

François Eudes *Editor*

Triticale

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Preface

Triticale is a relatively new crop species introduced in a number of countries around the world, where it usually occupies a niche market, with the exception of Poland where it takes a significant acreage. With this crop species came a hope to combine the quality attributes and agronomic performance of its respective parents, wheat and rye, which would offer a competitive advantage over crops on the market. While it seems not fulfill yet, this book reviews the current status of the research in this species and opportunities along four value chains.

The origin of hexaploid triticale and the implication in crop development are covered in the first part, made of three chapters. It starts with a review of the biology of triticale species and the biosafety of this crop in the field. This work describes triticale biology and maps the risks associated with the potential deployment of novel breeding tools which would result in regulated events. Conventional breeding and the introduction of novel breeding tools are addressed in the second chapter and takes us to foresee a technological adoption similar to its parent species, including the efforts and opportunities for a hybrid triticale. The success of triticale crop in commercial production, and its competitiveness over wheat, is to a large extent due to its tolerance level to abiotic and biotic stresses, extensively reviewed in two chapters. The third part of this book is dedicated to the genomics and biotechnology enablers. A large amount of sequence data are generated from wheat, rye, and triticale bringing considerable information at disposition of the scientific community. Triticale genomics and transcriptomics data are being developed along the traits of significance, and deployment of this knowledge could be emerging through genetic engineering and precision editing. Doubled haploid technologies have made huge progresses in triticale and could become a platform for editing an haploid genome, beside fixing the genetics of F1 hybrid offspring in a single step.

Triticale fits well with a few value propositions that have received significant attention as noted per the research efforts and volume of publications. With no doubt, triticale is a competitive grain as energy source in the livestock diet. Its use as feed is also well documented and implemented by the beef industry thanks to the large biomass and nutritional value as silage and for swath grazing practice.

The livestock feed value proposition supports existing or increased triticale acreage, and new bioindustrial opportunities emerge which would capture triticale fiber biomass. The biomaterial value proposition is reviewed and documented with numerous pictures. Triticale has also been bred for the food market, and significant progresses have been made to improve its quality, in particular its protein profile, for the bakery and the bread industries. These efforts are extensively covered in one chapter. Together, the last four chapters address in one part the current market and credible new uses in four value chains, which would be a pull for triticale crop.

I sincerely thank Springer Science for making the production of this book possible and I'm grateful for the assistance of their staff especially, Brian Halm, as well as Narayanasamy Prasanna Kumar at SPS. I greatly acknowledge all the contributors and authors of this book for sharing their knowledge, shared experience working with triticale crop, and topics covered in twelve chapters.

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Part I
Plant Biology and Breeding

Chapter 1

Biology and Biosafety

Vanessa Kavanagh and Linda Hall

Biology

Triticale (\times *Triticosecale* Wittmack) is an annual C3 cool-season grass within the Poaceae (Graminae) family. A recent crop addition, triticale, is an intergeneric hybrid of wheat (*Triticum* sp.) \times rye (*Secale cereale* L.). The maternal parent of triticale may be common or durum wheat (*Triticum aestivum* L. or *Triticum durum* desf.) and offspring are typically backcrossed to wheat multiple times to incorporate desirable agronomic traits (Kavanagh et al. 2010). Therefore, triticale has characteristics intermediate to parental species, but shares more traits with the maternal wheat parent.

With a plant height of \sim 115 cm triticale is taller than wheat, but shorter than rye with glaucous leaves, appearing 'blue,' similar to rye. Seeds are long (8–10 mm) and narrow with a thousand kernel weight approximately 20–30 % higher than Canadian Western Red Spring (CWRS) wheat (Salmon 2004a; Government of Saskatchewan 2011). Like many crop species, there is little primary dormancy and no secondary dormancy and germination time typically ranges between 2 and 7 days (Raatz et al. 2012). In western Canada, biomass production is up to 20 % higher in triticale than wheat due to its wide leaves, increased height, and large seed production (Government of Alberta Agriculture and Rural Development 2001;

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Salmon et al. 2004b; Government of Alberta Agriculture and Rural Development 2006). Spike length can range between 10 and 15 cm, contains ~25–30 spikelets, and may be awned or awnless (Mohammad et al. 2011).

Reproductive Biology

Triticale is cleistogamous (self-fertilized); however, it does have some propensity to open florets during flowering, reflective of its rye parentage (Oelke et al. 1990; Kavanagh et al. 2010). In addition, environmental stress such as excessive heat or prolonged drought has been demonstrated to induce pollen sterility and increase floret opening to facilitate cross-pollination (Dorofeev 1969; Waines and Hegde 2004; Singh and Jauhar 2006; Kavanagh et al. 2010). Pollination begins before anther extrusion, and stigmas are receptive for approximately 4 days (Wilson 1968; D'Souza 1972). Like wheat, anthers are first extruded in the middle of the spike and progress upwards and downwards (D'Souza 1972; Cook and Veseth 1991; Kociuba and Kramek 2004). The main stem flowering period is approximately 7–11 days with tillers often extending the flowering periods for several days to a week later (D'Souza 1972; Cook and Veseth 1991; Kociuba and Kramek 2004).

Anther extrusion has been reported to range between 31 and 72 % with an average production of 20,100 grains anther⁻¹ (Sapra and Hughes (1975), double that of wheat at ~9400 grains anther⁻¹ and half that of rye at ~42,000 grains anther⁻¹ (Yeung and Larter 1972; Sapra and Hughes 1975). Anther length is intermediate to wheat and rye, with rye being longest. Pollen longevity under ideal conditions was 110–120 min post-dehiscence; however, under desiccating conditions this period lessened to 60–70 min (Fritz and Lukaszewski 1989).

Genetic Composition

Phylogenetic analyses group triticale in the grass tribe Triticeae with *Triticum* L. (wheats), *Aegilops* L. (goatgrasses), and *Taeniatherum* Nevski (medusa heads); however, Triticeae has a complicated genetic composition, and placement is still unclear (Kavanagh et al. 2010; Bouchenak-Khelladi et al. 2008; Mason-Gamer 2005). Triticale may be octoploid ($2N = 56$; AABBDDRR) or hexaploid ($2N = 42$; AABBRR) depending on which wheat is crossed with rye (RR), i.e., common wheat (AABBDD) or durum wheat (AABB; Lelley and Gimbel 1989; Lelley 1992). The large genome of octoploid types is less stable and with the exception of Asia cultivars; most cropping triticales are of hexaploid type (Kiss and Vidiki 1971; Ammar et al. 2004; Oettler 2005, US national research council 1989). Interestingly, when two octoploid triticales are crossed, the resulting progeny is hexaploid (Pissarev 1966; Jenkins 1969; Oettler 2005), increasing the breeding and selection possibilities.

Although triticale inherits genes from both wheat and rye parents, allopolyploidization (combining genomes of two or more species) leads to sequence losses, modifications, and changes in expression (Xue-Feng et al. 2004; Boyko et al. 1984). While the majority of the wheat genome is retained unchanged (70–90 %), over half of the rye genome is altered or lost (~60 %; Xue-Feng et al. 2004; Boyko et al. 1984). The substantial alteration of the rye portion of the triticale genome reduces opportunities to cross triticale back to rye.

Triticale Biosafety

Protection of the environment and maintaining the segregation of conventional and genetically modified (GM) crops are key considerations when considering development, cultivation, and marketing of (GM) crops (Johnson et al. 2007; Lu 2008). Some of the potential environmental consequences of GM crops include transgenic movement from a GM crop to its non-GM counterparts or to wild or weedy relatives via gene flow (Beckie and Hall 2008; Ellstrand et al. 1999; Warwick et al. 2009). In addition to the environmental concerns such as the creation of new weeds (Gilbert 2013) and potential change of genetic diversity in progenitor species (e.g., see Lu and Yang 2009), transgene flow via pollen and seed may lead to the adventitious presence (AP) of transgenes in conventional commodities. AP increases concerns for food and feed safety and increases legal and international trade obstacles that import bans, shipment refusals, and costly delays and other barriers to trade (e.g., see Viju et al. 2014). Biosafety policies and regulations for GM crops have yet to be harmonized between trading partners or completed in all nations, furthering difficulties for those developing such crops.

To assess the risk of GM crops, gene flow mechanisms should be understood, gene flow quantified and, if significant, the consequence of gene flow evaluated (Johnson et al. 2007). This includes intraspecific gene flow risks between triticales; interspecific gene flow risks between triticale and its wheat and rye parents, as well as other wild relatives that may be present in the environment; and the propensity of transformed triticale to become a crop weed or significant source of AP in other crops in rotation.

Intraspecific Pollen-Mediated Gene Flow

Isolation distances of 3 m between different triticale varieties have been established by Canadian certified seed regulations (Canadian Seed Growers Association 2014) to reduce gene flow between triticale grown for seed. While these distances reflect the experience of crop breeders, data to quantify gene flow at these distances are lacking. Additionally, triticale is heterogeneous due to its more recent and variable background and may exhibit differences in PMGF potential across cultivars.

Viability underscores the need to be cautious when generalizing PMGF rates for biosafety purposes across the entire triticale cultivar spectrum.

Yeung and Larter (1972) reported that the first commercial triticale cultivar Rosner exhibited a 5 % PMGF frequency under greenhouse conditions. A recent examination by Kavanagh et al. (2012) investigated intraspecific PMGF under conventional agronomic conditions taking into account distance from the pollen source (0.2–50 m) and wind direction at flowering. Two cultivars with similar backgrounds were tested; however, the cultivar used as a pollen source had a blue aleurone xenia trait. As expected, PMGF decreased as distance from the pollen source increased with a maximum of 5.07 % occurring 0.2 m from the source and a minimum of 0.04 %, 50 m from the source (limits of the project design). At 50 m, gene flow ranged from 0.04 to 0.14 % with the highest rate reported in the direction of the prevailing winds. Because PMGF was recorded 50 m from the source, it is reasonable to expect that the pollen would have remained viable and gene flow continued past that point had the study extended beyond that distance. Interestingly, the rate of PMGF at the closest distance was very similar to the rate recorded by Yeung and Larter (1972) 40 years earlier in greenhouse trials. Wind direction also had a significant influence on PMGF as prevailing winds were west, southwest, and south during flowering and the highest rates of gene flow occurred in the easterly direction. Directional effects were seen to decrease as distance from pollen source increased. These are important considerations when developing triticale biosafety policies that may affect neighboring agricultural fields.

Quantification of PMGF at various distances from the source, while useful for developing isolation distances, can also be used to predict the quantity of GM seed contamination in adjacent fields. Kavanagh et al. (2012) reported that if the receptor field (from 0.2 to 50 m) had been harvested and uniformly blended, the percentage of AP would have been 0.22 %, below the European Union 0.9 % GM seed AP threshold. A 50 m field is a small field by commercial standards and AP would decrease with increased field size. Using a wheat model, Gustafson et al. (2005) reported an AP rate of 0.16 % in a harvest-blended wheat field that was 50 m surrounding a pollen source; however, the harvest-blended AP rate decreased to 0.02 % when the receptor field increased in size to 400 m. Distance and field scale are important considerations for the estimation of AP (Beckie and Hall 2008).

Interspecific Pollen-Mediated Gene Flow

Pollen-Mediated Gene Flow to Parental Wheat and Rye

It is assumed that compatibility between triticale and its parental species would be high; however, simple reproductive barriers (i.e., flowering times and pollination strategies) and genetic constrictions reduce the opportunity for successful hybridization to occur. However, variability between triticales makes generalization

difficult. Triticale may be created when rye is the maternal parent and wheat the paternal, or vice versa. Additionally, durum wheat or common wheat may be used, greatly affecting resulting genome size (42 vs. 56 chromosomes, respectively) and composition as durum wheat triticale progeny would consist of an ABR composition versus ABDR with common wheat. First-generation triticales are then crossed and backcrossed with themselves and/or wheat to further enhance desirable crop traits (i.e., increased yield and disease tolerance).

Hybridization risks between triticale and wheat under field conditions is reduced mainly due to their pollination strategies. Both are self-pollinated and florets are typically fertilized before they extrude their anthers and pollen made available to neighboring plants. However, instances of stress or genetic anomaly can lead to pollen sterility and surrounding pollen may reach the stigma during receptivity. Genetic barriers still need to be overcome, including the *Ph1* and *Ph2* genes that are present in both triticale and wheat that prevent homoeologous chromosome pairing (Jauhar and Chibbar 1999; Zaharieva and Monneveux 2006; Weissmann et al. 2008). When crossed with common wheat, Chaubey and Khanna (1986) obtained five viable seeds from 260 florets pollinated. Hills et al. (2007) attempted 2000 crosses each between two lines of triticale and a single durum wheat and common wheat cultivar. Despite emasculation and optimum greenhouse conditions, one triticale line (89TT108) produced no viable offspring when triticale was the paternal parent, and AC Alta demonstrated $\leq 1\%$ emergence although successful seed set was 75%. Kavanagh et al. (2013) reported PMGF rates of 0.0006% in common wheat grown adjacent (up to 1.6 m) to triticale and 0.0008% in durum wheat under small-scale field conditions, well below international market thresholds. Additionally, PMGF rates would be expected to diminish with increasing distance from the pollen source.

The PMGF potential from triticale to rye is considered to be low despite the fact that rye is an obligate outcrossing species. Should flowering be synchronous, triticale possesses the *Kr1-4* family of genes that has been exhibited to strongly inhibit hybridization with rye and other related species (Guedes-Pinto et al. 2001; Oettler 2005; Kavanagh et al. 2010) and paired with the *Ph* genes has made hybridization and PMGF to rye unlikely. Chaubey and Khanna (1986) attempted crosses with two triticale lines and a Russian rye and were able to obtain 20 seeds out of 110 florets pollinated. Of the 20 hybrid seeds, seven germinated; however, viability or fertility of the hybrids was not reported. Hills et al. (2007) reported rye to be the least compatible when crossed with two triticale lines (89TT108 and AC Alta), resulting in $\sim 20\%$ hybrid production when triticale was the paternal parent. Hybrid seed from those crosses was small, shriveled, and non-viable when the experimental triticale line (89TT108) was utilized; however, 38% germination was obtained when AC Alta was the paternal parent underscoring reproductive variations between triticales. Experiments were carried out in a greenhouse using worst-case scenarios (i.e., emasculation and hand pollination), and hybridization under field conditions is expected to be lower.

Non-parental Relative Compatibility and Hybridization Potential

Hybridization between wild compatible species is a widespread phenomenon that has given rise to many of the common plants present today. Poaceae in particular has experienced many historical spontaneous hybridization events (Ellstrand et al. 1999), and breeders should be cautious when selecting genetic transformation targets from this family. Within the Poaceae tribe Triticeae, triticale has 31 genera cohorts and ~300 species (Watson and Dallwitz 1992) where rare compatibility is expected to be observed. To date, few compatibility experiments have been performed with triticale as the paternal contributor and most risk has been inferred by genomic constitution.

Two crossing experiments using emasculation and embryo rescue examined triticale as the paternal donor and non-parental species as the maternal receptor (Gupta and Fedak 1986; Balyan and Fedak 1989). In the first, *Hordeum vulgare* L. (barley) was utilized as the maternal receptor and less than 10 plants were obtained from over 800 floret pollinations (Gupta and Fedak 1986). In the second, using *Hordeum parodii* Covas as the receptor resulted in less than 10 plants in over 990 pollinations (Balyan and Fedak 1989). From these assessments, the risk for hybridization and transgene movement between triticale and *Hordeum* is unlikely.

Kavanagh et al. (2010) has speculated on the outcrossing potential from triticale to wild relatives using genomic designation and parental outcrossing potential. The AABB or AABBDD portion of the triticale genome is derived from durum and common wheat, respectively, with the AABB portions of both species being very similar (Gill and Friebe 2002). Wild emmer [*Triticum dicoccoides* (Körn. ex Asch. and Graebner) Schweinf.] shares the same designation as durum wheat (AABB) and is thought to have been the progenitor to both cultivated species (Dvorak et al. 1998; Gill and Friebe 2002). While crosses between common wheat and wild emmer are unlikely, rare crosses between durum wheat and wild emmer have been reported in the South Caucasus when wheat was the female parent (Dorofeev 1968, 1969). It is important to point out that crosses in the other direction may be overlooked as it would usually occur in non-agricultural areas. Because the bio-safety risk lies when triticale is the male parent (off-type seeds within the field are expected to be treated as a modified crop already) based on this data PMGF to wild emmer is considered low. Another important reported natural hybridization event was between common wheat and jointed goatgrass (*Aegilops cylindrica* Host.; designation CCDD) in the USA when common wheat was the paternal parent (Morrison et al. 2002). Hybrids were found in weedy goatgrass populations in proximity to wheat fields and were not only fertile, but several hybrids identified were shown to be a backcross hybrid. Other reported PMGF events between common wheat and jointed goatgrass show herbicide resistance genes were confirmed to have moved into the wild goatgrass population (Perez-Jones et al. 2012). Both species share the D designation which may lead to easier crossing. Triticales containing this genome may also be at increased risk for outcrossing with jointed

goatgrass and should be tested for compatibility. *Agropyron intermedium* (intermediate wheatgrass) has been reported to readily cross with wheat under laboratory conditions; however, has not been reported to cross naturally (Kavanagh et al. 2010). Although triticale does not share a genomic designation (AABB/DD vs. EE), intermediate wheatgrass is found in proximity to agricultural areas and is a potential hybridization risk.

The RR portion of the triticale genome is from cereal rye (*S. cereale*); however, this designation is shared by all three accepted species in the genus, including *Secale sylvestre* Host. and *Secale strictum* (C. Presl) C. Presl (Wang et al. 1996). One study investigated hybridization potential between *Secale* species, including when cultivated rye (*S. cereale*) was the paternal parent; however, the cross—*S. sylvestre* × *S. cereale* was unable to set seed in 617 florets pollinated (Khush and Stebbins 1961). When rye was the maternal parent, the crossability (function of % seed set of parents, F1 germination, and fertility) was highest with *S. strictum* (26.3 %) and lowest with *S. sylvestre* (0.02–0.08 %). While already low, the risk of PMGF from triticale to *Secale* is lessened due to the specificity of the Kr gene family to inhibit outcrossing to the genus along with the substantial reduction of rye genes within the triticale genome.

As seen with compatibility issues between triticale and its parental species, using genomic constitutions to assess hybridization potential between triticale and its wild relatives is highly problematic. It does not describe genetic barriers that may exist to such pairing (i.e., the *Ph* and *Kr* genes described above) and polyploidization (pairing between species with differing designations) has been occurring throughout history, giving rise to both cultivated wheats (Kellogg et al. 1996). Underreporting may also be occurring as hybrids within weedy populations are likely to occur on the periphery of agricultural areas and go unnoticed. Increased monitoring and experiments conducted on likely candidates—identified either through designation, or as grass species most likely to occur in proximity to areas of triticale cultivation—may more accurately quantify risks and assist in the establishment of responsible biosafety protocols.

Weediness and Seed-Mediated Gene Flow

Seed persistence trials suggest triticale may not persist in the seed bank, reducing weediness and the risk of seed-mediated gene flow (SMGF). Seeds buried at a depth of 12 cm were non-viable after seven months and those buried less than 2 cm tended to germinate in the fall and be killed by winter conditions (Raatz et al. 2012). Seeds on the soil surface exhibited longest persistence of just over two years; however, these seeds would also be susceptible to disease and predation. Volunteer triticale can be controlled with standard agricultural practices. It should be noted that genetic modifications that alter seed properties, i.e., decreased seed shattering,

may confer seed fitness advantages and should be retested for persistence and SMGF propensity. There have been no reports of triticale becoming an invasive or weedy pest.

Volunteer triticale that emerges in subsequent crops may be a source of SMGF. When herbicides were applied pre- and post-seeding in field pea crops and herbicide-tolerant canola and wheat crops, >99 % of volunteers were reportedly controlled. However, the AP at harvest was ≥ 1 % of crop weight/weight in the canola and wheat crops (Raatz et al. 2014). This rate exceeds GM labeling thresholds in Europe and may be economically restrictive for GM consideration. Separation of triticale seeds may be possible in small seeded crops such as canola or camelina; however, within larger seeded crops or other cereal species separation could be problematic.

Summary

The hybrid origin of triticale has resulted in a morphology intermediate to its wheat and rye parents. Genetic composition is dependent on the wheat parent crossed; however, a larger portion of the wheat genome is retained than the rye genome. Traits such as disease resistance, increased biomass, and closed pollination strategy have increased the interest in triticale as a forage and seed crop and have also led to the consideration of triticale as a GM crop.

The biosafety of triticale has been investigated in recent years in light of its bioindustrial applications. Cleistogamy and strong genetic barriers greatly reduce triticale's biosafety risks. Aside from other triticale varieties, the most likely relative for natural hybridization is its maternal parent common wheat. Hybridization potential between paternal rye and triticale was shown to be low and natural PMGF events unlikely; however, hybridization experiments when rye was the maternal parent have not been reported. Outside of parental species, the greatest risk of natural PMGF may be to jointed goatgrass. While not documented to cross with triticale, several studies have reported hybridization between wheat in cultivation and goatgrass in neighboring weedy populations.

Pollen-mediated gene flow (PMGF) is expected to be higher in chasmogamous crops like corn and lower in those that are cleistogamous such as wheat and triticale (Messeguer et al. 2006; Hall et al. 2003; Jhala et al. 2011; Ellstrand 2014). In cleistogamous species such as triticale, SMGF from volunteers may present the greatest risk for AP and can be a source of PMGF (Beckie and Hall 2008). Raatz et al. (2014) have shown the AP can exceed 1 % from volunteers and admixture during harvest and processing, which may pose a substantial economic risk in certain markets. Although triticale-specific biosafety protocols to address PMGF and SMGF risks have yet to be developed, knowledge of the reproductive biology and synthesis of previous hybridization assessments can assist in enacting responsible policies to effectively reduce gene movement.

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Chapter 2

Triticale Breeding—Progress and Prospect

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Introduction

Triticale (\times *Triticosecale* Wittmack) is a man-made cereal crop that can be synthesized by hybridizing wheat with rye (*Secale cereal*, RR). The first triticale was produced by Scottish botanist A. Stephen Wilson in 1875 when he succeeded in pollinating wheat with rye pollen (Wilson 1876). However, these triticale plants produced sterile pollen and hence could not produce viable offspring. It was not until embryo rescue techniques (Laibach 1925) and colchicine-induced chromosome doubling (Blakeslee and Avery 1937) were developed that the prospects for triticale breeding became viable (Oettler 2005). Simmonds (1976) summarized the various types of triticale that can be synthesized with different chromosomal constitutions. Crossing with different species of wheat, e.g., *Triticum turgidum* (AABB) or *Triticum aestivum* (AABBDD) will produce either hexaploid (AABBRR) or octoploid (AABBDDRR) triticale, respectively. Among the various types of triticale, hexaploid triticale (durum \times rye) has been the most successful because of its superior vigor and reproductive stability. The octoploid type (common wheat \times rye) suffers greater genetic instability and associated floret sterility (Mergoum et al. 2009). The original goal for producing triticale was to produce a new cereal crop that combined the superior agronomic performance and the end-use qualities of wheat with the stress tolerance (both biotic and abiotic) and adaptability of rye. Major efforts around the world have been undertaken to develop hexaploid triticale with improvements in agronomic characteristics, end-use quality, and resistance to various biotic and abiotic stresses. The first North American triticale

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breeding program was established in 1953 at the University of Manitoba in Winnipeg, Canada, to develop a high yielding, drought tolerant triticale for human consumption to be grown on marginal land. This effort resulted in Rosner, the first licensed spring triticale variety in Canada (Larter et al. 1970). Dr. N.E. Borlaug initiated the triticale research program at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico in 1964 (Lelley 2006). By the early 1960s, hexaploid \times octoploid crosses in Hungary resulted in several secondary triticale populations (T-30, T-57 and T-64) that were used to initiate the on-farm trials on sandy soils (Kiss 1966; Kiss and Kiss 1981). Two of these populations (T-57 and T-64) resulted in the world's first triticale cultivars released for commercial production (Zillinsky 1985). Based on annual repeated crossing and progeny testing, Kiss (1966) concluded that the hexaploid type was the optimum ploidy-level for triticale. Kiss established modern triticale breeding with the development of secondary hexaploids since they were as competitive on marginal soils as rye, with 30–50 % higher protein concentration. These advanced materials were transferred to Polish scientists who made tremendous progress in improving adaptation (mainly frost resistance). Since the 1990s, many triticale cultivars have been produced that have gained widespread popularity across Europe (Wolski and Tymieniecka 1988; Bona et al. 2002). As a man-made crop, triticale relies on the incorporation of new variability through the creation of new primary and secondary triticale populations using various wheat, rye, and triticale accessions. The genetic variability for important traits among various germplasm sources provides the foundation for further improvement to the crop. Through germplasm exchanges, the genetic resources developed at CIMMYT and other breeding programs have become an integral part of modern breeding programs.

Breeding Goals

Triticale can be used as grain for human food consumption and animal feed (mainly for pigs and poultry), as well as forage for livestock in the form of silage, fodder, grazing, and hay. In general, triticale combines the high yield potential of wheat with the biotic and abiotic stress tolerance of rye, making it more suitable for the production in marginal areas (acidic, saline, or soils with heavy metal toxicity). Despite having many advantages over wheat, global triticale production is still very low. In 2013, about 4 million hectares of triticale were grown worldwide with Poland, Belarus, Germany, France, and Russia being the major triticale producing countries (Table 2.1, FAO Stat). The low adoption of triticale is due to factors including production concerns, availability of end-use markets, production economics, policy, and competition from wheat. Among the production factors, susceptibility to diseases, such as ergot, *Fusarium* head blight (FHB), and leaf spots, poses major threats. Spring triticale cultivars are generally later maturing than wheat, which limits production in short growing season countries such as Canada. The volume weight of triticale cultivars has also been generally lower than wheat,

Table 2.1 Worldwide triticale area and production in 2013 (FAO statistics)

Country	Area harvested (ha)	Yield (kg/ha)
Australia	99,178	1726
Austria	44,996	4981
Belarus	441,630	2882
Belgium	6096	7050
Bosnia and Herzegovina	11,500	4073
Brazil	42,582	2865
Bulgaria	13,700	2825
Canada	11,400	2596
Chile	20,878	5574
China	210,000	2167
China, Mainland	210,000	2167
Croatia	14,087	3397
Czech Republic	46,816	4576
Denmark	13,300	5594
Estonia	3241	2724
France	385,022	5278
Germany	396,900	6573
Greece	8700	1149
Hungary	118,406	3873
Kyrgyzstan	721	1717
Latvia	14,100	2596
Lithuania	143,900	3135
Luxembourg	4561	5645
Mexico	3417	2917
The Netherlands	1953	5085
Poland	1,176,700	3631
Portugal	20,725	1559
Romania	72,529	3378
Russian Federation	241,108	2412
Serbia	38,961	4206
Slovakia	11,780	3352
Slovenia	3490	3622
Spain	140,900	2794
Sweden	22,889	4880
Switzerland	9159	5505
Tunisia	13,000	2008
Turkey	35,402	3333
United Kingdom	11,000	3500