Triticale improvement and production

FAO
PLANT
PRODUCTION
AND PROTECTION
PAPER

179

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2004

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ISBN 92-5-105182-8

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Foreword

Triticale, the first successful human-made cereal grain, was deliberately produced in 1875 by crossing wheat with rye. Since then, the evolution of this crop has been the topic of keen interest for many plant scientists. According to the vision of early scientists, triticale should combine the best characteristics of both parents: wheat's qualities for making various food products with rye's robustness for adaptability to difficult soils, drought tolerance, cold hardiness, disease resistance and low-input requirements. The early excitement and publicity associated with triticale may appear to have exceeded the actual development of the crop. However, considering the thousand years during which most present major crops – such as wheat and rice – have evolved under domestication compared to the few years and modest effort devoted to triticale, it could be argued that the results are quite remarkable. Modern triticale cultivars perform as well as the best common wheat cultivars wherever scientific research has been sustained. Furthermore, in certain types of marginal soils, triticale cultivars outyield the best wheat cultivars. For instance, research results in the drought-prone regions of North Africa have shown that triticale can be an excellent alternative crop to wheat and barley. In cold, wet environments, the highly productive winter-type triticale cultivars developed primarily in Poland are continuously expanding into most cereals-based systems in Northern Europe.

Almost 3 million ha of triticale are grown today in the world. Triticale country reports presented in this book clearly indicate that today this crop is accepted worldwide with its area expanding significantly, particularly in stress-prone ecologies. Data on cultivar release and area are imprecise due to the lack of information from some National Agricultural Research Systems (NARSs) and sometimes due to the confidentiality required by the private sector. Present information available at the International Maize and Wheat Improvement Center (CIMMYT) shows that since the mid-1970s more than 200 cultivars have been released in more than 30 countries.

Initial problems related to low seed fertility and seed plumpness have been solved, and most current research focusses on improving grain quality for various food and feed uses and on improving adaptation to new areas. Food uses include bread, noodles, soft-wheat type products and malting. New alternatives for diversification have also emerged with the development of winter-type cultivars with higher forage biomass than spring cultivars. With these types, a substantial amount of biomass is available for grazing, cut forage, dual-purpose cultivation (first grazing or cut, then left for grain production), silage and hay production.

Triticale can certainly play a significant role in alleviating poverty for many needy families in some developing countries. Of particular interest is its good performance in stress environments and its diversified uses. However, as for any other crop, research efforts are still needed to improve adapted germplasm and determine best-crop management practices for these difficult areas. This will necessitate the interventions of many key players. In this context, this book presents state-of-the-art triticale production in the world. The first chapter gives a comprehensive overview of the history and evolution of triticale since its creation, whereas authors in the second chapter present the improvements accomplished at CIMMYT where the largest triticale breeding programme in the world is hosted. The world and agro-ecological level distribution of triticale, as well as its management as a crop, is covered in chapter three. The book examines extensively the actual and potential uses of triticale products in human and animal diets in chapters four and five. It also presents marketing strategies developed by the private sector, including practical examples on how triticale can compete with other cereal crops, in chapter six. Finally, the last section of the book presents the current situation of triticale production and research status in 13 countries, covering a very wide range of economic and scientific levels. Some of these country reports may be used as a model for those countries that are still in the embryonic stages of developing triticale technology.

While this book presents updated information on various aspects of triticale production, improvement, uses and marketing strategies in the world, it shows clearly that triticale potential has yet to be exploited and that most of its future success depends on efforts and resources allocated to research and development. Realizing this potential, the Food and Agriculture Organization of the United Nations (FAO) has rightly decided to bring out this publication hoping it will motivate researchers and policymakers' commitment to the further development of triticale in developing countries to enhance choices for farmers to diversify, increasing the income and sustainability of relevant production systems.

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Acknowledgements

This publication is indebted to the many scientists around the world that have contributed to the progress and promotion of triticale. Particular recognition must be given to the Triticale Program of the International Maize and Wheat Improvement Center (CIMMYT).

Each author of the several chapters within are thanked for their time, expertise and contribution, as well as for their patience in adapting to changing deadlines. Thanks are also given to the editors, Mohamed Mergoum and Helena Gómez-Macpherson, for their dedication and tireless effort in the preparation of this book.

The invaluable comments and contributions from the following FAO staff members are greatly appreciated: Andre Croppenstedt, Miranda Jabati, Michael Larinde, François Mazaud, Nicolas Sakoff, Manuel Sanchez and Edward Seidler. The excellent work of Ms. Anne Coulson in editing and formatting the text is also appreciated. Special thanks are given to Elcio Perpétuo Guimarães, Senior Officer, Crop and Grassland Service, for his assistance during the final stages of publication.

The work of Helena Gómez-Macpherson, former Agricultural Officer in the same Service, provided the backbone to the entire process and made publication of this book possible.

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The history and evolution of triticale

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In the first-ever published report describing a fertile hybrid between wheat and rye, Carman (1884) stated: "What do they promise! If the hybrids give us a grain less valuable than wheat or rye, nothing will be gained in this case, except the curious fact that a cross between two different genera of grain is possible." While the ambitious objective of creating a crop that combines all of the best attributes of wheat and rye in a single plant has not been fully realized, the overall attributes of today's triticale provides it with enough competitive advantages for it to be increasingly grown around the world. Judging from the close to 3 million ha of triticale grown today (FAO, 2003), one could easily argue that the descendants of hybrids between wheat and rye have delivered on their promise to provide humankind with another valuable cereal crop. Wherever intensive breeding efforts have been sustained, modern triticale cultivars are on a par with the best common wheats in terms of their yield potential under favourable conditions and are often more productive than most wheats when planted in different types of marginal soils. This result in itself is quite remarkable if one considers the very short history of triticale and the relatively modest investments in research to improve this species compared to other crops such as wheat.

The purpose of this chapter is to provide a chronological review of the important historical events that have shaped the evolution of triticale from a 'botanical curiosity', as it is often referred to in the literature, to a commercially viable and competitive agricultural crop.

GENOMIC STRUCTURE

Genetically, triticale (X *Triticosecale* Wittmack) is an amphiploid species stably baring the genomes of wheat (*Triticum* sp.) and rye (*Secale* sp.). By definition, the original or 'primary' triticales are the fertile, true-breeding progenies of an intergeneric hybridization, followed by chromosome doubling, between a seed parent from the genus *Triticum* and a pollen parent from the genus *Secale*. The great majority of today's triticales are descendants of primaries involving either common wheat (*Triticum aestivum* L., 2n=42=AABBDD) or durum wheat (*Triticum durum*, 2n=28=AABB) as the seed parent and cultivated diploid rye (*Secale cereale* L., 2n=14=RR) as the pollen parent. Hexaploid wheat-derived primaries, referred to as octoploid triticales (2n=56=AABBDDRR), were the first to be produced and extensively studied. However, in spite of very valuable breeding efforts during the first half of the twentieth century, they did not spread as cultivars to any substantial extent. Since the early 1950s, and to a greater extent during the last 40 years, the bulk of the breeding and research efforts has focussed on developing and improving hexaploid triticales (2n=42=AABBRR), amphiploids originally made between tetraploid wheat and diploid rye. Consequently, the majority of triticale grown worldwide today consists of hexaploid types. However, as will be discussed in the following sections, octoploid triticales have contributed greatly to the improvement of hexaploid types.

The creation of new species through allopolyploidization is certainly not specific to triticale. This process has marked the evolution of several plant species and has provided humankind with its most important food crop, wheat, which combines the genomes of two or three ancestral grass species, brought to thrive together harmoniously within the same cell through thousands of years of natural and human-driven selection. What makes the history and evolution of triticale as a species so unique compared to that of wheat or other allopolyploids is that its evolution occurred during the last 114 years (the first 'true' triticale according to today's definition was bred in 1888 by the German breeder Rimpau) and its most dramatic evolutionary events (i.e. allopolyploidization as a result of intergeneric hybridization followed by chromosome doubling) were almost all directed by humans. In this sense, the history of triticale is truly a striking statement in support of Vavilov's definition of plant breeding as "… evolution directed by the will of man" (Vavilov, 1935, cited in Briggs and Knowles, 1967). Furthermore, in the case of triticale, it would be appropriate to state that its evolution as a crop was almost entirely directed by the unwavering will of a few people. Given the competitiveness of modern triticales among other small grains, future breeders or agriculturalists may easily forget that the development of triticale was paved with many failures, disappointments and frustrations. It did indeed take the strong will of a handful of people to overcome what many scientists regarded as insurmountable biological barriers and to persevere in spite of the disappointing performances of the early triticales and the resulting scepticism of much of the scientific and agricultural communities. The short but fascinating history of triticale is best summarized by quoting Dodge who wrote: "Triticale is a product of a century of dreams and forty years of active pursuit of the all-but-impossible" (cited in National Research Council, 1989). However, one also needs to recognize that its history and rapid evolution were markedly shaped by fortunate natural events occurring at very critical moments. Two such events are rather remarkable and therefore will be discussed below in some detail.

THE FIRST HUMAN-MADE WHEAT-RYE HYBRIDS

The first report describing the production of hybrid plants between wheat and rye (among other combinations between pairs of different cereals and grasses) was presented to the Botanical Society of Edinburgh, Scotland, by the botanist Wilson in 1875 (Wilson, 1875). He succeeded in obtaining plants with attributes intermediate between those of the two parental species. Both plants were completely sterile as they produced completely dysfunctional pollen grains. Wilson concluded his report by writing: "…[the author] presumes to submit his observations for what they are worth to those who may intend going further into the subject".

In the 30 August 1884 issue of the *Rural New Yorker*, Carman published the first-ever illustration of a partially fertile wheat-rye hybrid plant. Not aware of Wilson's experiments, Carman made a controlled cross in 1883 between Armstrong wheat (a popular, awnless variety that, according to Leighty [1916], was later called Martin Amber) and an unidentified rye, which resulted in ten seeds. Of the nine seeds that germinated, eight produced fertile plants that "resembled wheat", while only one exhibited some rye traits and was only partially fertile. In his study of Carman's records, Leighty (1916) rightly concluded that the latter plant was the only possible "true" hybrid while the other eight must have been the result of pollination by wheat in spite of all the precautions taken during crossing. Interestingly, Carman went ahead and attempted to market progenies from these plants, erroneously advertised as wheat-rye hybrids. These varieties, named RYN No.2-Willits and RYN No.3-Roberts, were never cultivated to any significant extent. Even before Leighty's review of Carman's work (Leighty, 1916), the Australian breeder Farrer (1898) had expressed strong doubts as to RNY No.2-Willits having any trace of "rye blood". On the other hand, the nearly sterile plant and only probable true wheat-rye hybrid produced extremely variable progenies. Selection efforts within the resulting populations were not successful in completely fixing all observable traits. Nevertheless, a variety called RYN No.6 was apparently released from these selections and was even grown commercially to a certain extent, at least until the year Leighty (1916) published his account of Carman's work. In light of these accounts, it is very doubtful that Carman ever produced a true-breeding, stable wheat-rye amphiploid.

In 1888, the German breeder Rimpau (reported in Rimpau, 1891) performed a series of crosses between wheat and rye, which resulted in a unique, partially fertile true-hybrid plant baring 15 seeds. Three of these produced completely sterile plants, while the remaining 12 yielded fertile plants. Unlike the progenies of Carman's hybrid, those from Rimpau's hybrids were uniform in their appearance, resembled the mother F_1 plant, and most importantly, were true breeding throughout many subsequent generations. At the time Rimpau published his results, he probably did not realize the significance of his achievement, namely, that he had just produced the first stable amphiploid between wheat and rye – the first triticale – and that he had witnessed the origin of the first new cereal species. More than 45 years later, Linschau and Oehler (1935) and Müntzing (1935, 1936) established that the somatic cells of seedlings from the stable Rimpau strain had an average of 56 chromosomes as would be expected from an octoploid amphiploid between hexaploid wheat and diploid rye. Tschermak, according to whom this strain had been cultivated for more than 40 years at the garden of the Agricultural University of Vienna (Tschermak-Seysenegg, 1936, cited in Müntzing, 1979), provided the seed studied by Müntzing. Prior indication of the amphiploid nature of the Rimpau strain was provided by Moritz (1933), whose serological analyses identified protein components from both parental species.

Several other early attempts at producing artificial wheat-rye hybrids or exploiting natural wheat-rye hybrids identified in experimental plots were reported during the first two decades of the twentieth century. All of these either produced no hybrid seed at all or, when very few seeds were obtained, they were shown to be the result of an out-crossing with wheat (or rye to a lesser extent) pollen (see Briggle, 1969 and Lorenz, 1974 for a review of these events).

EARLY BREEDING WORK WITH OCTOPLOID TRITICALE PRIMARIES

Although the history of the development of triticale was mostly human-driven, nature did help, at least in two critical instances. One such instance was the mass appearance of natural wheat-rye hybrids in experimental plots at the Saratov Experiment Station in the southeastern Russian Federation in 1918, which provided Meister and his group abundant raw material (thousands of plants) to start an extensive botanical, cytological and agronomical characterization of wheat-rye hybrids. The resulting series of studies conducted from 1918 to 1934 by Meister and his co-workers, as well as by others inspired by the Saratov event, were instrumental in understanding the cytological basis and requirements for the production of the ancestors of triticale, or "wheat-rye hybrids of balanced types" as they were referred to at the time. First, it was shown that F_1 wheat-rye hybrids were incapable of self-pollination, and if any seed was produced, which would be a rare event, it would be the result of pollination by wheat or rye and the progenies of such an out-cross would segregate for both wheat and rye attributes (Meister, 1921). However, the most significant event reported later (Meister, 1928, 1930; Tiumiakov, 1928, 1930; all cited in Müntzing, 1979) was the identification and description of fertile, true-breeding hybrid derivatives with a phenotype intermediate between wheat and rye (much like Rimpau's hybrid), which were presumed to be allopolyploids. Meister (1930) also proposed the name of *Triticum secalotricum saratoviense* Meister to designate the "balanced-type hybrids". Conclusive evidence of the amphiploid/octoploid nature of the "balanced-type hybrids" identified by Meister came in 1930 as a result of a cytological analysis performed by Lewitsky and Benetzkaja (cited in Müntzing, 1979), which demonstrated a somatic chromosome number of 56 and provided the first-ever picture of what would be an octoploid triticale karyotype. These researchers also were the first to report on the general tendency for amphiploids to exhibit a disturbed pairing at meiosis (in both the male and female side) resulting in the formation of univalents, or unpaired chromosomes.

By 1934, with the increasing influence of Lysenko on the agricultural research scene in the former Soviet Union, most of the work on triticale had stopped at Saratov (Zillinsky, 1974).

Fortunately, the work of Müntzing at Svalöv, Sweden, and of Oehler and co-workers at Münchenberg, Germany, kept the research on wheat-rye amphiploids alive and resulted in the first breeding efforts to improve the agronomic attributes of early octoploid triticales. As outlined earlier, both groups provided evidence for the amphiploid nature of the Rimpau hybrid (Lindschau and Oehler, 1935; Müntzing, 1935, 1936) thereby setting a clear record regarding the creation of triticale as a species. Incidentally, one additional contribution of the Oehler group was to use, for the first time, the name 'triticale' to designate their wheat-rye amphiploids (Lindschau and Oehler, 1935), reportedly following a suggestion from Tschermak.

Several cytogenetic mechanisms have been proposed, by which a mostly sterile F_1 hybrid between wheat and rye could spontaneously produce fertile amphiploids (van der Berg and Oehler, 1938, cited in Lorenz, 1974). In 1935, Müntzing carefully examined 65 F_1 hybrid plants representing 15 wheat-rye combinations and revealed the presence of a few partly dehiscing anthers in two plants belonging to the same cross combination. Twenty to 60 percent of the pollen grains produced in the dehiscing anthers were apparently normal and probably contained un-reduced chromosomes as indicated by their large size. Through controlled pollination using this pollen, Müntzing was able to obtain a new amphiploid plant baring 56 chromosomes. Based on these results, he suggested that the mechanism by which the early spontaneous amphiploids were produced was the spontaneous formation of a small somatic sector, which includes anthers and ovules or a small area in the anther, with a doubled chromosome number (Müntzing, 1936).

During the mid-1930s and in later decades, Müntzing started intercrossing primary octoploid triticales (those developed in Sweden as well as some introduced from other countries) and crossing these with common wheat with the objective of improving the agronomic attributes of octoploid triticale. While progenies of such crosses were clearly superior to their parents, they were still inferior to wheats in their yield potential, mainly due to their partial sterility, tendency to lodge, shrivelled kernels and susceptibility to sprouting. In light of these results, the future of triticale as a crop appeared quite bleak all through the late 1930s and 1940s.

A breakthrough came with the development of a method to double plant chromosomes using colchicine, a chemical isolated from the autumn crocus (Blakeslee and Avery, 1937). However, although many new octoploid primaries could be produced easily without having to rely on rare spontaneous doubling as described above, the use of colchicine in the end was more beneficial to the development of hexaploid triticale towards which international attention was turning. After a lifetime working on octoploid triticales, Müntzing (1979) admitted: "It is possible that the interest in triticale as a potential new crop would have tapered off completely if the efforts had been limited to octoploid material. However, this was successfully prevented by an enormous development of work with hexaploid triticales."

DEVELOPMENT OF THE FIRST HEXAPLOID TRITICALES: THE BASIS FOR COMMERCIAL SUCCESS

As for octoploid types, hexaploid triticale development started with the production of non-amphiploid hybrids (Jesenko, 1913; Schegalow, 1924, cited in Müntzing, 1979). The first report of a true amphiploid was that of Derzhavin (1938), which involved cultivated durum wheat and a wild species of rye, *Secale montanum* (cited in Zillinsky, 1974). Hexaploid primaries that would play a more important role as starting material for breeding programmes in North America and Europe were those resulting from crosses between cultivated tetraploid wheats and cultivated rye. Their production was greatly facilitated by the availability of colchicine and the improvement of techniques for embryo culture on artificial media (to rescue embryos from non-compatible combinations that would otherwise starve and produce no seed). O'Mara produced the first of such primaries in 1948 at the University of Missouri, United States of America (O'Mara, 1948), soon followed during the early to late 1950s by Nakajima in Japan (Nakajima, 1950), Sánchez-Monge in Spain (Sánchez-Monge, 1959), Kiss in Hungary (Kiss, 1971) and Pissarev in eastern Siberia, Russian Federation (Pissarev, 1966). Driven by the belief that hexaploid triticale would be superior to its octoploid counterpart, these researchers produced numerous hexaploid primaries that finally represented a much wider genetic base than that produced for octoploids.

In 1954, a privately endowed research chair was established under the initiative of Shebeski at the University of Manitoba, Canada, with the explicit objective to develop triticale finally as a commercial crop. Under the leadership of Jenkins and Evans, the breeding and cytogenetics programme assembled a comprehensive collection of primary triticales from all over the world and, in 1958, started intercrossing these stocks and selecting improved recombinants while continuing the production of new primaries (hexaploids as well as octoploids). This work was implemented for the development of both winter and spring triticales.

Probably operating on a smaller scale, the Hungarian effort headed by Kiss and the Russian effort lead by Pissarev were to become important to the success of triticale because of their crosses between octoploid and hexaploid types that resulted in progenies with greatly improved agronomic attributes compared to their parental stocks (Kiss, 1971; Pissarev, 1966). By the late 1950s, the production of secondary hexaploid recombinants from crosses between octoploid and hexaploid triticale had become a widely used method in triticale improvement, including the University of Manitoba programme (Jenkins, 1969). According to Zillinsky (1974), octoploid triticales have contributed to the progeny of such crosses through improved meiotic stability and fertility, plumper seed, lower amylase activity and higher lysine content.

After producing his own hexaploid and octoploid primaries using local varieties of wheat, *Triticum turgidum,* and rye, Kiss made his first octoploid x hexaploid cross in 1954. By 1960, he obtained secondary hexaploid recombinants that were clearly superior to either parental type, except for their weak straw. According to Müntzing (1979), one such progeny, designated as Triticale No.30, was grown on some farms, but its lack of straw strength prevented its release to wider commercial production. Undeterred by such a setback, Kiss continued improving his material using octoploid x hexaploid crosses until he obtained two selections, Triticale No.57 and Triticale No.64, which were included in National Yield Trials in 1965 (Zillinsky, 1974). In 1968, Triticale No.57 and Triticale No.64 were the first-ever triticales to be released for commercial production, and a year later they were grown on 40 000 ha in Hungarian farmers' fields.

In 1969, the Canadian programme released its first commercial cultivar, Rosner, a spring type that demonstrated good potential as a raw product for the feed, brewing and distilling, and breakfast cereal industries. The same year, the first Spanish cultivar, Cachurulu, was released, but its adoption was hampered by its susceptibility to lodging, difficulty in threshing and lack of bread-making quality (Sánchez-Monge, 1973).

While these programmes had the undeniable merit of making triticale a commercial reality in their own countries, they developed material adapted to very specific agro-ecological environments, which collectively represented a rather minor fraction of the small-grain areas worldwide. Consequently, the global spread of triticale would have had to occur through the establishment of many breeding efforts worldwide, at least one in each country interested in taking advantage of the potential of this promising new crop. This was not the case thanks to the involvement of the International Maize and Wheat Improvement Center (CIMMYT). In addition to its global mandate to develop improved wheat and maize germplasm for the world, CIMMYT rapidly became an "international base for triticale breeding", starting in the early 1960s.

CIMMYT'S SPREAD OF SPRING TRITICALE THROUGH BREEDING FOR GLOBAL ADAPTATION

The International Maize and Wheat Improvement Center was officially founded in 1966 with Mexico as its base. Triticale research in Mexico started a few years earlier under its parent organization, the Office of Special Studies of the Rockefeller Foundation under the leadership of Norman E. Borlaug. According to Zillinsky (1974), Borlaug started believing in the potential productivity and nutritional values of triticale that could improve human nutrition in food-deficient areas after he observed the breeding material at the University of Manitoba in 1958. Although the plants left much to be desired, he thought that triticale improvement could be substantially accelerated if breeders could benefit from two crop cycles in the same year, as was the case for wheats in Mexico. Soon, the triticales from Manitoba started appearing in Mexico. The first of these lines were received in 1963 from Rupert from Chile, along with wheat populations (Zillinsky, 1974), and were immediately crossed to several Mexican dwarf, day-length insensitive wheats by engineers Rodriguez and Quiñones, reportedly out of mere scientific curiosity. In 1964, the Rockefeller Foundation funded a collaborative project between Borlaug's Mexican programme and the University of Manitoba with the objective of "developing a grain crop that would be competitive with other cereals, particularly in improving human nutrition in developing countries" (Zillinsky, 1974). First led by Borlaug until 1966, the CIMMYT triticale research programme was taken over by Zillinsky in January1968. He became the first full-time triticale breeder of this organization and remained in that position until 1982.

To reach their objective, the Canadian and Mexican groups intended to use the extensive germplasm base produced and/or collected at the University of Manitoba in crosses with the Mexican photoperiod-insensitive dwarf wheats, or primaries based on these, and subject the resulting segregating populations to a shuttle-breeding scheme involving selection under three strikingly different environments. During the winter cycle, triticale material was grown in the state of Sonora, Mexico, near Ciudad Obregón (at an experiment station of the Mexican Centro de Investigaciones Agricolas del Noroeste, CIANO) located at 28°N and at an elevation of 35 masl. This is a location with almost no rainfall during the crop cycle, where irrigation is essential but where high yields are generally achievable. The main disease is leaf rust, and the plants develop with increasing day-length. Material selected and harvested in Sonora was immediately send for planting during the summer cycle some 1 800 km south, in the state of Mexico near Toluca. The latter is a high-rainfall location situated at 18.5°N and at an altitude of 2 600 masl. The Toluca Valley is a heaven for several fungal diseases including yellow rust and those caused by *Septoria* sp. and *Fusarium* sp. During this cycle, plants develop with decreasing day-length. Differences in soil types and pH are also substantial between these two locations, with Ciudad Obregón having rather alkaline soils and Toluca showing various levels of acidity. In addition to these remarkably contrasting selection sites, material was sent during the summer cycle to near Winnipeg, Manitoba, Canada (50°N, 230 masl).

With the doubling of selection cycles each year, the tripling of the number of selection sites and the contrast between these, the access to a wide range of day-length insensitive and widely adapted wheat germplasm and the increased human and financial resources devoted to its improvement, triticale would finally be in a position to become a globally adapted crop. In 1967, after four cycles of selection using the shuttle-breeding scheme on populations from the first crosses, disease-resistant, advanced lines with enough day-length insensitivity were compared in replicated yield trials to the best CIMMYT dwarf wheats. However, even with such an apparently powerful set-up, these first results were much less than encouraging as the best triticales yielded about half as much as the common wheats (Zillinsky, 1974). Poor performance was attributed to excessive height, late maturity, high incidence of sterility and severe seed shrivelling, while the total biomass production in the triticales was at least as good as in the best wheats.

During the following cycle of 1968 and without dwelling much on the disappointing results, Zillinsky and his collaborators focussed their selection efforts on finding plants (among the hundred of thousands planted) with improved fertility. In this huge 'haystack' of plants, they indeed found some that would turn out to be the 'needles' for which they were looking. A few F_4 plants from the cross designated as x308 between two hexaploid triticales exhibited what they considered improved fertility (15 percent seed-set above the best original hexaploid according to Zillinsky [1974]). Advanced progenies of these plants, subsequently named Armadillo, exhibited much more than improved fertility. They were characterized by higher test weights and grain yields and enhanced day-length insensitivity compared to the previously bred lines. They also were early maturing, shorter in stature with one gene for dwarfness and had good nutritional quality (Zillinsky and Borlaug, 1971). Also of great importance was the observation that all of these improvements were readily transmitted to the progeny of crosses involving Armadillo and that the latter was more readily crossable to common or durum wheat or rye.

The appearance of Armadillo came at a highly critical time – as the first evaluation of the products from the CIMMYT/University of Manitoba effort revealed very disappointing results – and has probably been instrumental in keeping triticale breeding alive at CIMMYT as well as the hopes for triticale to ever become a global cereal crop. Although the CIMMYT breeders of that time can be credited with several outstanding achievements, the advent of Armadillo was not of their doing. This event was in fact one of the two acts of nature, mentioned previously in this chapter, that would bare great significance on the history and evolution of triticale as a crop. Armadillo was shown to be the product of a natural out-cross between the F_1 hybrid of cross x308 and an unidentified dwarf common wheat. Nonetheless, CIMMYT breeders took full advantage of this fortunate event, and by the end of 1970, Armadillo was in the pedigree of virtually every advanced line. Later, Gustafson and Zillinsky (1973) demonstrated that Armadillo retained chromosome 2D from wheat and lost chromosome 2R from rye; and it became the primary example of what are referred to as ‘substituted’ triticales (one or several chromosomes of the rye complement substituted by the same number of chromosomes from wheat) as opposed to ‘complete’ triticales (lines possessing all seven rye chromosomes).

The International Triticale Yield Nursery (ITYN) was distributed for the first time in 39 locations worldwide in the 1969/70 crop season, providing the first opportunity to assess the yield potential and adaptability of triticale on a global scale. According to Zillinsky (1974, 1985), results were again disappointing, and the first lines distributed (including some Armadillo lines) were more narrowly adapted than the regular CIMMYT wheats (Mackenzie, 1972). However, noticeable progress became evident starting from the second and third ITYNs and continued steadily thereafter.

One characteristic the Armadillo lines did not provide was resistance to lodging and the ability to withstand high nitrogen input, which explained the persisting gap in grain yield between the best triticales and the elite dwarf wheats. Resistance to lodging through shorter straw, as well as increased yield and test weight and wider adaptation, were obtained with the cross between an octoploid primary called Maya 2 (based on semidwarf wheat INIA 66) and Armadillo. These lines (collectively called M2A) made their appearance in the fifth ITYN in 1973/74, which was grown at 47 locations worldwide. For the first time, the yield of the top five triticales outyielded by 15 percent the bread wheat check (Varughese, Baker and Saari, 1987). In 1977/78, the average yield over 71 locations of Mapache, one of the lines from the M2A cross, was higher than that of any of the 50 best CIMMYT bread wheats included in the International Spring Wheat Yield Nursery (ISWYN) (Zillinsky, 1985). To date, a total of 19 cultivars have been released worldwide from the M2A cross (Skovmand, Mergoum and Pfeiffer, 1998).

By the mid-1970s, the gap in yield between spring wheat and spring triticale had been closed, and the global adaptability of spring triticale had been established, merely 15 years (30 selection cycles) after the first triticale cross was made in Mexico. The challenge of making spring triticale a globally adapted commercial crop, competitive with other small-grain cereals, had been won.

In light of the success of the M2A lines, which like Armadillo are substituted triticales, one could have easily thought that the presence of one chromosome from common wheat would be necessary for triticale to be competitive with wheats and base a selection programme on this assumption. However, improvement of the complete types was wisely continued and resulted in the development in 1976 of two groups of lines, namely Drira and Beagle, which soon demonstrated to be as competitive and widely adapted as the M2A lines (Varughese, Baker and Saari, 1987). In fact, there is a body of evidence from analyses of data from international nurseries that indicates similar performance of both types under favourable conditions, but a clear superiority of complete types over substituted types under many forms of stress conditions (limited water availability, acid soils, nutrient deficiency or toxicity and high disease pressure) or in marginal lands (Varughese, Pfeiffer and Peña, 1996).

Between 1975 and 2000, the global distribution of CIMMYT spring triticales through its international nurseries resulted in the release for commercial production of 146 cultivars in 23 countries across five continents. In addition, encouraged by the successful establishment of spring triticale worldwide, some countries started local breeding efforts, producing their own primaries and often crossing them with CIMMYT lines, with the objective of developing material with greater specific adaptation to their own environments or to address local market requirements. Such efforts were started in Australia, Brazil, Portugal and India (development of white-grain types), just to name a few.

LARGE-SCALE EXPANSION OF WINTER TRITICALE

Whereas the area sown to spring triticales has become more and more important and involved an increasing number of countries as a result of the CIMMYT work, the majority of the world's triticale area is still sown to winter or more or less facultative types. This expanding area of winter triticale is concentrated mainly in Northern Europe and North America.

After his pioneering work opened the door for the commercial use of triticale, Kiss had to phase out his activities in Hungary in 1970. Promoting international cooperation between the countries of the former Eastern Block under Soviet influence, state officials decided that Poland was better suited for triticale research than Hungary, and Kiss was forced to transfer his breeding material to Polish scientists.

A little earlier, in 1968, Wolski and his collaborators had started an intensive winter triticale breeding effort making good use of Kiss's valuable germplasm. Much of their early work was based on triticale x hexaploid wheat crosses (Banaszak and Marciniak, 2002), culminating in their first release in 1982 of Lasko, which would become the widest grown triticale in the world. It was registered in eight countries in Europe, as well as in New Zealand. By 1986, a significant portion of the rye area in Poland, more than 300 000 ha, was replaced by triticale. The next year, with some 600 000 ha sown to triticale, Poland became the largest producer in the world. Today, Polish winter triticale cultivars are widespread all over Europe, North America and New Zealand, demonstrating competitiveness under a remarkably wide range of environmental conditions. Wolski and his collaborators have provided adapted material to several countries/regions that did not have intensive triticale breeding efforts and therefore have contributed substantially to the spread of the winter types and the resulting expansion of the area of triticale worldwide.

Other winter triticale improvement efforts have been conducted since the early 1960s in both Eastern and Western Europe; though none the size and success of the Polish programmes, they resulted in valuable material with adequate specific adaptation to the different agro-ecological areas they were targetting. Programmes in the Russian Federation, Ukraine, France, Romania and former Yugoslavia, to name a few, have yielded widely grown cultivars in each of these countries. By the mid-1980s, the success of all of these programmes, from a breeding standpoint, demonstrated that winter triticale could be bred to be competitive practically everywhere winter wheat is grown in Europe.

CONCLUDING REMARKS

This chapter has attempted to provide a chronological review of the history and evolution of triticale, from the first tentative steps towards its creation as a species to the most important events that have helped establish it as the successful commercial crop it is today. Whereas the competitiveness and wide adaptability of triticale are no longer questionable, its further expansion worldwide faces several types of challenges in the future.

From a breeding standpoint, the spectacular progress in yield and agronomic performance may have resulted in narrowing the genetic base of the triticale cultivars produced by the major breeding programmes around the world. If this trend is confirmed and nothing is done to counteract it, triticale might find itself in a vulnerable position, which might ultimately hamper its expansion. As its area grows, triticale is increasingly exposed to various pathogens, and the opportunities for these pathogens to produce physiological variants with severe virulence on major cultivars are enhanced accordingly. The identification, use and maintenance of as much genetic variability as possible for genes conferring resistance to various pathogens of economic importance needs to be ensured to prevent such potentially devastating genetic vulnerability.

ACKNOWLEDGEMENTS

The authors would like to thank John E. Woolston, from CIMMYT's Information Services, for his valuable help in obtaining historical triticale publications.

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Triticale crop improvement: the CIMMYT programme

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Cereals are worldwide the most important cultivated crops and account for the main source of energy and protein in human and domesticated animal diets (Rajaram, 1995). Addressing the increasing demand for food in developing countries continues to be a major concern worldwide, due to the high population growth rates aggravated by natural calamities, such as drought, diseases and pest epidemics. Today, many developing countries rely on importing large quantities of wheat, rice, maize and barley to meet their food and feed grain needs (Curtis, 2002). Increasing national cereal production in these countries can be achieved through increasing average yield per unit area or expanding the area devoted to cereals into more marginal lands. Under these environmental conditions, an additional crop, which provides farmers with improved production alternatives, will make a significant contribution to farmers' income. Triticale (X *Triticosecale* Wittmack), the 'human-made' crop, developed by crossing wheat (*Triticum* sp. L.) and rye (*Secale cereale* L.), which is adapted to harsh, low-input, sustainable farming systems, is a viable alternative (Plate 1). Triticale, though a newly cultivated crop, is rapidly expanding in several production systems (Pfeiffer, 1994; Hinojosa *et al.*, 2002). Its ability to produce higher biomass and grain yield compared with other cereals over a wide range of soil and climatic conditions has enhanced its adoption in more than 30 countries. Triticale today is cultivated on nearly 3 million ha (FAO, 2003).

A BRIEF HISTORY OF TRITICALE AT CIMMYT

Triticale, the successful 'human-made' cereal grain, was first deliberately produced in 1876 and has developed during the last 100 years. Interest in triticale at the International Maize and Wheat Improvement Center (CIMMYT) dates back to 1958 when Norman E. Borlaug (at that time with the predecessor organization, the Office of Special Studies of the Rockefeller Foundation) attended the First International Wheat Symposium at the University of Manitoba, Canada. What became the CIMMYT Triticale Improvement Program started in 1964 under the leadership of Borlaug, followed by Frank J. Zillinsky in 1968 (Zillinsky and Borlaug, 1971). This programme, in cooperation with the University of Manitoba, was funded initially by the Rockefeller Foundation. In 1971, the Government of Canada undertook complete funding of the CIMMYT Triticale Improvement Program.

In the beginning, several major hurdles had to be overcome to tailor triticale to become a viable crop. Early triticales, though vigorous in growth habit, were extremely late, very tall, highly sterile, day-length sensitive and had shrivelled seeds. The first major breakthrough came by serendipity when a triticale plant resulting from a natural out-cross to unknown Mexican semidwarf bread wheat was selected in 1967. The selected line, named Armadillo, made a major contribution to triticale improvement worldwide since it was the first triticale identified to carry a 2D(2R) chromosome substitution (D-genome chromosome substitution for the respective R homeologue). Due to this drastic improvement in triticale germplasm, numerous cultivars were released, and the crop was over-promoted to farmers as a 'miracle crop'. This premature excitement disillusioned many farmers and scientists and hampered adoption of the crop (CIMMYT, 1976).

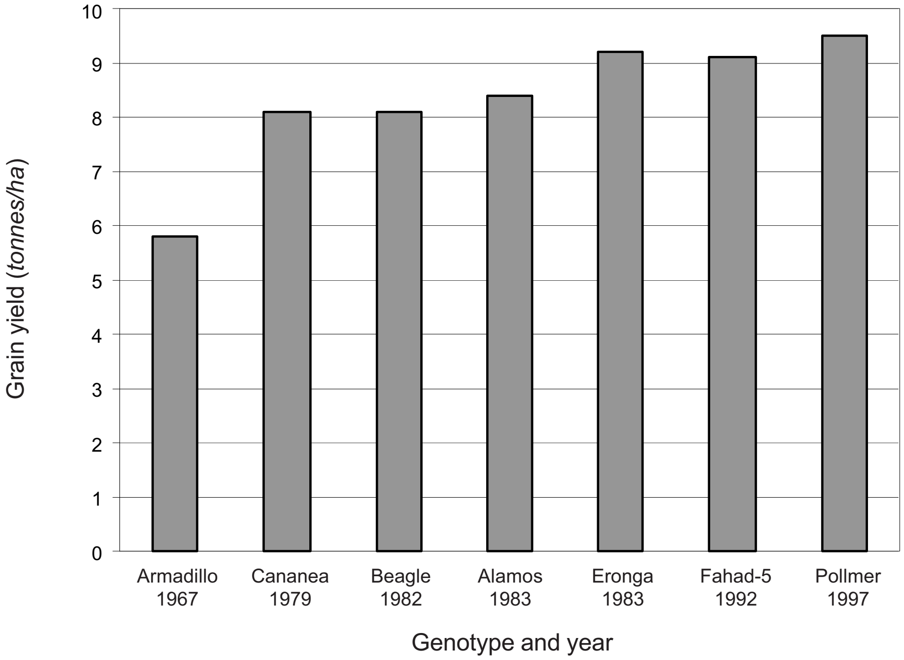
By the late 1980s, data from international yield trials indicated that complete hexaploid triticale (AABBRR genomic representation) was agronomically superior to 2D(2R) substituted hexaploid types, particularly under marginal growing conditions. Thereafter, triticale germplasm at CIMMYT was gradually shifted towards complete R genome types to better serve these marginal environments.

Today, CIMMYT is the principal supplier of improved spring triticale germplasm for many national agricultural research systems around the world. The spring material is also an ancestral constituent of most winter triticales.

MAJOR ACHIEVEMENTS OF TRITICALE IMPROVEMENT AT CIMMYT

Three decades of research on triticale by CIMMYT in collaboration with National Agricultural Research Systems (NARS) around the world have resulted in substantial improvements of triticale. Today, triticale is an accepted crop in many countries, and areas grown to this crop are expanding. In 2003, triticale occupied nearly

FIGURE 1
Genetic progress in grain yield of spring triticale at CIMMYT, 1967-1997; estimated genetic progress over period is 120 kg/ha/year



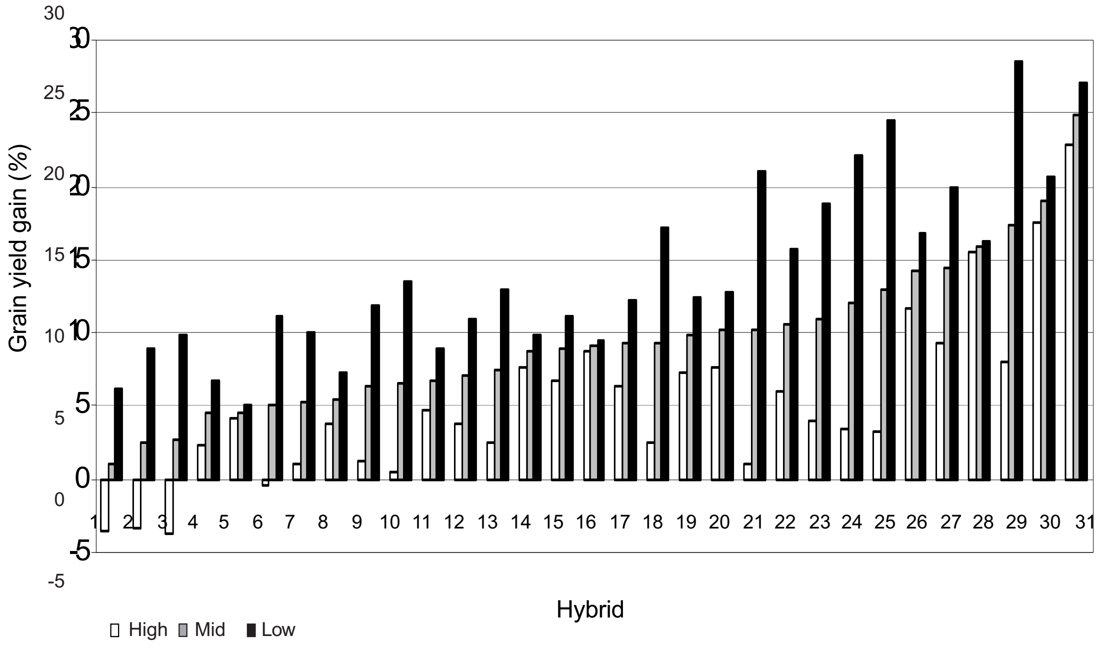
3 million ha worldwide, compared to about 1 million ha in 1988 (Varughese, Pfeiffer and Peña, 1996a; FAO, 2003). Ample evidence now exists showing that triticale has potential as an alternative crop for different end-uses in a wide range of environments, particularly for marginal and stress-prone growing conditions (Pfeiffer, 1995).

Since 1969, when CIMMYT first distributed triticale germplasm internationally, national programmes have released cultivars derived from this germplasm. Data on cultivar releases based on CIMMYT spring triticale germplasm are very sketchy due to the lack of information from some NARSs or the confidentiality required by the private sector. However, present information available at CIMMYT shows that since the mid-1970s more than 200 cultivars have been released in more than 30 countries from direct CIMMYT germplasm introductions (advanced lines) or through selection from segregating populations. Some releases from the newly distributed winter and facultative CIMMYT nursery (TCLWF) have been reported from several countries such as Mexico.

Yield potential

Since the establishment of the CIMMYT triticale breeding programme in 1964, improvement in realized grain yield potential has been remarkable. In 1968, at Ciudad Obregón, Sonora, Mexico, the highest yielding triticale line produced 2.4 tonnes/ha with a test weight of 65.8 kg/hl. Eleven years later under similar conditions, the best triticale line yielded 8.5 tonnes/ha with a 72 kg/hl test weight (Zillinsky, 1985). The yield potential of triticale continued to increase in the subsequent ten years of breeding at CIMMYT. Under near optimal conditions at Ciudad Obregón, a comparison of maximum-yield trials of triticale developed in the 1980s and 1990s revealed an average increase of 1.5 percent/year (Sayre, Pfeiffer and Mergoum, 1996). This yield progress was mainly due to a substantial increase in harvest index (16 percent), grains/m^2 (17 percent), spikes/m^2 (12 percent) and test weight (12 percent) and a decrease in plant height (11 percent). Hence, today's high-yielding CIMMYT spring triticale lines (e.g. Pollmer-2) surpassed the 10 tonnes/ha yield barrier under optimum production conditions at Ciudad Obregón (Figure 1) (Sayre, Pfeiffer and Mergoum, 1996). Obviously, compared to early developed triticale, the new strains are characterized by higher harvest index and test weight, significantly increased number of spikes/area and grains/spike and generally shorter stature (Pfeiffer, 1995; Sayre, Pfeiffer

FIGURE 2
Grain yield gains (heterosis) in percentage of low-, mid- and high-yielding parents of 31 spring triticale hybrids developed at CIMMYT using a chemical hybridizing agent under a high-input environment at Ciudad Obregón, Sonora, Mexico, 1995/96 and 1996/97



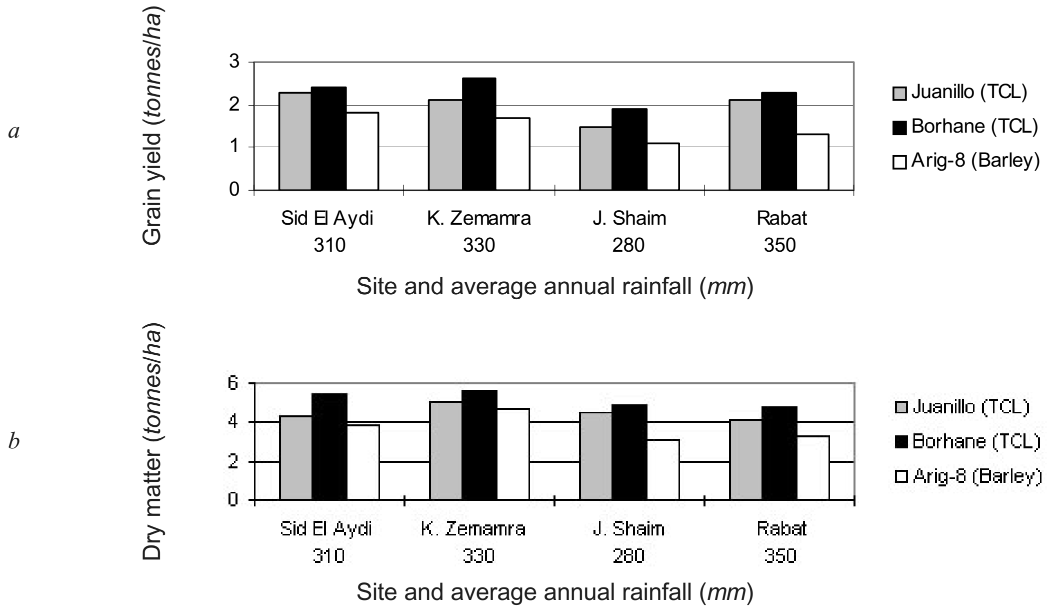
and Mergoum, 1996). Parallel progress was achieved in other essential agronomic production components, such as lodging resistance, early maturity and threshability, which is an important trait for smallholder farmers.

In recent years at CIMMYT, substantial research efforts have been devoted to exploring the utilization of triticale hybrids as a new way to enhance and 'break' the yield barrier. Several hybrids produced via chemical hybridizing agents (CHA) were evaluated for their agronomic performance and physiological traits under full-irrigated conditions at Ciudad Obregón (Figure 2). Grain yield distributions for the hybrids showed substantial heterosis for grain yield, up to 27 percent of the high parent. Hybrids, which yielded less than the low parent, had in general very high biomass, but the harvest index was low due to excessive plant height and late maturity. The cytoplasmic male sterile (CMS) system is also being explored as a sustainable way to produce hybrids in developing countries.

Adaptation

Germplasm expressing high, stable yields as a result of input efficiency and responsiveness, and resistance to a wide range of biotic and abiotic stresses is a hallmark of CIMMYT's cereal improvement philosophy (Rajaram *et al*., 1993). Hence, the development of triticale with wide adaptation over a large range of environments has been a major objective of the CIMMYT Triticale Improvement Program. Triticales, particularly those with a complete R genome, exhibit a competitive yield advantage in marginal lands, which are afflicted with abiotic stresses, such as low and erratic rainfall, soil acidity, phosphorus deficiency, trace element toxicity or deficiency and shallow marginal soils. These triticales also perform well in crop situations where diseases, insect pests and weeds constitute biotic production constraints. Hence, elite germplasm selected from advanced CIMMYT germplasm has shown since the early 1980s (e.g. Beagle, Eronga, etc.) and with the latest selections (e.g. Rhino 's', Bull/Manatti, Fahad-5, Pollmer, etc.) improved adaptation and good performance in contrasting environments. Similarly, early maturity, a typical characteristic of substituted triticale and many new complete lines, allows escape from terminal developmental stress, such as heat or frost, in highly productive environments, such as the irrigated subtropics and Mediterranean climates. Maturity differences between complete and substituted types are now smaller.

FIGURE 3
Performance in grain yield (a) and dry matter (b) of new triticale Borhane versus old triticale Juanillo and barley Arig-8 in four sites of the arid and semi-arid zones of Morocco; yields are relatively low in Rabat, Morocco, due to sandy soils with very low water retention that prevail in the costal region compared to other dryland sites



Under marginal land conditions, where abiotic stresses related to climatic (drought, extreme temperatures, etc.) and soil conditions (extreme pH levels, salinity, trace elements deficiency or toxicity, etc.) are the limiting factors for grain production, triticale has consistently shown its advantages compared to the existing cultivated cereal crops (Figure 3). Data, reports and experience from the arid and semi-arid regions of North Africa, for instance, have shown that triticale is an excellent alternative crop to the other cereals, particularly wheat and barley (Plate 2) (Belaid, 1994; Mergoum, Ryan and Shroyer, 1992; Saade, 1995; Varughese, Pfeiffer and Peña, 1996a). Since its cultivation is similar to traditional grown barley or wheat and it offers many more end-use alternatives for both humans and animals, triticale can be grown in stressed environments with low input for grazing, grain and straw production. In addition, in the relatively high-input areas (irrigated and high-rainfall regions), it can be used as forage or for dual purposes.

Similarly, under acid soils, such as in southern Brazil, triticale has demonstrated high tolerance to low pH levels. This enables the crop to be grown on relatively extensive areas, estimated at 130 000 ha in 2001 (do Nascimento Junior *et al.*, 2002), mainly in the southern regions of Rio Grande do Sul, Paraná and Santa Catarina. New promising triticales combining higher yield and other desirable traits (test weight, scab tolerance, early maturity, etc.) have been identified among modern CIMMYT germplasm, or its derivatives have been identified by national scientists, to replace or complement the existing cultivated cultivars.

Input-response efficiency

Response to input, such as nutrients or water, is a key element for triticale to be adopted by farmers, particularly under marginal conditions. Significant progress has been made in developing input-efficient triticales. Under high-input conditions, CIMMYT early developed triticale variety Beagle (1980s) compared with the later advanced line Fahad-5 (1990s) showed significant differences in grain yield under varying nitrogen (N) levels (Figure 4). Whereas Beagle yields were significantly lower than average triticale yields, Fahad-5 produced more grain than average for all N treatments. Yields of both cultivars at 0, 75, 150 and 300 kg/ha N were 1.3 and 1.6, 4.3 and 5.0, 5.3 and 7.0, and 6.0 and 7.5 tonnes/ha for Beagle and Fahad-5, respectively (Sayre, Pfeiffer and Mergoum, 1996). The yield differences between the two cultivars increased drastically with the N level applied. These results demonstrate clearly the substantial genetic

FIGURE 4
Grain yield response of new Fahad-5 versus old Beagle CIMMYT-developed triticales to nitrogen levels under high-input conditions at Ciudad Obregón, Sonora, Mexico

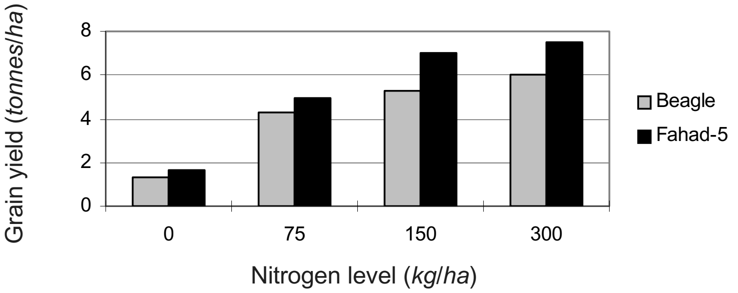


FIGURE 5
Triticale grain yield and straw dry-matter response to nitrogen levels under drought conditions in Morocco

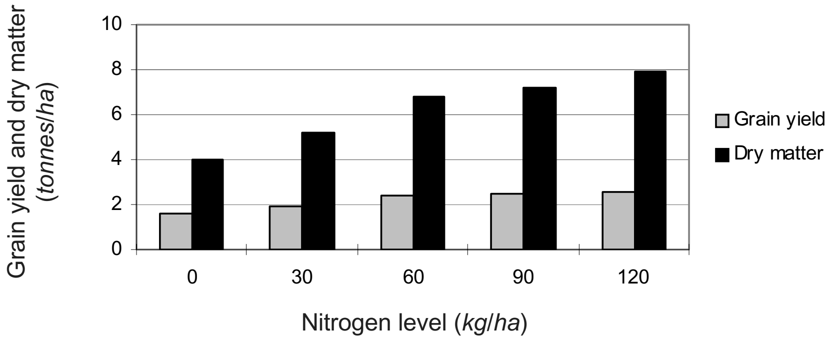
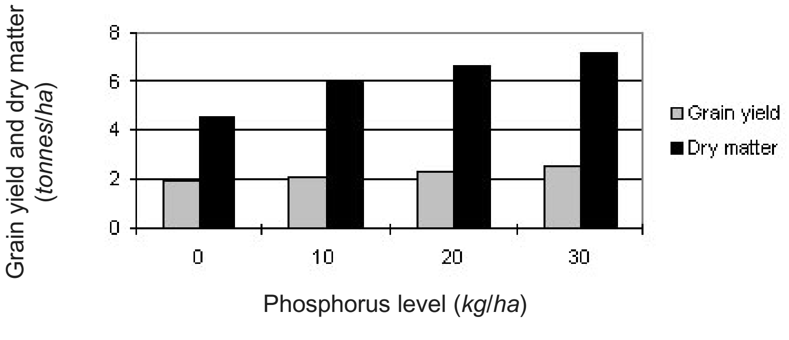


FIGURE 6
Triticale grain yield and straw dry-matter response to phosphorus levels under drought conditions in Morocco



progress achieved by CIMMYT in identifying improved lines with better N use under both low and high inputs. Under the drought conditions of North Africa, the grain and biomass yield response of triticales has shown to be substantially higher with larger increments of nitrogen and phosphorus inputs (Figure 5, Figure 6) (Mergoum, Ryan and Shroyer, 1992). Similarly, data collected over years in different agro-ecological zones of Morocco have shown that triticale outyielded both best wheat (bread and durum) and barley cultivars in semi-arid zones at high elevation and in the Atlantic coastal areas (Mergoum, 1989). In sandy coastal soils, where triticale yielded more than 5 tonnes/ha, neither wheat nor barley exceeded 1 tonne/ha (Mergoum, 1989; Mergoum, Ryan and Shroyer, 1992). Similar results have been reported elsewhere showing the adaptation of triticale to stressed environments, particularly to water stress (Aniol, 2002; Barary *et al.*, 2002).

End-use quality characteristics

Triticales have been selected for better grain type (e.g. grain plumpness and test weight) since the improvement programme was started at CIMMYT in 1964. The most significant improvement for plumper grain was obtained concurrent with the identification of Armadillo and its derivatives. The test weight of the best Armadillo selections in 1970 at Navojoa, Sonora, Mexico, was 73.7 kg/hl compared to 65.8 kg/hl of the best line in 1968 (Zillinsky and Borlaug, 1971). Substantial progress has continued for improved test weight, and some modern triticales can reach 80 kg/hl under favourable environmental conditions.

While the shift in breeding emphasis to complete R genome and 6D(6A) triticale in the 1980s was accompanied by an improvement in test weight, leavened bread-baking quality was negatively affected. Since 1990, due to specific end-use and market requirements, more emphasis has been given to developing triticale for specific end-uses, such as milling and baking purposes, feed grain, dual-purpose forage/grain and grazing types. Low gluten content, poor gluten strength and high levels of alpha-amylase activity caused mainly by pre-harvest sprouting generally result in triticale flour with weak dough that is unsuitable for many bread-making operations. However, there is pre-harvest sprouting tolerance and gluten quality variability in triticale, which allows breeders to select for improved dough quality (Amaya and Peña, 1991; Peña, Mergoum and Pfeiffer, 1998) and therefore bread-making quality.

In general, facultative- and winter-habit triticale produce higher forage biomass than spring types. Therefore, their use for forage (grazing), cut forage, silage, cut forage/grain or hay has been proven through the release of several forage-specific cultivars. In addition, in many countries cereal straw is a major feed source for animals and in some years can have greater value than grain (Benbelkacem, 1991; Mergoum, Ryan and Shroyer, 1992; Ouattar and Ameziane, 1989). Under arid and semi-arid conditions, triticale has been shown consistently to produce higher straw yields than wheat and barley (Mergoum, Ryan and Shroyer, 1992).

Pest and disease resistance

Initially, diseases did not appear to be a serious constraint to triticale production, probably because the areas grown to triticale were not sufficient to cause serious shifts in pathogen virulence. As triticale area expanded, this situation changed, and most wheat and rye diseases now also occur on triticale (Zillinsky, 1985; Singh and Saari, 1991; Mergoum, 1994). Since 1971, CIMMYT has monitored the major diseases affecting triticale around the world. In comparison with wheat, triticale appears to have good resistance to several common wheat diseases and pests including: rusts (*Puccinia* sp.), *Septoria* sp., smuts (*Ustilago* and *Urocystis* sp.), bunts (*Tilletia* sp.), powdery mildew (*Blumeria graminis*), cereal cyst nematode (*Heterodera avenae*) and Hessian fly (*Mayetiola destructor*). It also resists virus diseases, such as barley yellow dwarf, wheat streak mosaic, barley stripe mosaic and brome mosaic (Varughese, Pfeiffer and Peña, 1996a; Skovmand, Fox and Villareal, 1984). However, triticale has relatively greater susceptibility than wheat to diseases such as spot blotch (*Bipolaris sorokiniana*), scab (*Fusarium* sp.) and ergot (*Claviceps purpurea*) and bacterial diseases caused by *Xanthomonas* sp. and *Pseudomonas* sp., which preclude the immediate commercial introduction of triticale in those areas where wheat is otherwise better adapted (e.g. Zambia and parts of Brazil) (Skovmand, Fox and Villareal, 1984).

The reaction of triticale to many diseases meets the expectations of a combined resistance found in the two parental species. The disease and insect resistance reactions of one or the other of the parents is reflected in triticale progeny, or the reaction of triticale is intermediate between that of wheat and rye, as in the case of take-all (*Gaeumannomyces graminis*) and Russian wheat aphid (*Diuraphis noxia*).

Preliminary results on the behaviour of triticale compared with inoculation by several cereal pathogens under greenhouse conditions show that triticale can be as vulnerable as any other cereal to most prevalent diseases. Similar findings on the susceptibility of triticale to certain pathogens, such as yellow rusts (Zillinsky, 1974; Saari, Varughese and Abdalla, 1986), *Septoria* (Zillinsky, 1983; Saari, Varughese and Abdalla, 1986; Skajennikoff and Rapilly, 1985; Eyal and Blum, 1989), *Bipolaris sorokiniana* (Bekele *et al.*, 1985; Skovmand, Fox and Villareal, 1984; Zillinsky, 1983) and *Pyrenophora tritici-repentis* (Martens, Seamen and Atkinson, 1988; Saari, Varughese and Abdalla, 1986; Felicio, Camargo and Leite, 1988), were also reported previously. The virulence of isolates, particularly those of pathogens *Pyrenophora* *tritici-repentis*, *Bipolaris sorokiniana* and *Septoria nodorum*, originating from both bread wheat and triticale, suggests that, probably, the same race can attack both wheat and triticale. Early work had shown that some pathogens, such as leaf rust (*Puccinia triticina*) (Fuentes, 1973; McIntosh and Singer, 1986) and stem rust (*P. graminis* f. sp. *tritici*) (Lopez, Rajaram and de Bauer, 1973), have a wide host range, including triticale and wheat. However, new recombinants from *tritici* and *secali* races for certain pathogens can also be considered (Lopez, Rajaram and de Bauer, 1973; Fuentes, 1973).

CURRENT AND FUTURE CHALLENGES

Future challenges are guided by CIMMYT's mission, which is to help poor farmers by increasing the productivity of resources committed to cereals in developing countries while protecting natural resources (Rajaram *et al.*, 1993). The relatively low adoption of triticale by farmers in several countries is in contrast with encouraging international nursery data, cultivar releases and reports from NARS scientists and on-farm data, which indicate the high production potential of triticale, particularly for small farmers in marginal environments. However, there are several transitory social- and economic-related issues that limit triticale expansion in many countries (Saade, 1995). Improvements in several economic and biological traits are required in order to tailor this crop to fit farmers' needs and market requirements. Following are some challenges that the authors believe will play an essential role in the future of triticale.

Genetic variability

Due to a lack of natural evolution and the relatively 'young' nature of the crop, triticale breeders have been continuously facing challenges associated with generating enough genetic diversity for continued crop improvement. Hence, a strategy for crop enhancement is necessary that emphasizes the maintenance and generation of genetic diversity, while carefully balancing diversity objectives required to ensure long-term progress with the relatively narrower frequency of favourable alleles necessary to achieve short-term breeding goals.

In triticale, the lack of inherent genetic diversity may be overcome by the varied spectrum of potentially introduced diversity. For example, spring and winter wheat and rye gene pools are accessed through direct interspecific (wheat x triticale) and intraspecific (winter triticale x spring triticale) crosses. Octoploid x hexaploid triticale crosses guarantee an influx of cytoplasmic variability. Many modern triticale lines developed from such crosses carry D(A) and D(B) whole chromosome substitutions or chromosome translocations and add valuable traits to triticale. Genetic systems from wheat alien species, e.g. *Aegilops tauschii* (syn. *Triticum tauschii*), are transferred into triticale via wheats carrying alien introgressions.

Furthermore, results from CIMMYT International Triticale Yield Nurseries suggest adaptive advantages of complete triticale carrying a 6D(6A) substitution. The optimal chromosomal constitution of triticale – the make-up of homeologous AA, BB, DD and RR chromosomes or chromosome arms – has yet to be defined, and unique optimal chromosomal configurations for the diverse agro-ecological zones and end-uses are likely to emerge. Unique combinations can be constructed in hybrid triticale.

Modification of phasic development for specific adaptation

The development of populations with specific traits facilitates the combination of desirable traits from different unadapted genotypes with adapted germplasm. Recently, more emphasis has been directed towards improving certain triticale agronomic traits, including grainfilling duration and rate, earliness and tillering capacity, but quality parameters have also been addressed, such as test weight, protein content and gluten strength enhancement (Boros, 2002).

Triticale in general requires a longer grainfill period than wheat, although the number of days to flowering can be similar. In arid and semi-arid zones, where there is potential for triticale production to expand, terminal drought is frequent. With its slower maturity, triticale production may be limited under such climatic conditions by vulnerability to terminal stress and late/early frost situations with drastic effects on grain yield. Therefore, future research efforts should focus on shortening the grainfill duration and increasing the grainfill rate.

Biotic stresses

Although triticale has shown good resistance to most prevalent diseases and insects in most cereal-growing areas, with the spread of this crop and the race specialization of pests, triticale has become vulnerable to certain diseases or insects. During dry years in North Africa (1992-1995), several triticale genotypes became susceptible to a new emerging biotype of Hessian fly and Russian wheat aphid. Selection for resistance to these pests is now included in the CIMMYT programme.

Reports from Ecuador and the highlands of Mexico (Toluca) (CIMMYT, 1996) showed that more than 20 percent of CIMMYT triticale germplasm was susceptible to a new race of stripe rust (*Puccinia striiformis*) (Plate 3). The Toluca strain at least is suspected to have overcome *Yr9* in wheat. Consequently, efforts now concentrate on the development of different sources of resistance to stripe rust in CIMMYT germplasm. Similarly, in Australia in 1984/85, two new races of wheat stem rust (*Puccinia graminis tritici*), races 34-2,12 and 34-2,12,13, arose that proved virulent on 90 percent of CIMMYT introductions and on nine of the ten current Australian triticale cultivars. Locally produced germplasm and the few resistant adapted CIMMYT introductions rapidly replaced susceptible materials in Australian breeding programmes, and a testing service for resistance to race 34-2,12,13 was established (K.V. Cooper, personal communication).

Abiotic stresses

Breeding for the abiotic stresses of marginal lands (acid, sandy or alkaline soils), trace element deficiencies (copper, manganese and zinc), or trace element toxicity (high boron), and the different types of moisture stresses will still constitute a major effort in spring and winter/facultative triticale improvement at CIMMYT. This can be achieved by exploiting key locations during selection, screening and yield testing and through shuttle-breeding involving NARSs (e.g. Brazil for acid soils and sprouting and Morocco for terminal drought and sandy soils).

End-use quality requirements

Animal feed and forage

The advantage of triticale in farming systems has been primarily in animal feeding. To date, most of the triticale production is used either as animal feed grain, forage, or both (Belaid, 1994; Saade, 1995). Facultative- and winter-habit triticales, in general, produce higher forage biomass than spring types; therefore, they are more suitable for forage grazing, cut forage, silage, cut forage/grain or hay. Forage and forage/grain dual-purpose triticales are a new area of breeding and research at CIMMYT. Such triticales may complement crop and livestock enterprises in developing countries. In contrast to grain triticales, the requirements in terms of growth habit are highly environmental and management specific, particularly for dual-purpose and multiple-forage harvest situations (Plate 4). A new international triticale nursery consisting of facultative and winter grain and forage triticale advanced lines (FWTRITICALE) has been created to complement the existing international nurseries. Several advanced lines have already been selected and released from this nursery. In the northern states of Mexico, released winter triticales AN 31 and AN 34 and promising lines TCL 38, TCL 39 and TCL 78 from the joint programme of the Universidad Autónoma Agraria Antonio Narro in Saltillo, Coahuila, Mexico, and CIMMYT outperformed substantially the forage production of other crops, such as barley, ryegrass and oats (Figure 7).

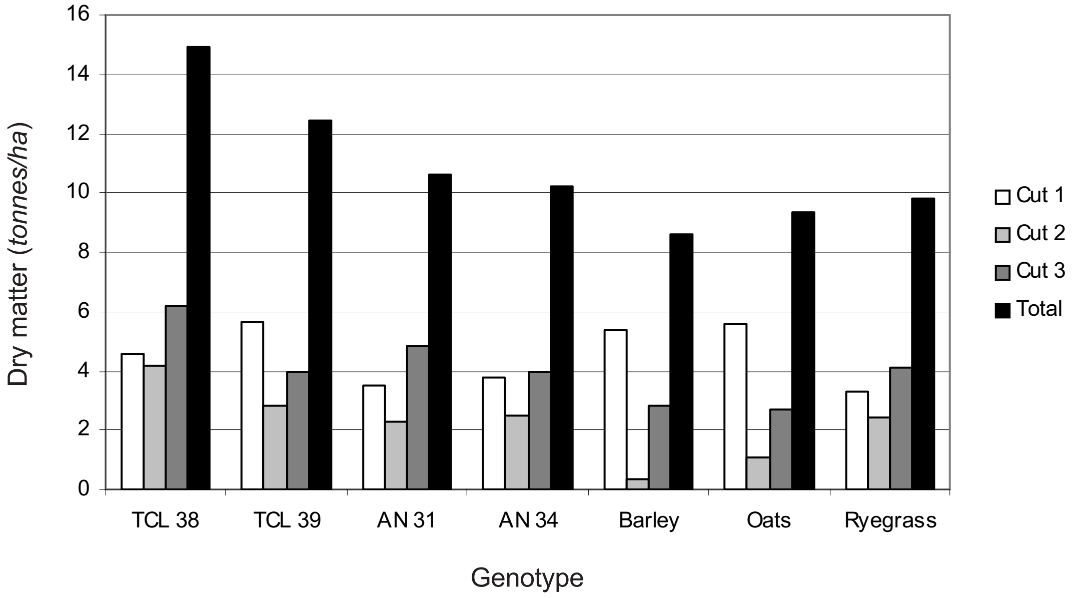
As animal feed, triticale has clear advantages. Its amino acid composition fits the nutritional requirements of monogastrics and poultry very well (Belaid, 1994; Pfeiffer, 1994; Saade, 1995; Varughese, Pfeiffer and Peña, 1996b). Studies in Algeria and Tunisia have shown that triticale can substitute for maize in poultry feed rations (Belaid, 1994; Saade, 1995). Chemical analysis of promising triticale lines should become a regular technique in cultivar screening in the future at CIMMYT in order to identify genotypes with a desirable nutritional profile. Research should focus on the characterization of the nutritional value of triticale genotypes and the selection of new cultivars with improved biological value for poultry, e.g. with high crude protein content and metabolized energy.

In many countries, cereal straw is a major feed source for animals and can have higher value than grain, especially in dry years (Benbelkacem, 1991; Mergoum, Ryan and Shroyer, 1992; Ouattar and Ameziane, 1989). Triticale usually surpasses wheat and barley in straw production, particularly in arid and semi-arid zones (Mergoum, Ryan and Shroyer, 1992). Research characterizing straw quality requirements and potential is required.

Human consumption

Triticale grain and flour is generally a good source of vitamins and mineral nutrients (Lorenz, Reuter and Sizer, 1974). In addition, protein concentration is similar to wheat, while lysine levels can be enhanced (Villegas, McDonald and Gilles, 1970). Thus, selection for enhanced nutritive value will impact those communities where cereal-based diets predominate, in particular with women and children. Similarly, new methodologies, particularly in plant transformation using molecular biology techniques, which have been shown to be more successful with triticale versus other cereals, could be investigated as a promising tool to improve the nutritive quality of triticale.

FIGURE 7
Dry-matter forage production (total and per cut) of winter triticale cultivars AN 31 and AN 34 and lines TCL 38 and TCL 39 compared to barley, oats and ryegrass in northern Mexico



Milling and baking

Recent reports indicate that triticale is widely used as feed grain and/or forage, while its utilization for human consumption is still limited. Until recently, breeders have concentrated their efforts on improving triticale agronomic characters and disease resistance, while less attention has been given to the improvement of traits associated with grain colour and bread-making quality (Peña, 1994). However, today's triticale can substitute for soft wheat to make various soft-wheat type products, such as cookies and biscuits.

Genetic gains for quality traits based on existing genetic variability and heritability estimates (Pfeiffer, 1994) indicate that progress can be expected. High-yielding, complete triticale germplasm is now available with acceptable loaf volumes (Plate 5). However, relying on the existing variability for baking quality parameters may not solve the inherent limitations in the bread-making quality of triticale. Current baking quality improvement strategies focus on the accumulation of favourable non-enzymatic endosperm proteins. In hexaploid wheat, the genes for non-enzymatic storage proteins are located on the chromosomes of group 1 (glutenins and gliadins) and group 6 (gliadins). Among those, the high molecular weight (HMW) subunits of glutenin coded by presumably homologous gene loci on the long arm of chromosome 1A, 1B and 1D are closely associated with bread-making quality (Pfeiffer *et al.*, 1996). Crosses have revealed at least 21 allelic variants at glutenin subunit loci *Glu-A1*, *Glu-B1* and *Glu-D1*. The relative importance of the glutenin subunit loci *Glu-A1*, *Glu-B1* and *Glu-D1* approximates a ratio of 20:30:50 (Pfeiffer *et al.*, 1996).

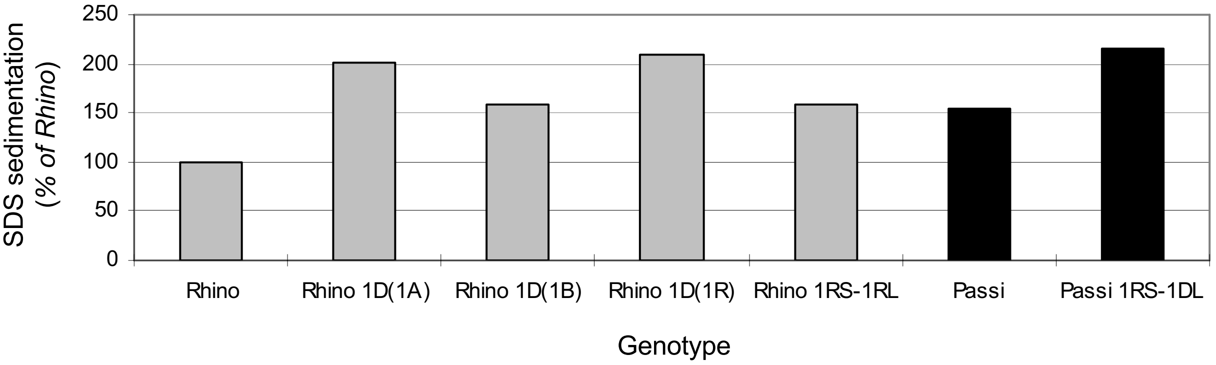
Hexaploid triticales not only lack the *Glu-D1* genes for quality, but complete triticales carry the major endosperm secalin proteins *Sec-1*, *Sec-2* and *Sec-3* on the rye genome, which may negatively affect baking quality (substituted triticales carry *Sec-1* and *Sec-3*). The favourable HMW loci on *Glu-A1*, *Glu-B1* and *Glu-D1* have been transferred to triticale and are being combined in targetted crosses, aiming to impact significantly gluten strength and bread-making quality in triticale. The effect of transferring *Glu-D1* HMW glutenin subunits into triticale is shown in Figure 8.

High alpha-amylase activity is a common defect of triticale grain (Trethowan, Peña and Pfeiffer, 1994). High levels of enzymatic activity have a detrimental effect on the functional properties of bread-making dough. Selection for reduced enzymatic activity and tolerance to pre-harvest sprouting is necessary to improve utility and marketing stability.

Grain characteristics

Dark colour and shrivelled grains still remain a major handicap for triticale expansion and use in many

FIGURE 8
Effect of D-genome chromosome substitutions or translocations on quality parameters of spring CIMMYT triticales Rhino and Passi



Source: Varughese, Pfeiffer and Peña, 1996b.

countries, particularly when the grain is ground to obtain wholemeal flour to produce baking products (for example, flat breads in North Africa and India). Therefore, since the 1995/96 crop cycle, substantial emphasis has been given to these traits, and an intensive crossing programme was launched to incorporate these traits into the best performing triticale genotypes. Advanced white grain triticale lines (F_5, F_6 and F_7), selected based on white colour, were included for the first time in yield test trials at Ciudad Obregón in 1997/98. Best performing lines with yield similar to traditional dark grain were distributed to NARSs through the International Triticale Screening Nursery and the International Triticale Yield Nursery. However, more selection cycles might be needed to combine the white grain colour trait into most best quality lines that exist in CIMMYT germplasm in order to meet quality standards for human uses of triticale.

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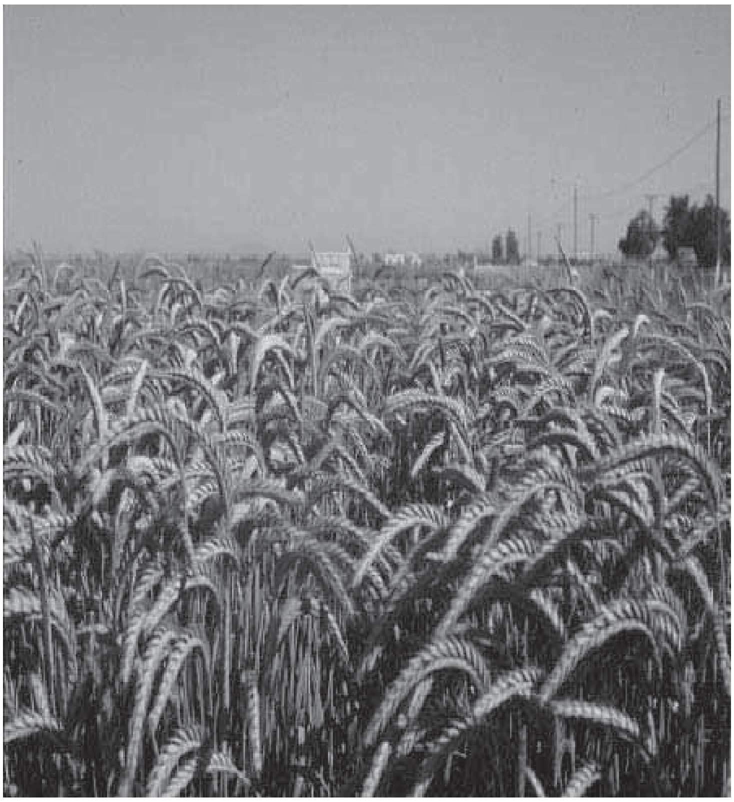
PLATE 1
Triticale, still a 'promising' crop with great potential, yet to be fully exploited
M. Mergoum



a - awnless triticale at early-milk stage suitable for forage or hay use in Morocco

b - early-maturing triticale for grain production in Morocco

PLATE 2
CIMMYT triticale Juanillo 'S' showing tolerance to drought in a barley nursery in a very dry environment at Sidi Laydi, Settat, Morocco
M. Mergoum

PLATE 3
*Resistant versus susceptible triticale lines to the new stripe rust (*Puccinia striiformis*) race at Toluca, Mexico*
M. Mergoum

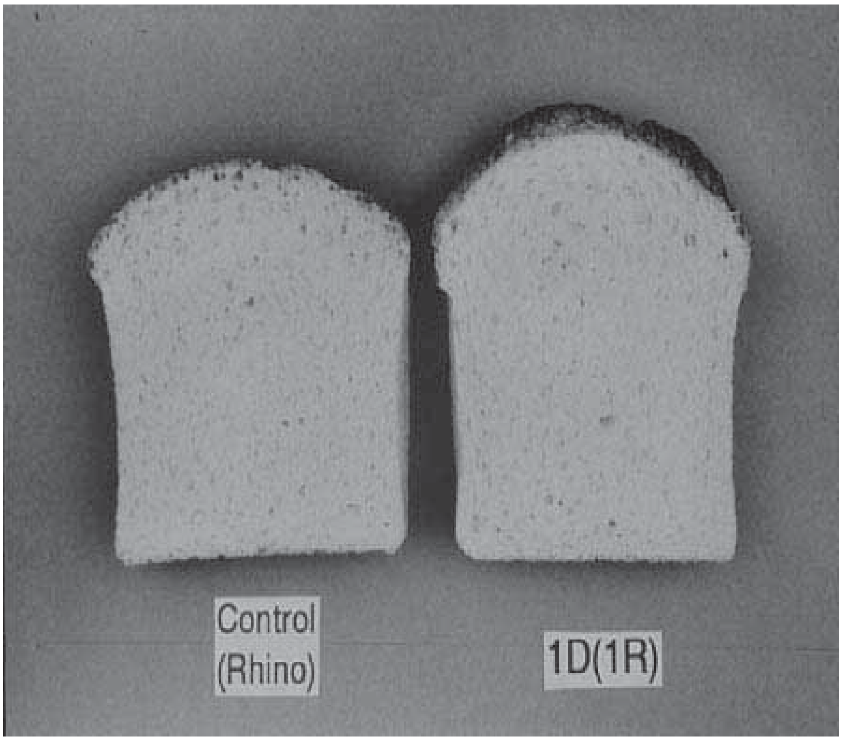
PLATE 4
High forage production for silage using triticale in northern Mexico
A.J. Lozano del Río

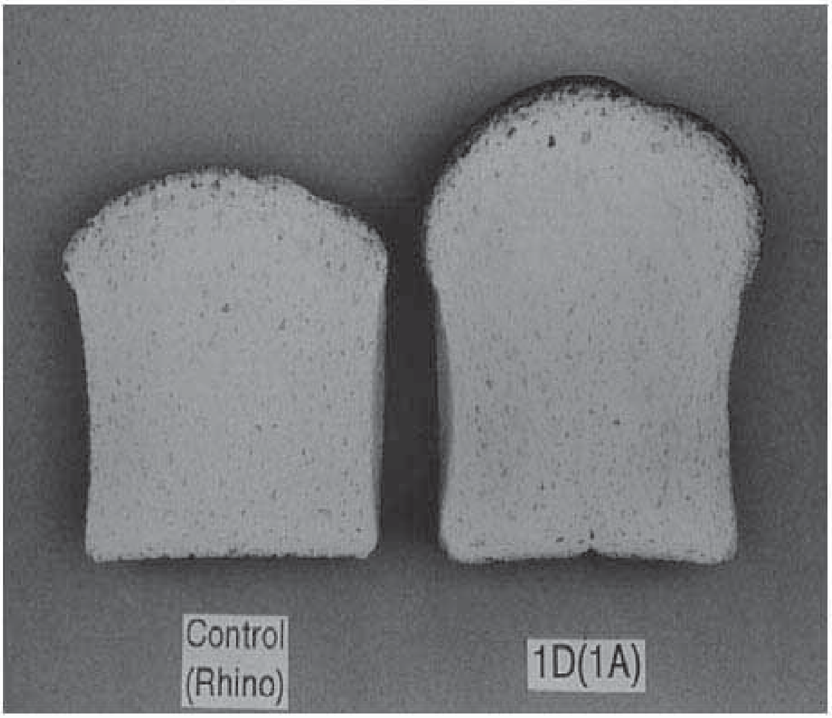
PLATE 5

Bread loaves showing quality variability in Rhino spring triticale

R.J. Peña

a - 1D-chromosome substitution for 1R chromosome compared to complete Rhino





b - 1D-chromosome substitution for 1A chromosome compared to complete Rhino

Triticale production and management

D.F. Salmon, M. Mergoum, H. Gómez Macpherson

Triticale as a species has not had the opportunity to evolve over the last millennium in a fashion similar to its parental species wheat and rye. It was not until the latter part of the nineteenth century that it was first described as a robust combination between wheat and rye. Early attempts at hybridization between the two species resulted in sterile offspring. It was not until the 1930s that a method involving the chemical colchicine was discovered that resulted in chromosome doubling and subsequent fertility.

The initial interest in triticale was the potential of this new crop to combine the genetic attributes of both wheat and rye. In other words, a human food and animal feed crop that could be grown on marginal land under limited soil fertility and moisture.

In the early stages, work concentrated on two types of triticale, the hexaploid combining the A, B (durum and turgidum) and R (rye) genomes and the octoploid combining the A, B, D (bread wheat) and R genomes. The fact that the octoploid produced very large spikes and embryo rescue was not required in it resulted in much of the work during the first half of the twentieth century being focussed on octoploids. However, the relatively poor seed development in the octoploid versus the hexaploid, as well as instability, resulted in many programmes converting to breeding hexaploids in both the winter and spring versions of triticale. In more recent years, work has been conducted on tetraploid triticale, which combines the R genome of rye with the A and/or B genomes from wheat ancestors.

One of the most significant breakthroughs in triticale during the last part of the twentieth century was the development of the Armadillo type of triticale at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico during the 1970s, which greatly enhanced the levels of self-fertility in the crop. A second major development was seed plumpness. Plump-seeded triticale types from CIMMYT greatly advanced the potential for triticale in human food and animal feed. A third factor that has significantly impacted winter triticale is the development of excellent agronomic types by winter breeding programmes in Poland, thereby allowing triticale to expand into very high-yielding areas of Europe where lodging of tall winter triticale was a problem and providing valuable germplasm for agronomic improvement in areas where winter hardiness tended to be coupled with poor agronomic type (Northern Europe and North America). These factors have had a major impact on the development and utilization of triticale (see chapter "The history and evolution of triticale").

PRODUCTION

Triticale worldwide

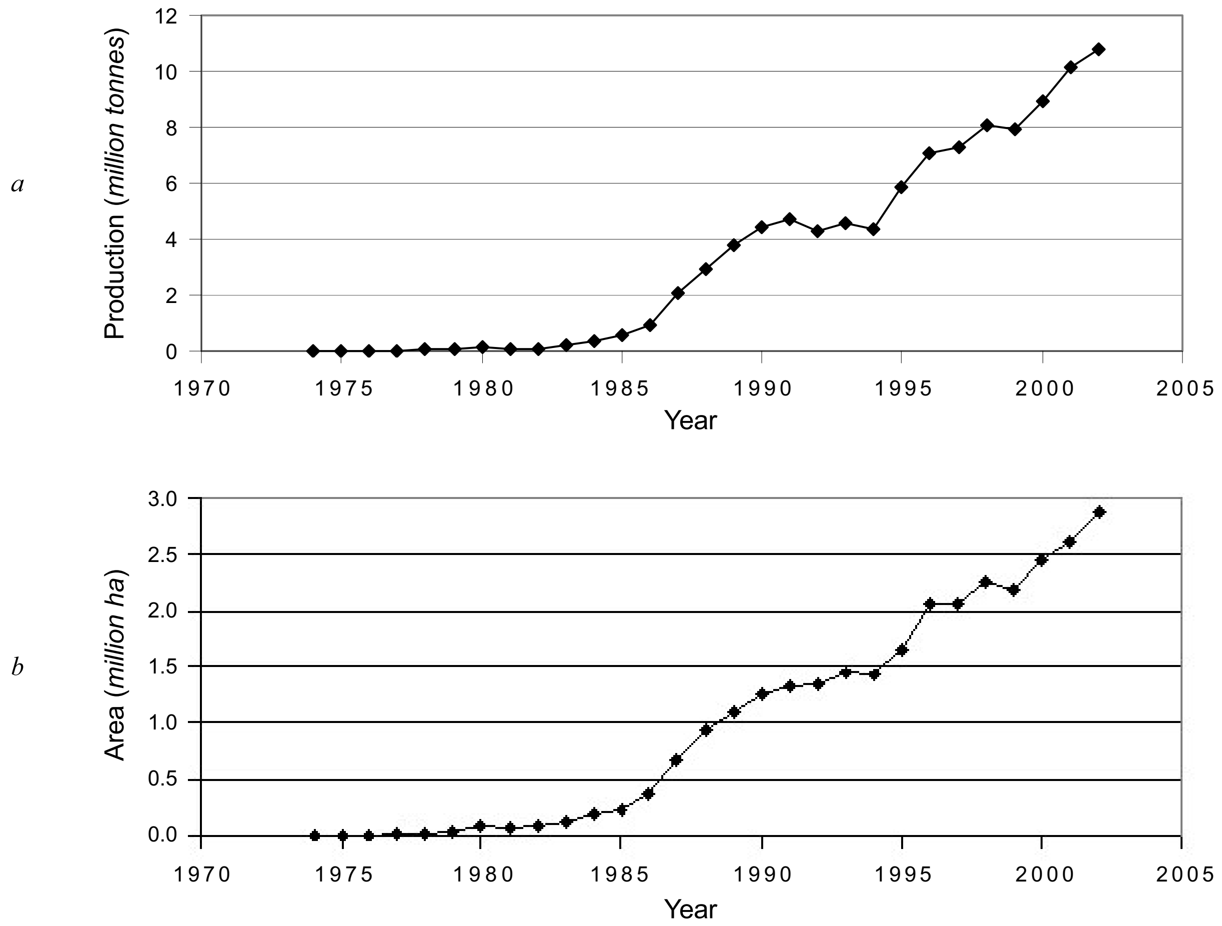
The evolution of triticale as a commercial crop was slow until the mid-1980s (Figure 1). Since then triticale production has increased at an average rate of 150 000 tonnes/year (an approximate 18 percent increase per year), reaching nearly 11 million tonnes in 2002 (FAO, 2003). In this same year, sorghum, oat, millet and rye world production was approximately 54, 25, 23 and 21 million tonnes, respectively. However, in contrast to triticale, the world production of these cereals has decreased in the last fifteen years, and the trend seems to be continuing.

The steady increase in triticale production has been mostly due to an increase in the area planted, which has increased at an average rate of 578 000 ha/year (23.6 percent/year) since the mid-1980s (Figure 1). At present, the total area planted to triticale worldwide is nearly 3 million ha (FAO, 2003).

Triticale yield has also increased since the mid-1980s, particularly when shorter, spring-type varieties became commercially available allowing an escalation in the use of fertilizers without increasing the risk of lodging. The new varieties had higher harvest index and yield (see chapter "Triticale crop improvement: the CIMMYT programme"). Additionally, in the mid-1980s, highly productive winter triticale varieties were developed in Poland, and the crop extended into favourable environments in Northern Europe.

At the world level, the average annual increase in triticale production per hectare since 1985 has been nearly 100 kg/ha/year, which is remarkable compared to 45, 39, 28 and 21 kg/ha/year for maize, rice, wheat and barley, respectively, during the same period. In 2002, the highest country average yields were 6.8, 6.3 and 5.5 tonnes/ha in Switzerland, Belgium and France,

FIGURE 1
Worldwide triticale total production (a) and area planted (b), 1974-2002



Source: FAO, 2003.

respectively (FAO, 2003). In contrast, production per hectare was approximately 1 tonne/ha in rainfed environments where inputs are very low.

Although triticale is grown in many countries of the world, the major producers are in Europe. In 2002, approximately 88 percent of triticale was produced in Europe, 9 percent in Asia and 3 percent in Oceania (FAO, 2003). The major European producers were Germany, Poland and France, whereas most of the Asian production was in China. In this same year, 75 percent of the total hectares planted in the world to triticale was in Europe, 16 percent in Asia and 9 percent in Oceania, mostly in Australia. Although used primarily as a forage crop, triticale has been increasing dramatically in the Americas.

The most significant increases in production have been in central and eastern European countries. Poland, for example, had winter triticale production levels that exceeded 800 000 ha during 2001 compared to 20 000 ha in 1985 (FAO, 2003). In the same year, China, Germany, Poland and France produced nearly 80 percent of the world triticale, and most of it was consumed internally as feed (Table 1). At present, trade in triticale is not a significant factor. Germany is the main exporting country (164 398 tonnes in 2001), followed by Hungary. In the case of triticale imports, most of it was carried out by European countries (a total of 152 500 tonnes in 2001), the Netherlands being the main importing country.

Production zones

Triticale closely overlaps the areas of adaptation common to the extremes of its wheat and rye parents. As a consequence, environment determines which type of triticale is the most suitable for production. Currently, there are three categories of triticale: (i) spring types that do not require a cold treatment/vernalization to move from the vegetative to reproductive phase; (ii) intermediate or facultative types that have some cold treatment requirements but will go into the reproductive phase

TABLE 1
Triticale statistics of main triticale-producing countries, 2001

Statistic	China	France	Germany	Poland
Production (*tonnes*)	640 380	1 123 196	3 418 892	2 697 862
In relation to world (%)	6	11	34	27
Area (*ha*)	202 000	240 776	533 492	838 274
Yield (*tonnes/ha*)	3.17	4.66	6.41	3.22
Imports (*tonnes*)	2	8 937	2 099	579
Exports (*tonnes*)	25 526	8 611	164 398	381
Stock (*tonnes*)	-	-	-170 593	-353 060
Feed (*tonnes*)	200 000	1 083 522	2 911 000	1 950 000
Seed (*tonnes*)	67 000	40 000	90 000	213 000
Waste (*tonnes*)	26 000	-	68 000	150 000
Processed (*tonnes*)	325 000	-	-	12 000
Other utilizations (*tonnes*)	-	-	17 000	20 000

Source: FAO, 2003.

without a cold treatment; and (iii) winter types that require a cold treatment after germination to go into the reproductive phase.

Potential production areas

Potential production areas for triticale can in part be defined in a similar fashion to wheat as described by Fischer (1981). In general, spring triticale can be grown for grain production in most environments that have a sufficiently long growing season and adequate moisture either from natural rainfall or from irrigation, as well as in areas where winter conditions are not severe. As a consequence, spring triticale may be most suited to:

- High-latitude (45° or higher) areas, such as the northern Great Plains of North America, the Russian Federation, republics of the former Soviet Union and northern China, where spring triticale is sown in the early spring.
- Lower to middle latitude (between 45° and 30°) areas, such as the Mediterranean, the southern part of South America, Pakistan, India and parts of China, where the winters are sufficiently mild and adequate moisture is available either through natural sources or irrigation; spring triticale is sown in the winter.
- Low-latitude (less than 30°N or 30°S) areas, such as Kenya, the United Republic of Tanzania, Zambia, Ethiopia and central and northern South America, where crops are grown under rainfed conditions and sown in the early part of the spring and summer on upland (greater than 1 500 m) production areas.

The potential areas for production of winter types tend to overlap to a significant degree with spring triticale. The intermediate or facultative types may be grown for grain as well as for a grazing and high-yielding forage crop in many areas that do not have strong vernalizing conditions and do not require cultivars with high levels of hardiness. The winter types require a significant period of time (four to eight weeks) of low temperatures (above freezing but below 9°C) to cover the vernalization requirements as well as to ensure adequate development of cold tolerance. Winter triticale is generally suited to:

- Planting in the autumn in high-latitude areas where conditions are cool enough to fulfil vernalization and hardening requirements and where there is sufficient snow cover to ensure winter survival, such as Northern Europe, the northern Great Plains and eastern North America, parts of the Russian Federation and China.
- Planting in the autumn in middle- to high-latitude areas where conditions are cool enough to fulfil vernalization requirements but without extreme requirements for winter hardiness, such as Eastern and Western Europe, the United States of America, central China, as well as parts of Turkey and the Islamic Republic of Iran.

Photoperiod

Triticale has a wide area of adaptation around the world. Although general climate and latitude have an important impact on the decision whether to grow a spring or a winter type, photoperiod can be a concern. During the early stages of triticale breeding, spring types used in northern latitudes tended to be daylight sensitive. In this case, they required in excess of 12 hours of light to initiate change from the vegetative state. In a similar fashion, the obligate winter types required not only the vernalization period but also long days. The development of daylight-insensitive (CIMMYT) types has greatly eliminated this problem for the production of triticale at lower latitudes where day-lengths are short (Krull *et al.*, 1968).

Much of the spring germplasm utilized in current programmes in high-latitude countries has a strong CIMMYT background, and many of the varieties produced are daylight-insensitive types. On the other hand, much of the winter germplasm may still have a significant degree of daylight sensitivity. Daylight sensitivity in spring types may be an advantage (A. Hede, personal communication) in climates, such as some of the former Soviet Union republics (Kazakhstan) and parts of northern China, that are hot and dry in the summer and have cold winters without adequate snow cover to support winter types. Delay in heading while photoperiod requirements are being fulfilled may result in higher production than in the day-neutral types. However this has yet to be confirmed.

CULTIVATION

Adaptation zones

Triticale performs well under rainfed conditions throughout the world and excels when produced under good soil fertility and irrigation. Although triticale responds very similarly to wheat grown under a wide range of environments, it is in general superior under stress conditions. Many triticale cultivars carry tolerance to acid soils (Baier, de Sousa and Wietholter, 1998) and high aluminium toxicity (Butnaru, Moldovan and Nicolae, 1998) and may have tolerance to other problems, such as soils high in manganese, which is typical of some soils in Australia (Zhang, Jessop and Alter, 1998). The acid tolerance and aluminium tolerance are more similar to its rye ancestors.

In areas where abiotic stresses, such as drought, extreme temperatures, extreme pH levels, salinity and trace elements deficiency or toxicity, are prevalent, triticale has consistently shown to be very competitive compared to the other cultivated cereal crops. Previous work in the dry regions of North Africa with low inputs (Belaid, 1994; Mergoum, Ryan and Shroyer, 1992; Mergoum, 1994; Ouattar and Ameziane, 1989; Saade, 1995; Varughese, Pfeiffer and Peña, 1996) has clearly demonstrated that triticale offers additional end-uses and alternatives for humans and animals, such as grazing and straw. In high-input areas (irrigated and high-rainfall regions), triticale can be used as forage or for dual purposes.

Triticale performance under acid soils (in Brazil for example) has demonstrated excellent tolerance to low pH levels. For this reason, triticale has been grown on a substantial area (more than 120 000 ha) in Brazil in the southern regions of Rio Grande do Sul, Paraná and Santa Catarina (see chapter "Triticale crop improvement: the CIMMYT programme").

Crop establishment

As with all cereals, triticale should be planted into a firm seedbed and placed near moisture. This can pose a problem when planting winter cereals. Although triticale has a very large seed and has a very robust embryo, in cooler climates it has been observed in the early stages of development to be slow growing compared to other cereal species, such as barley and wheat. This may be due to the early development of a massive root system versus early top growth, which is in contrast to the general perception that triticale as a species is a very robust and competitive crop during its growth in many of its adapted production zones. Triticale seed size generally is larger than that of commonly grown wheat varieties (Plate 1). Consequently, spring triticale can be seeded more deeply than other small cereals and therefore benefit from stored moisture in the soil, which allows better crop establishment early in the season, particularly in drought-prone areas. Seeding equipment needs to be set to account for a seed that may be 10 to 20 percent larger than wheat.

Seed placement during the planting process is very important when dealing with winter triticale cultivars grown in areas that have extremely severe conditions during the winters at high latitudes as well as at high elevations in the middle latitudes. Work conducted in the northern Great Plains of North America has indicated that winter triticale varieties equal and in many cases exceed the winter hardiness of the best winter wheats if planted early during the autumn and if planted shallow (no more than 2.45 cm deep). It appears that winter triticale varieties take longer to develop their maximum cold tolerance, and deep planting increases the time to emergence and results in a less robust crown, a factor extremely important in winter survival under severe winter conditions. Winter survival under these conditions is greatly enhanced by using snow trapping (Bauer and Black, 1990), planting practices with minimum soil disturbance and trash cover (Plate 2).

The use of minimum soil disturbance has advantages for the production of both spring and winter triticale types. In Mexico, Sayre *et al.* (1998) noted a slight yield advantage for triticales grown under zero-tillage. Use of minimum soil disturbance techniques such as zero-tillage maintains straw on the production fields, reduces erosion, increases soil microbe activity, improves soil tilth, maintains soil fertility and reduces the usage of expensive agricultural fuels. However, in areas with severe cereal diseases, where pathogens can be carried over on cereal crop residues, good rotation practices with non-host species are essential.

Fertilization, weed control and pest control

Triticale has a very extensive root system and can mine the soil more efficiently in conditions where fertility is poor. When any new crop is introduced into a production area there usually is only limited information on fertilizer usage. Fertility work is very specific to climatic and soil zones. In general, triticale will respond favourably to cultural practices commonly used for the parental species wheat. However, work conducted at CIMMYT in Mexico (Sayre, Pfeiffer and Mergoum, 1996) demonstrated clearly the substantial genetic progress achieved by CIMMYT in identifying improved lines with better nitrogen use under both low and high inputs. Under drought conditions in northern Morocco, the grain and biomass yield response of triticales have shown to be substantially higher with larger increments of nitrogen and phosphorus inputs (Mergoum, Ryan and Shroyer, 1992).

Good soil fertility along with vigorous germination and fast emergence may be one of the most efficient ways to reduce weeds through competition (Schoofs and Entz, 2000). A vigorously growing crop usually is relatively weed-free. Triticale is a relatively new crop in many parts of the world and as a consequence may not have many, if any, herbicides or pesticides recommended for it. In most cases, the herbicides and pesticides that work on wheat and rye will work on triticale. However, Haesaert, Deryche and Latre (1998) have indicated that triticale may be less tolerant to some herbicide cocktails than wheat. Newer herbicides as well as pesticides are now being released with recommendation for use on triticale in many parts of the world.

Harvest and storage

Seed size may also be of concern when harvest is occurring. Triticale varieties generally have a large seed and a large embryo with an elongated beak compared to bread wheat. Caution must be taken to ensure that any mechanical harvesters, such as modern combines, are appropriately set so that there is no damage to the embryo. Embryo damage and seed cracking can have a significant impact on seed viability during storage. This can be a problem since many triticale varieties are hard to thresh compared to wheat and rye. Some of the reduced-awn varieties, such as the winter triticale Bobcat, carry the wheat rachis (R. Metzger, personal communication) and are easy to thresh.

In triticale without the wheat rachis, threshing frequently results in incomplete seed and chaff removal from the spike, and breakage may occur at the rachis nodes. In the wheat rachis types, breakage does not occur. Improvements in threshing will be an excellent improvement where mechanical threshing equipment is not readily available or economically feasible.

Triticale has a very soft-textured kernel and may be subject to damage from insect infestation during the storage process. Triticale should be stored in a dry, well-ventilated area to reduce potential damage from moisture. Preferred harvest moisture to reduce damage due to heating caused by moulding is 14 percent or less.

END-USES IN AN INTEGRATED CROP PRODUCTION SYSTEM

Livestock feed

Chapters “Food uses of triticale” and “Triticale as animal feed” address the uses of triticale products in detail. However, it is very difficult to discuss production without referring to utilization since production and end-use are an integrated process. Production of triticale allows for the development of diversified rotations, which may reduce weed and disease problems and improve soil husbandry while ensuring a stable, high-quality source of food and feed. As a consequence, it is important to emphasize a few examples where triticale has contributed substantially in feed or forage.

To date, the most common usage of triticale grain as a feedstock has been in poultry and hogs. Work carried out in Poland by Boros (1998) indicated that no negative effects occurred in broiler chickens when being fed either hexaploid or octoploid types of winter triticale. With the exception of the tetraploid type, triticale was similar to wheat and superior to rye as a major ingredient in broiler feed rations. Similar results have been reported in studies involving turkeys and waterfowl.

Other studies conducted on feeding hogs identify triticale as a good source of feedstock with an excellent balance of available amino acids for blended and supplemented feed rations. In particular, work conducted by Jaikaran *et al.* (1998) on spring triticale and Myer (1998, 2002) on winter triticale demonstrated the value of the crop in hog diets. The work of Jaikaran *et al.* consisted of comparisons with hulless barley and maize versus triticale. In this circumstance, triticale performed equally well under all stages of development of the hog as well as in factors involved in determining carcass quality and cooking parameters. Myer's work demonstrated that triticale was very acceptable even in diets fed to very early-weaned hogs, a situation where the hog's digestive system is newly developed so any dietary deficiencies have a major impact on growth.

Triticale is also being used as a source of feed for ruminant species, such as cattle, sheep and goats. The lower levels of gluten and of beta-glucans put triticale in a favourable position for feeding ruminants. The performance of dairy animals as well as meat animals fed triticale is very similar to those fed maize or barley. The high energy content of triticale and the lower tendency to acidify the gut of a ruminant are major factors in good health and long-term production.

Livestock fodder

The use of triticale as a grazing crop (Plate 3) to supplement native pasture, as a silage crop, as a conserved hay crop and as green chop is rapidly increasing. Triticale is used as an important source of fodder in most countries in which it is grown. Recently, triticale areas grown for grazing, forage, silage, hay and dual purposes have increased substantially. Many triticale varieties with different growth habits and agronomic traits aimed at forage production have been developed around the world. Most of these triticale cultivars are awned. However, awnless cultivars have recently been released, which will further increase triticale promotion as a forage crop (Gibson, 2002).

In North America, the use of cereals, in particular winter types, as a grazing crop for livestock is a very common practice. In areas where the winter is mild and the plants continue to grow well into the winter, winter triticale planted in the autumn is a valuable, high-quality source of fodder during the winter. In colder regions, winter triticale, which is seeded in the early spring and remains vegetative, provides very inexpensive grazing well into the late autumn and early winter (Baron *et al.*, 1993). Similar work has been carried out using spring triticale grown during the winter months in Australia and other countries including parts of southern Africa and the Mediterranean and Mexico (Lozano *et al.*, 1998; Lozano del Río *et al.*, 2002). Schoofs and Entz (2000) found that grazing systems involving triticale had an equal effect on weed control for some common weed species as the use of a herbicide.

The most extensive work on triticale, both winter and spring, has been the production of whole-plant silage, dried hay or green chop, which is harvested and fed directly to livestock. In general, triticale produces yields equal to if not superior to other small-grain cereals (excluding maize), such as barley and oat, that have traditionally been used for this purpose. As indicated by Khorasani *et al.* (1997) and Benbelkacem (2002), the quality of forage from spring triticale is quite similar to barley. Early harvest as green chop, dried hay or silage may remove weed species prior to seed production, reducing the weed population in future crops. In climates where early seeding and snow trapping are required for the production of winter cereals, stubble from a silage crop is of considerable value.

Human food

Although the original intention for the development of triticale was production of human food, and the nutritional content certainly indicates high quality, this has not been a major use of the crop. Triticale has been noted for many years as an excellent product for making chapatti tortillas and many forms of leavened bread. The major problem appears to be changing traditions and the need to improve baking quality to a level more similar to wheat. Current breeding programmes in many parts of the world are seriously working on this problem, and gradual improvements are occurring (Peña, Mergoum and Pfeiffer, 1998). It is apparent that the next major breakthrough in triticale breeding, production and utilization will be its development as a human food.

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PLATE 1
Comparison of triticale and common wheat seed
D.F. Salmon

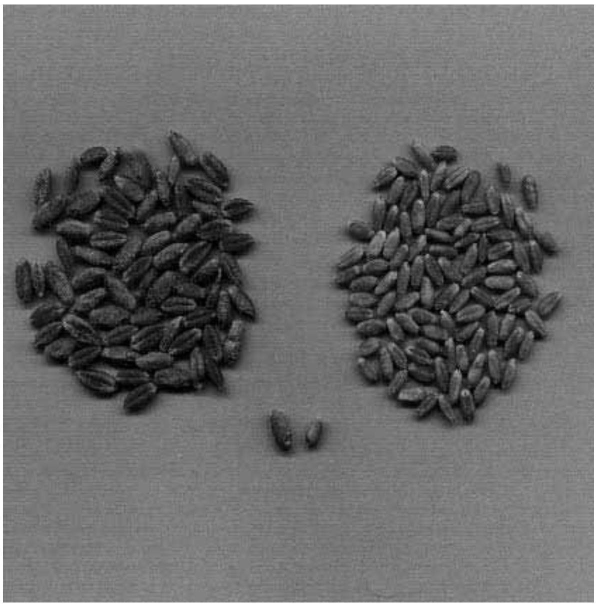

PLATE 2
Winter cereal planted in a minimum-tillage system
D.F. Salmon

PLATE 3
Plains bison grazing on a forage blend that includes triticale
D.F. Salmon