation, breeders are working on improving new crop species. The prime example is Kernza™, which is a perennial intermediate wheatgrass developed by The Land Institute, KS, USA. Kernza™ is a dual use crop that can be harvested for forage, as grain or both and has a perennial nature. These crops have been successful in other countries and we can use what has been learned to incorporate these crops in our current systems. All three of these nontraditional crops have multiple purposes from fodder and forages, food for human consumption to bioenergy and biofuel, and therefore deserve a closer look for crop diversification and additional opportunities for farmers.

# CHAPTER 2
# TRITICALE

## History and Development

Stephen Wilson started an experiment in 1873 where he wanted to make a hybrid from a cross between two grass crop species. Between 400 and 500 crosses of wheat *(Triticum aestivum L.)*, spelt (*Triticum spelta*), rye (*Secale cereale*), barley *(Hordeum vulgare)*, wheatgrass *(Thinopyrum intermedium)* and oats (*Avena sativa*) were all used for this experiment and of these, 2 crosses were successful. The successful crossing where wheat was used as a female parent and rye as a male parent produced a hybrid crop species, known as triticale(Wilson, 1873). In 1877, the German breeder Rimpau made the first "true" triticale when we apply plant breeding in terms of the current nomenclatures and with a goal of breeding(Mergoum et al., 2004).

Wheat x rye crosses are considered primary triticale while most commercial varieties are hybrids of two primary triticale. These hybrids are termed secondary triticale. The earliest triticale were octoploids, but only hexaploid varieties have the performance to justify taking them to a commercial market(Mergoum et al., 2009).

Triticale was developed with the goal to combine higher yield and the superior quality of commercial wheat with the disease resistance and stress tolerance of rye. Triticale can have a spring, winter, or facultative growth habit and can resemble wheat or rye in appearance. In 2018, most of the triticale produced worldwide was from Europe with Poland being the top producer, followed by Germany and then France (*FAO Stat*, 2020). Locations that can take full advantage of triticale's multiple uses have developed niche and commercial markets. Triticale can even be used in the brewing process and there is potential for increased use with further breeding(Glatthar et al., 2005). The grain from triticale can be used for human consumption or as a feed grain. This useful crop can also be used for forages, cover crops to biofuel. In 2018, triticale production in Poland was nearly half of the total production of wheat in the country. According to the official results, Polish wheat production was at 9.8 million tonnes, while triticale production was at 4.1 million tonnes (*FAO Stat*, 2020). When we look at triticale production from a global standpoint, Europe produced 89.7% of the triticale grain grown in 2018(*FAO Stat*, 2020). The United States of America and the rest of the Americas produced 2.1% of the total production while Asia was the second highest at 7.4% (*FAO Stat*, 2020).

**Breeding Methods and Innovations**

The first commercial variety of hexaploid Triticale in North America was Rosner released in 1969. The initial crosses of this tetraploid wheat and spring rye were carried out in 1954 by the plant science department at the University of Manitoba, Canada(Larter et al., 1969). Early triticale breeders were challenged by many agronomic hurdles that included tall, lodging plants to small and shriveled seed. A major milestone in triticale breeding occurred in 1967 when a semi dwarf, Mexican bread wheat cross pollinated a triticale resulting in the first homeolog substitution. This led to the subsequent breeding and selection of the line "Armadillo". At a National Research Council in 1989, Norman Borlaug described the event by describing the wheat pollen as promiscuous, while it moved from a research plot to find a lonely and sterile triticale, that he even labeled as a degenerate. This event set the stage for the accelerated breeding and contributions from the wheat and rye genomes.

In triticale, there are many options and varieties with varying and mixed chromosome compositions that have been selected with the end goal of acquiring the most advantageous agronomic traits(OETTLER, 2005). Depending on the wheat varieties used in crossing, we can have a hexaploid triticale (durum wheat x rye) or an octoploid triticale (wheat x rye). These primary triticales can then be crossed with other primary triticales(Arseniuk, 2019).

There are many desirable agronomic traits and range from yield and seed quality to disease resistance to the ability to succeed in adverse soils and temperatures. The ability to quickly identify and screen for the genes controlling these traits is crucial in optimizing genetic gain and getting these varieties to market. A high-density genetic consensus linkage map from 911 triticale lines was developed in 2011 and paved the way for more modern molecular approaches(Alheit et al., 2011). Maps such as these are used in advanced genetic approaches such as association mapping, genomic selection and in QTL and marker studies(Alheit et al., 2011). This was not the first map, but the higher marker density and uniform coverage paves the way for advancements in molecular breeding techniques.

Doubled haploids speed up cultivar development, and are also useful in molecular mapping studies(Liu et al., 2016). In a 2016 study, quantitative trait loci were studied for grain and biomass yield, plant height, thousand kernel weight and tiller density (Liu et al., 2016). The relationship of grain and biomass yield QTL was low and not inversely related(Liu et al., 2016). This experiment shows that breeding efforts can improve these two important traits without hindering the other and makes it possible to stack or pyramid several QTL at the same time. Marker assisted selection is enabling the multipurpose breeding of triticale and will lead to more varieties that have strong grain and strong biomass yield components.

Traditional plant breeding in triticale consist of controlled crossing to make segregating populations, and then superior individuals are selected, based on their phenotypic characteristics. The process of inbreeding and screening new potential releases in nurseries and multiple locations can be slow. With just conventional plant breeding methods, and no offseason nurseries, it can take between 15-20 years for an new variety to reach market(Arseniuk, 2019).

There are multiple breeding paths that lead to cultivar commercialization. The use of double haploids in cultivars is increasing in efficiency and is a valuable tool for triticale breeding. Genomic selection is also increasing the speed of breeding. A study comparing different colchicine treatments and timings was able to reach a success rate of double haploid production of up to 95% for certain genotypes of winter hybrid triticale(Ślusarkiewicz-Jarzina et al., 2017). Spring triticale double haploid success rates averaged 81.5% while winter triticale double haploid success rates averaged 83.5% (Ślusarkiewicz-Jarzina et al., 2017). A 2016 simulation model study to optimize plant breeding projected a selection gain increase in triticale of 37.5% when genomic selection was implemented in addition to phenotypic selection, compared to just phenotypic selection alone over the same time period(Marulanda et al., 2016). This model study is a good example of the gains available when genomic tools are implemented.

Rye brings a robust disease and stress tolerance to a triticale and continued work on plant diseases are discovering new approaches to handling complex environments, but there are still some shortcomings. Triticale is susceptible to the fungal disease ergot (*Claviceps purpurea*), but grain can be cleaned with a gravity table. Triticale is considered “ergoty” if it contains more than 0.1% ergot infected seed by weight. This is a good example of where we can look for good agronomic practices to protect our crops. Proper rotations and plantings can help to alleviate ergot pressure and we have mechanical processes to separate damaged or infected seed.

In a 2015 publication, four doubled haploid populations were screened for fusarium head blight resistance, 17 quantitative trait loci for resistance were detected and six were reported for the first time(Kalih et al., 2015). Triticale is a relatively new crop when compared to wheat and rye and there is still large amounts of information and insights we can learn from the plant as it is developed into a more commercialized crop. There is a very large pool of rye and wheat cultivars that have their own unique characteristics we have not fully explored and when we start to combine these into a single plant, the amount of genetic diversity can be overwhelming. A long with this genetic diversity, we need to take into account how specific cultivars react to different environments and it is important to test in different locations.

Regional extension trials are a good starting point to look at how a specific variety will react in a specific region. In the 2019 variety trial for winter triticale at the University of Kentucky, the highest yielding line produced an average bushel per acre of 27.3 kg. Planting took place on October 10th , 2018 and harvest occurred on June 26th 2019(Bruening et al., 2019). In a similar variety test looking at forage yield from North Dakota State University, the highest yield forage line yielded 5245.6 kilograms per hectare in dry mass. This was planted on September 18th, 2018 and then harvested on June 24th.  Regional trial networks are very important in testing varieties across different locations and environments,

**Summary**

Triticale has similar agronomic requirements as wheat and rye. Winter triticale can be drilled at the same time as winter wheat and spring triticale can be drilled as early as practical. The same equipment for wheat can be used to harvest and store triticale seed, but a market should be identified before trying to grow triticale as a cash crop(Oelke, 1989). The same equipment used in for traditional cereal silages can also be used for triticale. Triticale has been embraced in certain parts of the world and can be an outstanding replacement in animal feed or forages. Triticale combines the advantages of wheat and rye in a single plant with improved grain and silage. Northern and western states are seeing an increase in triticale use as animal feed while its use as a forage has been growing in the southern United States. There are still limited options for triticale as for human consumption. Flour quality between triticale lines is highly variable, but there are several modern lines that have an improvement on individual traits, such as milling yield, flour brightness and grain hardness(Pattison, 2013). Protein content can be comparable to bread wheat under the right agronomic conditions, but the high variability among most quality traits is from the lack of emphasis in breeding programs(Pattison, 2013). Overall, the increased resistance to environmental stresses and strong dual uses for this as grain or fodder make this a viable option in many farming operations. Triticale production does have associated risks. There is a lack of labeling for chemicals, no crop insurance in some areas, lack of certified and registered seed stock, and the amount of funding and investments in research and technologies is lagging behind other crops(Arseniuk, 2019). Compared to traditional crops, triticale is much younger and its time of domestication is not comparable. There are many attributes of this plant that are desirable and needed, but further work of plant breeders is needed to push this plant to its fullest potential.

# CHAPTER 3
# RYE

## History and Development

The overall stress tolerance of rye compared to wheat and barley is what led to its earliest plant breeding as a cultivated crop. The cultivated rye we know today started out as a weed in the earliest barley and wheat fields. When wheat and barley seed was transported around in the beginning of its cultivation, it contained weed seed and rye was one of them. Where wheat and barley struggled, rye was successful and rye with less brittle rachis and improved seed were eventually selected. It eventually became an alternative to wheat and barley under right conditions(Sencer & Hawkes, 1980). Rye's earliest progenitors are traced back to *Secale montanum* in southern Europe and Asia or possibly *Secale anatolium* in the Middle East and Asia(Oelke, 1989). Even though most of the rye grown in the United States is not harvested for grain, the ability to grow in a wide range of environments make this plant an interesting alternative.

Rye made its way to North America in the 16$^{th}$ and 17$^{th}$ century but the first breeding program started in Germany in 1867(Al-Khayri et al., 2019). Rye is mostly a European crop with 11.7 million tonnes of rye produced in 2018 with the United States producing 450,580 tonnes of grain in 2018(*FAO Stat*, 2020). When we look at the Food and Agriculture Organization of the United Nation's 2018 data on the production share of rye grain from a world view, 81% is traced back to Europe. North and South America contributed 4.9% of total production while Asia accounted for 19%(*FAO Stat*, 2020).

Most of the rye grown in the U.S. is for non-seed purposes. Rye is often used with other cover crops, in pastures or fields for hay. The genetic diversity of commercially available cultivated rye remains high, in part because of the multiple end uses and in part because of where it was domesticated and its history as a weed(Parat et al., 2015). When comparing plants by a monoploid genome size, Rye is 40% larger than bread wheat, but up to 92% of the rye sequence is believed to be highly repetitive sequences(Bartoš et al., 2008). A whole genome draft sequence of the 7.9 giga base pair sequence was completed in 2016 (Bauer et al., 2017). Ten inbred lines and one wild relative were used in the construction that resulted in more than 90 million single nucleotide polymorphisms that lead to the Rye600K genotyping array(Bauer et al., 2017). These molecular data will be useful from genomic breeding methods in rye and even helpful to barley and wheat breeding. Comparative and functional studies will be able to use this tool.

**Breeding Methods and Innovations**

Rye has considerably fallen behind wheat and barley in terms of genetic research. A quick search on the National Institute of Health's sequence database Genbank® resulted in 1.4 million hits on rye (*Secale cereal)* with 5.2 million barley (*Hordeum vulgare)* and 4.2 million hits on common wheat (*Triticum aestivum).* This does not portray the importance of rye in current agricultural systems. Rye is a parent of Triticale and has useful gene translocations being used in wheat today(Bartoš et al., 2008). Several examples of rye improving wheat breeding are the 1BL/1RS translocation, 1B(R) substitution and 1AL/1RS translocations. The translocations 1AL/RS, 1BL/1RS, and 1DL/1RS bring improved agronomic performance, particularly when it comes to the disease and pest resistances(Graybosch, 2001). These translocation can come with a detrimental effect on flour quality and can impact end use(Graybosch, 2001). Originally the 1BL/1RS translocation came from rye, but several scientists have successfully used hexaploid triticale as a source of this translocation(Rabinovich, 1998). These events are in commercial wheat cultivars around the world and are a good example as to how valuable a related species can be to a commercial breeding program(Rabinovich, 1998). These translocations are valuable because they bring a completely new facet of genetic diversity that may be the key to increasing the agronomical and economic impacts of these crops. These translocations are responsible for numerous genes that cover leaf, stripe and stem rusts, powdery mildew and they even have insect related genes(Mondal et al., 2016).

Rye is a very hardy plant and can thrive where other cereals fail, but it is still important to test varieties in different environments and local county extension trials are a good source of localized adaptions. In a 2019 University of Kentucky variety trial, the highest yielding rye variety yielded 68.8 bushels an acre where the standard bushel for rye in 56 pounds. The highest wheat varieties yielded over 100 bushels per acre where the standard bushel weight is 60 pounds. They were planted on October $18^{th}$, 2018 and harvested June $26^{th}$, 2019(Bruening et al., 2019). In the 2019 Minnesota variety trials, the highest winter rye yielded over 120 bushels per acre. There were 4 hybrids and 9 open pollinated varieties. Of the commercially available winter ryes, the hybrid varieties for grain yields were up to 50 % more prolific than the open pollinated varieties(Wiersma et al., 2019).

Germany has a strong history in rye production with its first hybrids commercially released in 1984. A 2017 German study looked at hybrid and population varieties of rye over 26 years.  From 1984 to 2014, hybrid varieties increased yield by 23.3% while the population varieties increased yield by 18.1% (Laidig et al., 2017). These hybrids eventually came to dominate the market with approximately 81% of the German rye grain production(Laidig et al., 2017). Hybrid rye breeding started in 1970 and there were two distinct heterotic groups to begin with, Carsten (Pool C), and Petkus (Pool-P) (Fischer et al.,2010). Inbred lines were produced from each pool and then elite lines were crossed within each pool to produce the second cycle of parental inbred lines.

Rye is the most winter hardy of the small grains and does well in the early spring and late fall when compared to other cereals. In a 2017 study looking at frost tolerance, a frost tolerant Canadian line was crossed with a high yielding European line. Three major QTL were detected with one being in common with barley and wheat. This common QTL explained 14.4% of the genotypic variation in the test crosses. The QTL associated with the frost tolerance of the Canadian line accounted for 29.3 % of the genetic variation of frost tolerance(Erath et al., 2017). This new resource will benefit northern North America and northern Asia where winter hardiness is an important trait. When this trait is coupled with high performing lines, the potential growing area increases and allows for improvement in yields over a wider geographical range.

Western Canada serves as a good example of rye's increased geographic footprint. Winter rye had an increase yield of 27% when compared to spring planted rye in western Canada(Larsen et al., 2017). There is progress in thousand kernel weight and test weight as well. A study looking at lines released from 1964 to 2015 showed a reduction in height of .45cm $yr^{-1}$ accompanied by a gain in test weight of .05kg per hectoliter a year(Larsen et al., 2017). This sustained improvement is a good example of the potential gains when breed for the right environments.

There is a high amount of genetic diversity in rye for plant bred to exploit. The high amount of diversity stems from the multiple end uses where it was domesticated. In northern Europe, grain yield was emphasized, while around the Mediterranean, the forage aspect was the priority. Eastern European rye has slightly less diversity, but this is because the domestication was more intense early on(Parat et al., 2015). The exploitation of genetic diversity is one of the tools plant breeders have in abundance with rye and that can be carried over to various other crops through direct hybridization or transgenes.

**Summary**

Growing rye is like growing barley or wheat. There are winter varieties that have a vernalization requirement and there are also spring varieties. The cost of producing rye is comparable to wheat and barley, but the chemical and fertilizer input costs can be lower. The equipment is the same(Oelke, 1990). When used as a cover crop, cereal rye has positive effects on soil and weed suppression. When seeded in the spring, cereal rye can be an affective part of an integrated weed management strategy in a crop such as watermelons in Georgia(Vollmer et al., 2019). Along with the weed suppression capabilities of a rye cover, it helps manage soil erosion and nitrogen leaching, but the amount of nitrogen that cereal rye can recycle and put back into the soil is still questionable and requires more research(Pantoja et al., 2016). The research and improvement of this species has already proven to be valuable to other cereals and with an increase in notoriety, it has the potential to expand its growing area. The stress tolerances alone make this plant worthy of more research and development.

# Chapter 4
# Intermediate Wheatgrass

## History and Development

Intermediate wheatgrass (IWG), (*Thinopyrum intermedium)* is a perennial grass that was first introduced in the United States in the 1930s, but domestication did not begin at the Rodale institute until 1986(Wagoner et al., 1990). Intermediate wheatgrass germplasm for this program originated from the Soviet Union, Iran, Turkey, eastern Mediterranean and Northern Great Plains Research Center in North Dakota(Wagoner et al., 1990). There are many uses and potential benefits to growing intermediate wheatgrass commercially and include everything from improved soil health, foraging, baked goods, to being included in beer.

Intermediate wheatgrass can be beneficial to other related species. As an example, two powdery mildew genes found in wheat are from intermediate wheatgrass, Pm40 and Pm43(Mondal et al., 2016). The relationship between the wheat family (Triticum), the barley family (Hordeum) and wheatgrass family (*Thinopyrum*), was studied by looking at a combination of start codon targeted polymorphism markers and conserved DNA-derived polymorphism markers(Guo et al., 2016). Of the 57 markers initially used in this study, 27 were selected and 26 of these selected markers were present in at least one Thinopyrum species and on Triticum species(Guo et al., 2016). These markers will be useful for introgressions. By proving that these new markers are able to be tracked through species, plant breeders have another tool to use when it comes to novel trait introgressions and marker assisted selection. Another example of how intermediate wheatgrass has improved wheat was by transfer of the gene Sr74 for stem rust resistance(Mondal et al., 2016).

**Breeding Methods and Innovations**

The first consensus linkage map for intermediate wheatgrass was presented in 2016. This map confirmed that this is an allohexaploid and very similar to other Triticaceae genomes(Kantarski et al., 2017). Of the 10,029 markers that were identified, 3601 were in at least two of the screened populations. This map has implications to other commercially grown crops, especially wheat. The map will be useful in identifying introgressions in wheat that originated from intermediate wheatgrass and will as well as being used in mapping intermediate wheatgrass varieties that have valuable trait(Kantarski et al., 2017). Linkage maps and increased marker coverage across the intermediate wheatgrass genomes will lead the way for molecular breeding techniques. In a 2019 publication, 17 agronomic traits focusing on grain yield in intermediate wheatgrass, which included everything from shattering, threshing to seed size, were studied and genotyping of the lines was performed using genotype by sequencing. 111 QTL were identified from a cross between lines from the University of Minnesota. This study is based on one family, with limited genetic variation. Based on projections of fixating the significant QTL,  theoretical improvement of the traits studied range from 12% to 188%(Larson et al., 2019).

Intermediate wheatgrass has several advantages over conventional grasses. Perennial crops in general can improve the overall soil health, can help with soil erosion, used for livestock, mixed with legumes to cut down on nitrogen inputs or mixed with other perennial grains to form “functionally diverse grain polycultures”(Ryan et al., 2018). Perennial grains such as intermediate wheatgrass may be a good source of disease resistance. Ten perennial grain ascensions were studied for disease resistances to tan spot, wheat mosaic virus, barley yellow dwarf virus and take all and there were resistances to three out of four, but not take all(Cox et al., 2005). Conventional breeding methods have yielded notable gains in intermediate wheatgrass development. From 1955 to 1971, a Canadian recurrent mass selection breeding program was able to increase seed yields of intermediate wheatgrass by 10.2% per cycle for open pollinated cultivars and 20.3% for controlled pollinated cultivars(Knowles, 1977). This conventional program involved visually selecting the best 50 plants out of 1000 plants(Knowles, 1977).

Kernza™ is a commercialized intermediate wheatgrass and is a trademark of the Land Institute. Kernza™ breeding is ongoing at the Land Institute in Salina, Kansas and the University of Minnesota. As of 2019 the demand and consumption of Kernza™ grain has outpaced production and there has there have been investments by General Mills and several brewers(Muckey, 2019). Because six weeks with temperatures between 32 and 50 degrees are needed for this plant to enter a reproductive stage and produce seed, it is currently grown in Colorado, Iowa, Illinois, Kansas, Minnesota, Montana, New York, Ohio and Wisconsin. Of the 686 acres of Kernza™ that were planted in 2018, 183 were in Minnesota(Muckey, 2019).

In 2017, 1/3 of the Kernza® growers were surveyed on their views and experiences with this new crop. These farms averaged 6 hectares and farmers specifically targeted marginal areas on their farms for this production. Grain was not harvested every year, but there was an emphasis on the dual purposing of this crop.  It was used for forage, and bedding. Three out of the ten farmers  were not able to harvest for grain and there was issues with stand establishment because of late planting dates(Lanker et al., 2019). Kernza® was seen as more valuable of a crop by farmers who had cattle or who were able to take full advantage the benefits not associated with grain yield, and there was even some pessimism by farmers when they tried to compare Kernza® to corn and soy(Lanker et al., 2019). There are no approved herbicides for weed control in Kernza® and the farmers coming from a traditional row crop background struggled with the amount of weeds in their field(Lanker et al., 2019).

Kernza® and intermediate wheatgrass in general has several agronomic characteristics that may make processing more labor intensive and more expensive to harvest and preserve. The seed size is still smaller and less dense than wheat and may require specialized equipment to harvest. The grain needs dehulled in addition to cleaning(Muckey, 2019).

A 2018 publication highlights the progress and success a conventional breeding program can have with intermediate wheatgrass.  Six cycles of breeding were described with the ultimate goal to increase seed yield per head, percent naked seed, and mass per seed(DeHaan et al., 2018). The initial 961 clonal colonies, or genets came from the Rodale Research Institute and the Big Flats Plant Materials Center after preliminary rounds of selection. The top 5 individuals were crossed, and seed was collected in 2006. Cycle 2 consisted of 2466 plants with roughly half coming from the controlled crossing in cycle 1. Plants were ranked and the top 50 were selected by a combination of total yield per plant, yield per head, percent naked seed, 200-seed mass and an agronomic disease score(DeHaan et al., 2018). Individual populations based on naked seed percentage and height were also started.  Cycle three consisted of 4800 individuals from crossing in the previous cycle and was transplanted to the field site in 2009. 94 of these plants were selected and used to for crossing. This led to cycle 4 being transplanted in 2011. 13,983 total plants were transplanted, and this marked the first year that first year plantings were screened, and selections were made. In the previous cycles, plants were harvested and evaluated in their second year. 1161 plants were selected, and cleaned seed was used to select the bets 71 plants. These 71 individuals were the base for cycle 5. In 2014, 11042 plants were screened, 2220 were harvested and cleaned and ultimately 66 plants were selected to be used in the greenhouse for crossing. Cycle 6 consisted of a total of 20,360 plants and was narrowed down to 16(DeHaan et al., 2018). There were some issues with vernalization requirements and timing in regard to plant development, but overall, projections were at 140 % increase in seed yield per head, 181% increase in percent naked seed, and 60% increase in mass per seed(DeHaan et al., 2018). Heritability estimates for these threes traits were .29, .49, and .39 with their average selection differentials of 79, 19, and 87%(DeHaan et al., 2018). This is a good example of the current timeframe breeding in intermediate wheatgrass and highlights the gains possible.

**Summary**

Intermediate wheatgrass is currently a very novel crop with a very specific niche market. Plant breeding and agronomy research shows that there is a lot of room for improvement and that grain and forage biomass production are valuable. Intermediate wheatgrass cannot currently compete with traditional row crops in terms of grain production but the ability to excel on marginal or slopped land coupled with its multipurpose nature warrant more research. The close relation to wheat will help fuel research along with the perennial and sustainable nature.  The major roadblocks to expanding intermediate wheatgrass production are the availability of seed, a clear market and supply chains(Muckey, 2019).

# Chapter 5
# Summary and Conclusions

The value in the afore mentioned niche crops lies in their ability to excel in adverse growing conditions and their ability to fill several roles on the farm. On marginal or unproductive soil where traditional row crops are not economically viable, these three dual purpose species can excel. Diversification on small farm operations is a vital aspect for survival and the United States dairy industry is a prime example. Dairy cows follow strict diets, but rye grain has been proven to be a viable replacement for barley and in some cases, there has been an improvement in the end product(Tretsven, 1935). In 1961, there were over 17 million milk producing cows in the United States and in 2018 the United states had just over 9.4 million cows (*FAO Stat*, 2020). According to the April 2020 dairy forecast through the USDA, the number of cows will be contracting even more in 2020. According to USDA report, the United States lost 3,279 registered dairies, down from 37,468 in 2018. That loss of about 9% of the registered dairies is a wake-up call to small farm operations and showcase the need to diversify. This is a prime example of where these crops can benefit the farmer, because of their ability to potentially produce grain as a cash crop or feed or provide fodder. Traditionally unproductive acres are the prime location to grow Kernza, rye or triticale.

As a niche food crop, these three plants thrive. According to the United States alcohol, tobacco products and firearms code of federal regulations, a rye whiskey has to be fermented with a mash of no less that than 51% rye. Specialty crops like this commonly have unique or improved quality traits that are desired and can be sold at a premium. Triticale can replace wheat or rye flour in baked good and there is potential in the improved quality traits through a concerted breeding effort(Mergoum et al., 2004).

Advances in these three crops does not stay with only these crops. Breakthroughs in all of the agronomic traits can positively influence farmers and research in other crops. Genes from all three of these separate species can be found in wheat. The ongoing research for these crops is bringing them closer to viability on a broader scale and thus there is need to keep the public informed on the progress of these crops. Without a well-informed public and support of local extension offices, these plants will remain tertiary crops.

The population of the world was reported to be 7.7 billion people in 2019 by the united nations and is projected to be over 8.5 billion by 2030(United Nations, 2019). One of the Sustainable Development Goals for the United Nations focuses on hunger and malnutrition and when it is coupled with the rising population, agricultural innovation becomes a priority. Previous generations of plant breeders gave us tools from genetic engineering, molecular breeding to various high throughput systems. It is now the responsibility of the next generation to exploit those tools to their fullest capabilities and to make their own innovations and breakthroughs in this everchanging field. Goals such as exploiting genetic diversity to improved varietal development to new innovation are vital as the world moves forward.

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