Wheat Landraces: Genetic Resources
for
Sustenance and Sustainability

by

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Summary

Traditional wheat farming communities contributed, for millennia, to the evolution and enrichment of on-farm conservation of diverse wheat landraces, and developed efficient seed exchange systems to ensure the continued evolution and diversification of these landraces. Farmers developed and utilized diverse wheat landraces to meet the complexity of a multitude of spatio-temporal agro-ecological systems and to provide reliable sustenance and a sustainable food source to local communities. The present genetic structure of, and the changes within, these landraces were largely shaped and determined by traditional cultures and local cropping systems. Wheat landraces are comprised of complex, variable, genetically dynamic and diverse populations, in equilibrium with both biotic and abiotic stresses in their environment. The genetic structure of wheat landraces is an evolutionary approach to survival and performance, especially under arid and semi-arid growing conditions and organic inputs. The combined effects of natural and farmer selection have led to architecture of genotypes representing different combinations of traits, such as growth habit; cold; heat or drought tolerance; early growth vigor; competition with weeds; disease tolerance; water and nutrient use-efficiency; time to heading and maturity; seed filling duration; and quality traits suited for diverse sustenance objectives and local food preferences. Historically, traditional farmers planted diverse assemblages of wheat landraces to lower the risk of failure and increase food security because they had limited capacity to control the spatially heterogeneous and temporally unpredictable environment. This practice led to the development of landrace meta-populations of wheat and the emergence of farmers' seed systems through which they accessed and exchanged diverse genetic material. Traditional management of wheat landraces contributed more to the conservation of a general level of diversity than to the conservation of genetically stable and distinct populations. Therefore, a wheat landrace is far from being a stable, distinct, and uniform unit; its diversity is linked to the diversity of the material sown in its immediate geographical area, and to the level and frequency of seed exchange among farmers. During the last century, the introduction of high-yielding varieties, and the structural changes in wheat farming systems, led to the loss of genetic diversity and fragmentation of meta-population structures of wheat landraces. However, the persistent cultivation of some wheat landraces attests to their continued value to farmers, or to their competitive agronomic or nutritional advantage relative to modern varieties. The social value of wheat landraces should be raised to approximate or exceed that of high-yielding wheat varieties if farmers are expected to continue growing and managing them on the farm. This will allow evolutionary processes that mold landrace diversity to continue and will reverse the fragmentation of their meta-populations, especially in their centers of diversity.

Introduction

Wheat domestication was responsible for the increase in human population by enabling humans to produce food in large quantities, thereby contributing to the emergence of the human civilization. The domestication of wild emmer (*Triticum dicoccoides*, Figure 1), the progenitor of all cultivated wheats, was one of the key events during the emergence of agriculture in Southwest Asia, and was the prerequisites for the evolution of tetraploid durum and hexaploid bread wheat. However, the domestication of wild emmer in the Fertile Crescent and the subsequence breeding of domesticated durum and bread wheat drastically narrowed their genetic diversity. Upon domestication, it was estimated that initial diversity was reduced by 84% in durum wheat and by 69% in bread wheat

Historically, traditional farmers planted diverse assemblages of wheat genotypes (i.e., landraces) to lower the risk of failure and increase food security because they had limited capacity to control the spatially heterogeneous and temporally unpredictable environment. This practice led to the development of landrace meta-populations of wheat and the emergence of farmers' seed systems through which they accessed and exchanged diverse genetic material. A meta-population structure, defined as a group of subpopulations interconnected by gene-flow and seed exchange among farmers, villages and eco-geographical regions, favors a dynamic evolution of diversity.

Figure 1. Wild emmer wheat, the immediate progenitor of cultivated wheats, in its natural habitat (left, photo of wild emmer in Karadagh Mountains-Gaziantep region of southern Turkey by H. Özkan) and under high input agriculture (right, photo by A.A. Jaradat).

Wheat landraces are composed of traditional crop varieties developed by farmers through years of natural and human selection and are adapted to local environmental conditions and management practices. As distinct plant populations, landraces are named and maintained by traditional farmers to meet their social, economic, cultural, and environmental needs. They are alternately called farmers' varieties or folk varieties to indicate the innovative role of farmer communities in their development and maintenance.

The genetic structure of wheat landraces is an evolutionary approach to survival and performance, especially under arid and semi-arid growing conditions. The combined effects of natural and human selection have led to architecture of genotypes representing different combinations of traits, such as growth habit, cold, heat or drought tolerance, early growth vigor, time to heading and maturity, seed filling duration, and quality traits. As a result, wheat landraces developed into complex, variable, genetically dynamic and diverse populations, in equilibrium with both biotic and abiotic stresses in their environment. Throughout their history, farmers subjected wheat landraces to strong selection pressures. Wheat landraces developed multilocus structures as a result of selection, genetic drift, or fragmentation of their populations. These structures predominantly are retained through selection, isolation, lack of migration, and restrictions on outcrossing and genetic recombination. Little has been done to understand the genetic structure of wheat landraces and the inter-specific diversity available in the subsistence agro-ecosystems they still dominate in parts of the Old World.

Durum and bread wheat landraces have been largely replaced, in their center of diversity, by monocultures of pure genotypes. This genetic erosion resulted in significant loss of valuable genetic diversity for adaptation to low or organic inputs and for resistance to biotic and abiotic stresses. The pure genotypes may not have the wide adaptation and the diverse genetic background already present in landraces that they replaced. The development of new varieties from landrace populations is a viable strategy to improve landrace yield and yield stability, especially under stress and future climate change conditions. Due to their high nutritive value, modern wheat cultivars are superior to other cereals in providing energy and high quality protein for billions of people around the world. However, the need is urgent to increase the yield potential and improve nutritive quality and tolerance to biotic and abiotic stresses of cultivated wheat in view of climate change, rising demand for healthy wheat products, and the increasingly alarming loss of its wild genepool.

Wheat landraces are valuable sources to broaden the genetic base of cultivated wheat. The development of new varieties from landrace populations is a viable strategy to improve landrace yield and yield stability, especially under stress and future climate change conditions; also, these landraces harbor genes and gene complexes for quality traits, tolerance to biotic and abiotic stresses, and adaptation under a wide range of low-input and organic farming systems.

Wheat Evolution and Domestication

The domestication of wheat around 10,000 years ago marked a dramatic turn in the development and evolution of human civilization, as it enabled the transition from a hunter-gatherer and nomadic pastoral society to a more sedentary agrarian one. Two of the most important traits in the evolution of bread wheat and other cultivated grasses constitute the domestication syndrome. These are:

1. An increase in grain size, which was associated with successful germination and growth of seedlings in cultivated fields, and
2. The development of non-shattering seed, which prevented natural seed dispersal and allowed humans to harvest and collect the seed with optimal timing. Size and shape of the wheat grain are independently inherited traits and the domestication process resulted in a switch from production of a relatively small grain with a long, thin shape to a more uniform larger grain with a short, wide shape.

The complex history of domesticated wheat evolution (Figure 2), suggested that various traits arose independently at different stages. Grain size, for example, may have increased early in domestication through changes in grain width and length, followed at later stages by further modifications in grain shape. Later during the course of wheat evolution, the decrease in phenotypic diversity in grain morphology in modern commercial wheat is attributed to a relatively recent and severe bottleneck that may have occurred either during the transition from hulled to the modern free-threshing wheat, or even more recently as a result of modern breeding programs.

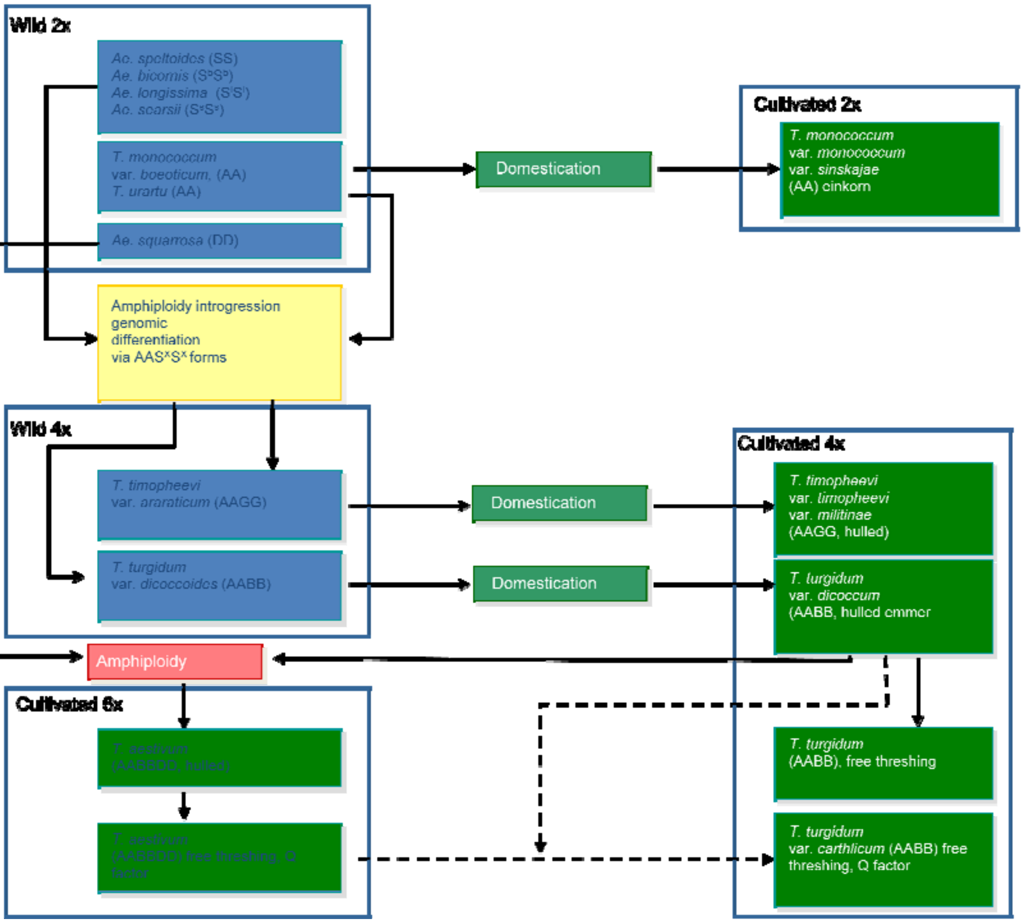

Figure 2. Ploidy levels and species relationships in the course of wheat domestication (Source).

Molecular genetics and archaeological data have allowed the reconstruction of possible domestication scenarios leading to the development of landraces, old and then modern cultivars. For diploid (2x, Fig. 2) *einkorn* and tetraploid *turgidum* (hard) wheat (4x, Fig. 2), a single domestication event has likely occurred in the Karadagh Mountains, Turkey. Following a cross between tetraploid turgidum and diploid goat grass, the resultant hexaploid (6x, Fig. 2) bread wheat was disseminated around the Caucasian region, then around the world. These events, although resulted in wheat domestication, created genetic bottlenecks, which excluded potentially adaptive alleles. More recently, the same phenomenon was repeated upon the development of high yielding wheat varieties at the expense of losing much of the diversity in wheat landraces and old cultivars. A significant decrease of genetic diversity has been observed related to the replacement of bread wheat landraces by elite cultivars which appear to be associated with loss of some quality traits such as protein content and glutenins quality.

Throughout most of last ~10, 000 years, farmers have been behind the development and conservation of wheat genetic diversity. The landraces and old cultivars they developed can be considered as evolutionary links between wild emmer wheat, the wild progenitor of all domesticated wheats, and advanced wheat cultivars. Landraces are alternately called farmers' varieties or folk varieties to indicate the innovative role of farmer communities in their development and maintenance. The extinction of traditional farming systems, the aging and exodus of rural population, and more recently, environmental degradation, have led to the extinction of many local landraces. As a consequence, during the last century most of the unique cereal biodiversity has disappeared and the information regarding landraces and traditional cultivars is presently very scarce. Several authorities estimated that almost 75% of the genetic diversity of crop plants was lost in the last century. This erosion of these genetic resources results in a severe threat to the world's long-term food security. Although often neglected, the urgent need to preserve and utilize landrace genetic resources as a safeguard against an unpredictable future is evident.

Origin and Characteristics of Wheat Landraces

Thousands of years of cultivation aided by natural and human selection have resulted in the evolution of immense diversity of genotypes in the predominantly self-pollinated wheat species. Throughput their evolutionary history, wheat crops have been shaped and molded by people to meet diverse end uses, cultural practices, and to respond to changing socio-economic and growing conditions. A number of socio-cultural factors, food traditions, and agro-ecological environments favored the cultivation and utilization of diverse wheat genetic resources, including primitive or hulled (e.g., *Triticum monococcum, T. dicoccum, T. spelta*), and free-threshing wheat species (e.g., *T. durum, T. polonicum, T. compactum, T. aestivum*), constituting what is now known as landraces. Each wheat species or landrace has particular significance in the food culture, as a source of daily diet, and of food and drink for special occasions. Wheat landraces generally have both private and public values. To the farmers who grow them, landraces constitute a private good; whereas, to institutions engaged in their conservation and improvement, landraces constitute a public good and a source of useful genetic material.

Traditional management of wheat landraces contributed more to the conservation of a general level of diversity than to the conservation of genetically stable and distinct populations. Therefore, a wheat landrace is not necessarily a genetically and phenotypically stable, distinct, and uniform unit; its diversity is linked to the diversity of the material sown in its immediate geographical vicinity, and to the level and frequency of short- and long-distance seed exchange among farmers. Wheat landraces embody not only diverse alleles and genotypes but also evolutionary processes such as gene flow between different populations (mainly via seed exchange) and local knowledge systems such as folk taxonomies and information about selection for specific quality attributes or for heterogeneous environments. The complexity of the population structure of wheat landraces may arise from the number of different homozygotes and the occurrence and frequency of heterozygotes in populations. Therefore, characterization of the population structure of wheat landraces is critical to identify and correctly interpret the association between their functional and molecular diversity. Such information is essential to utilize landraces as donors of traits in wheat breeding, to define the areas of adaptation of different landraces, to identify priority areas for on-farm conservation, and to understand the genetic consequences of the interaction between climate change, growing environments and farmers' practices.

As compared to modern wheat varieties, landraces, with relatively higher biomass, may not invest in larger root dry mass, but rather in increased partitioning of root mass to deeper soil profiles, increased ability to extract moisture from those depths, and higher transpiration efficiency. In addition, their increased concentration of soluble carbohydrates in the stem shortly after anthesis ensures adequate translocation of assimilates to the developing grain. Therefore, early maturity, with some yield penalty, is a valuable trait that can be derived from wheat landraces to combat the typically-encountered season-end drought in rainfed wheat production regions. Facultative growth habit is a unique characteristic of some wheat landraces; it provides flexibility of sowing either in the fall as a winter crop or, after the failure of the crop to overwinter, again in the spring.

Under growing conditions with limited nitrogen availability, wheat landraces and old varieties with a taller growth habit and lower harvest index absorb and translocate more nitrogen into the grain than modern varieties, presumably due to greater pre-anthesis uptake and an increased buffering capacity in genotypes with high vegetative biomass. Therefore, appropriately selected landraces with well-developed root systems could be a source of variation for nutrient uptake, and the improvement of seed quality.

Mineral content in modern wheat cultivars has significantly decreased, including copper, iron, magnesium, manganese, phosphorus, selenium, and zinc. High levels of these nutrients can be found in landraces and old low-yielding varieties. Because wheat landraces have been developed mostly in environments with low nutrients availability, they represent a source of variation for selection of varieties adapted to cropping systems with low fertilizer input. Compared to the cost associated with the formation of new roots, arbuscular mycorrhiza may considerably increase the active absorbing root surface with minor cost to the wheat plant, thus enhancing the uptake of phosphorus, in particular, and other macro- and micro-nutrients, in general.

Only a limited number of studies have focused on quality aspects of organic wheat production. This trait is of particular concern to organic farmers and consumers since protein content in organic cereals tend to be lower due to the difficulty and costs of foliar application of inorganic nitrogen fertilizers applied later in the growing season. A higher protein content and quality without the need for late-season nitrogen inputs are therefore major breeding objectives. However new varieties should be particularly suitable for whole-meal bread making and artisan baking processes, combining sensory and nutritional qualities (e.g., increased micro-nutrients) as the consumers of organic bread expect highest organoleptic quality.

Farm households allocate resources for production of favorite or preferred landraces, expecting benefits to accrue from their subsequent consumption or sale in local markets. Farmers continue to grow a wheat species or landrace and maintain it if it meets their production and consumption needs. Therefore, direct use values, particularly the quality traits that farmers consider as valuable for consumption are indicators of private value. Socio-cultural values motivate farmers to retain some preferred landraces on the farm, and they appreciate the special organoleptic qualities and multiple uses of these landraces, despite the availability of improved wheat varieties in their locality. Landraces, especially those having multiple home uses, are more likely to be maintained for the foreseeable future. Therefore, home use values can serve as a strong incentive to encourage continued cultivation and utilization of wheat landrace by farm households. Nevertheless, research will be necessary to verify some of the claims made by farmers concerning peculiar culinary qualities of their preferred wheat landraces. These include, for example, better nutritional value of the grain or its products, and superior medicinal or aesthetic value of local drinks made from wheat landraces.

Conventional and Alternative Wheat Production Systems

The industrial food production system still leaves 1.3 billion people under-nourished. Currently, industrial agriculture uses 2-3 times more fertilizer and 1.5 times more pesticides for the production of 1 kg of food than ~40 years ago. Also, the prevailing industrial agriculture uses 10 times more energy than low-input (i.e., ecological) agriculture and consumes on average 10 energy calories for every food calorie produced. Therefore, the sustainability of this production system, including wheat production, is questionable in view of the rising energy cost and expected global climate change.

Approximately, 95% of organic production is based on crop varieties that were bred for the conventional high-input agricultural sector. Such crop varieties, including wheat, lack important traits required under organic and low-input production conditions. Historically, this is primarily due to selection in conventional breeding programs being carried out in the background of high inorganic fertilizers and chemicals for crop protection. Also, some of the traits, such as semi-dwarfism, that were introduced to address wheat lodging in high-input systems have negative side effects on plant architecture and competitiveness. Some of the negative impacts of dwarfing genes include reduced size and depth of root systems, poor nutrient use efficiency, increased reliance on high inorganic nitrogen inputs to attain satisfactory protein contents, decreased competitiveness against weeds, increased susceptibility to diseases, and decreased robustness against mechanical weed control and thereby greater reliance on herbicides.

Organic and low-input wheat production systems, compared with conventional systems, are more diverse at the soil, crop, field, whole rotation, and landscape level, with greater emphasis on the integration of crop and livestock production on the farm. The high biodiversity of organic wheat farms provides many ecological services that, to a large extent, enhance farm resilience. Integrating the biodiversity gains from agronomic practices with genetic diversity at the wheat crop level provides insurance against the impact of biotic and abiotic stresses on wheat yield and quality.

Modern wheat breeding employed high nitrogen and other chemical inputs to the point that high-yielding varieties, unlike old varieties and landraces, became dependent on readily and consistently available chemical inputs. Wheat species and varieties within species have different nutrient requirements and growth capacities. Landrace genotypes usually have high nitrogen use efficiency and are able to produce high yields at low soil nitrogen availability. Moreover, significant genetic variation in many landraces for nitrogen use efficiency has been demonstrated, making breeding for tolerance to nitrogen deficiency stress feasible and practical.

In organic and low-input systems, nutrient uptake efficiency can be improved by the capacity of crops to establish and sustain efficient plant growth-promoting rhizosphere bacterial communities and arbuscular mycorrhizas. This strategy improves nitrogen uptake efficiency because this assemblage of soil biota protects the root systems against attacks by soil-borne pathogens, maintains efficient mineralization and delivers nutrient supplies to plant roots, and supports the establishment of active arbuscular mycorrhizas associations. Breeding programs and high-input production systems during the last ~50 years, focused on high-input farming, might have selected against such rhizosphere competences. Nevertheless, significant efforts are needed to explore the potential of improving wheat crop health and nutrition via beneficial plant-soil-microbe interactions before breeding programs targeting traits associated with such interactions for organic wheat production systems can be developed.

Weed control remains a problem in organic or low-input wheat production systems. Wheat varieties are genetically variable in their ability to compete with weeds and considerable variation was found in the relative competitive advantage of wheat varieties over annual weeds under organic and low-input production systems. Wheat landraces, typically characterized by tall plants, long coleoptiles, and early vigor, provide early groundcover which is vital to weed suppression; this trait provides a competitive advantage over early emerging weeds and increased resistance to mechanical weeding operations in organic production systems. In wheat, emergence is strongly influenced by coleoptiles length, a moderately heritable trait that can be effectively improved through breeding.

Selection within landraces of genotypes tolerant to mechanical weed control, a regular management practice especially in reduced tillage and organic wheat production systems, has the potential of becoming an efficient component of breeding strategies for wheat competitiveness. Many no-tillage systems are dependent upon herbicide applications. However, in reduced or minimum tillage systems, herbicide-free management practices are feasible and could be further implemented in organic wheat production systems if varieties with increased competitiveness or resistance to mechanical weed control are developed.

Future Value of Wheat Landraces

Wheat landraces constituted, until recently, a dynamic and essential component of the overall agricultural biodiversity which has been valued almost exclusively as a source of traits that can be used in scientific breeding programs and to improve the productivity of new crop varieties. Arguably, however, agricultural biodiversity can make a far greater contribution to increase productivity, and a wider deployment of agricultural biodiversity is an essential component in the sustainable delivery of a more secure food supply.

Wheat landraces have been largely displaced by high-yielding cultivars in many developing countries and are rarely cultivated in developed countries because of their low yield potential and susceptibility to diseases when compared with high-yielding cultivars under high external input farming systems. However, landraces and old cultivars out-yield, and have better quality attributes than, high-yielding cultivars under organic and low-input farming systems. Agronomic and socio-economic studies indicated that farmers’ selection for desirable agronomic and quality traits is a major force shaping the dynamics of wheat landrace populations; therefore, sustained on-farm conservation and sustainable utilization of these landraces will ensure their continued evolution and contribution to sustainable local food systems.

The future value of wheat landraces may depend on:

1. How strongly our food traditions can be linked to the conservation of wheat landraces,
2. How does increased knowledge of food traditions and improved culinary arts help create or expand market demand for wheat landrace products,
3. How environmental factors can impact quality and culinary attributes of wheat landrace products, and
4. How does the accrued knowledge, along with on-farm conservation, improve livelihoods of individual farmers and rural communities?

Additionally, research results indicated that some wheat landraces grow well in alien environments suggesting that a wheat landrace displaced from its original habitat may be grown in newer habitats were its culinary qualities are in demand, or were farmers' options are limited. Therefore, augmenting on-farm conservation activities with non-breeding approaches would ensure the survival of wheat landraces for the foreseeable future.

On-Farm Dynamic Conservation and Sustainable Utilization of Wheat Landraces

Clearly much landrace germplasm has been collected during the 1970-1990 era and is being conserved across the world mostly in long-term national and international genebanks. However, a small portion of this diversity is being conserved and used on-farm where it continues to evolve. Both of these conservation methods have its merits and limitations. On-farm conservation is the sustainable management of genetic diversity of locally-developed traditional crop cultivars and landraces along with associated wild and weedy species or forms within traditional agricultural systems. This conservation strategy provides a natural laboratory for evolution to continue and helps a gradual buildup of traits imparting adaptation to specific eco-geographical regions and those matching the requirements of farmers, local communities and populations to continue. Several authorities indicated that the need for on-farm conservation of landraces is one of the most important recent questions in plant genetic resources management.

Farmers continue to grow and maintain a wheat landrace if it meets their production and consumption needs. The total cost and benefit of landraces to farmer households are central to their on-farm conservation and continued utilization. Farmers maintain crop landraces if these are valued either for economic, cultural, social, or even ecological reasons. Therefore, direct use values, particularly the quality traits that farmers regard as valuable for consumption are considered to be proxy indicators of private value of a landrace.

Research results indicate that the likelihood of wheat landraces to be conserved on the farm increases when the markets for their derived products are expanded through improved consumer access to information on recipes, nutritive and cultural values. Therefore, local knowledge of landrace diversity, when documented through interaction with farmers and linked to food traditions, local practices and social norms, is vital for on-farm conservation and increases their competitive advantage if farmers have other alternative options.

For example, socio-cultural values and culinary attributes motivated farmers in central Ethiopia to conserve a durum wheat landrace on their farms; they appreciate its peculiar organoleptic qualities and multiple uses, including 14 dishes and two drinks, despite the availability of several improved durum wheat varieties in their locality. Moreover, hundreds of farmers who accessed the landrace through reintroduction program expressed their appreciation and future commitment to growing and conserving it on the farm. This example strongly indicated that farmers in a community collectively can sustain more crop and landrace diversity than individual farmers, thus meeting overall conservation needs and objectives (i.e., private and public values of a landrace). A renewed interest in and increased demand by farmers to grow this durum wheat landrace and the promotion of landrace-derived products generated income, created green jobs for local communities, and supported on-farm conservation of the landrace. Along with economic benefits, on-farm conservation and utilization of this (and other) wheat landraces is also linked to peoples' cultural, social and ritual values. However, for individual farmers, private values of a landrace are the main motivating factors for growing landraces as a source of income and a means of survival. Therefore, *ex situ* conservation in a genebank may be the only practical option to conserve landraces having low private but high public value.

On-Farm Research, Breeding and Selection of Wheat Landraces

With the objective of defining and addressing the practical research needs of farmers, more formalized approaches to genetic diversity conservation and utilization of landraces are being pursued by the scientific community through participatory on-farm research, breeding, selection, and seed exchange programs. Such programs proved to be useful in solving practical problems in complex and diverse farming characteristic of organic and low-input production systems. This approach of participatory research and development provides better targeting of local environmental conditions, better selection criteria important to the end-users, faster and greater adoption of improved landrace cultivars by farmers, and increase or maintenance of genetic diversity. It gives voice to farmers and elevates their indigenous knowledge to the status of science. Several commercial wheat breeding companies have allocated part of their breeding efforts to breeding wheat, among other crops, for low-input and organic farming, using pedigree selection or bulk populations with annual selection being carried out under organic conditions in early generations, followed by selection under low-input conditions in advanced generations.

Wheat breeding programs, focused on the development of varieties for organic and low-input systems, utilize landraces, modern varieties, and wild wheat species in crosses, selection, and progeny testing. Progeny is selected for optimal grain yield, baking quality, enhanced nutritional value, improved nutrient use efficiency, and weed competitiveness directly under organic systems. This approach resulted in 5-30% higher grain yield as compared to the yield achieved from indirect selection under conventional systems.

Participatory plant breeding programs, including selection of parents, design of crosses, selection of progeny and field testing, originated in developing countries to meet the needs of low-input, small-scale farmers in marginal environments that are not targeted by commercial breeding programs. Such programs typically involve wide range of stakeholders, including farmers, breeders, extension agents, vendors, industry, rural cooperatives, and consumers. The participatory nature of these programs requires all stakeholders to influence any of the major stages of the breeding and selection process. Stakeholders become co-researchers as they can help to set overall goals, determine specific breeding priorities, make crosses, screen germplasm entries in the pre-adaptive phases of research, take charge of adaptive testing and lead subsequence seed multiplication and diffusion processes. The rationale for participatory plant breeding programs is that joint efforts of stakeholders can deliver more benefits to all stakeholders than when each actor works alone and focuses only on a specific objective.

The concepts and practices of participatory plant breeding gained greater attention in breeding programs for organic farming systems due to the special needs of farmers for varieties suitable for organic farming, and because investment in the small organic market is not always attractive for commercial plant breeders. In conventional systems, inorganic fertilizers and synthetic chemicals often encourage homogeneity across a diversity of agro-ecosystems. Organic and traditional low-input farms are often more heterogeneous, and experience a greater diversity of weed, insect, and disease pressure, and use more diverse crop rotations, crop sequences, different tillage and soil management options, fertilization, and non-chemical crop protection methods. To develop varieties suitable for such diverse agro-ecosystems, it is essential to integrate evolutionary breeding principles with strong participatory selection and management components. This type of breeding strategy utilizes a combination of natural selection, which favors adaptation and fitness, and farmer selection, which favors high yield, to develop varieties with optimal adaptation to, and specific quality traits required by, organic farming systems. However, wheat landraces may not have the appropriate structure of their genetic variation in order to respond to multiple selection pressures at once; landrace populations may be limited in their evolution if the selection pressures select simultaneously in opposite directions. Nevertheless, landraces may have an advantage over improved varieties since they tend to have relatively high levels of genetic diversity which could be a source of adaptive variation.

Currently, there are three approaches for breeding and selecting wheat varieties for organic and low-input systems, these are:

1. Selection is carried out under conventional farming conditions and organic farmers are expected to test released wheat varieties and select the ones that perform well under their particular organic conditions,
2. Initial crosses and early selections are focused on traits required in conventional systems, but advanced generations are evaluated and selected under organic conditions, and
3. Crosses and selection strategies focus on traits demanded by the organic sector and selection is carried out under organic conditions throughout the breeding and selection program.

The level of breeder-driven and farmer-driven activities may differ in all three approaches. In addition, farmers may develop their own selection and breeding programs which are often based on locally-adapted old varieties and landraces.

The general perception among farmers is that wheat landraces have better nutritive value than modern high-yielding varieties. Future participatory research has to determine whether it is the nutrient content, bioavailability, or digestibility that makes products from wheat landraces more filling and nutritious. Wheat improvement programs need to better address farmer concerns about landrace quality. Selecting and breeding for wheat end products, for example, with shorter cooking time or longer shelf life, are of particular significance to farmers and consumers alike. High genotype x environment interactions for quality traits (e.g., grain protein and nutrient concentrations) have been reported in wheat, therefore, temporal stability should be considered when selecting landraces as donor germplasm for breeding purposes.

Public and Community Seed Saving and Exchange Systems

Global biodiversity and plant genetic diversity constitute the raw materials humans rely on for food, fiber, forage, fuel, medicine and many industrial products. The National Plant Germplasm System (NPGS), a publically-funded germplasm conservation system, is a part of the Agricultural Research Service (ARS) of USDA and is responsible for collecting, conserving, characterization, evaluation, distribution, and exchange of a rich and diverse genetic resources collection containing about 500,000 accessions. The wheat genetic resources are housed at the National Small Grains Collection (NSGC), which is part of NPGS-ARS. The NSGC is an active germplasm collection that maintains seed samples representing global diversity of the small grains including wheat (*Triticum*, see list of species and subspecies below), barley (*Hordeum*), oat (*Avena*), rice (*Oryza*), rye (*Secale*), triticale (*X Triticosecale*), and various wild relatives (including *Aegilops*).

Germplasm is maintained in the form of seed or live plants, representing current, obsolete and primitive crop varieties and landraces, wild and weedy relatives of crop species, and wild species collected from around the world. The Germplasm Resources Information Network database (GRIN) describes collection holdings of the NPGS. The NSGC's *Triticum* spp. collection currently includes the following species and subspecies that can be accessed through the active links: *Triticum aestivum* subsp. *aestivum* (44,975 accessions), *T. aestivum* subsp. *compactum* (113 accessions), *T. aestivum* subsp. *macha* (31 accessions), *T. aestivum* subsp. *spelta* (1,295 accessions), *T. aestivum* subsp. *sphaerococcum* (32 accessions), *T. ispahanicum* (7 accessions) , *T. monococcum* subsp. *aegilopoides* (918 accessions), *T. monococcum* subsp. *monococcum* (210 accessions), *T. timopheevii* subsp. *armeniacum* (269 accessions), *T. timopheevii* subsp. *timopheevii* (42 accessions), *T. turgidum* subsp. *carthlicum* (95 accessions), *T. turgidum* subsp. *dicoccoides* (921 accessions), *T. turgidum* subsp. *dicoccon* (620 accessions), *T. turgidum* subsp. *durum* (8,403 accessions), *T. turgidum* subsp. *paleocolchicum* (4 accessions), *T. turgidum* subsp. *polonicum* (80 accessions), *T. turgidum* subsp. *turanicum* (107 accessions), *T. turgidum* subsp. *turgidum* (457 accessions), *T. urartu* (210 accessions), *T. vavilovii* (3 accessions), and *T. zhukovskyi* (7 accessions).

The GRIN database contains passport data, information which describes where and when an accession was collected, donated or developed. Crop-specific descriptor lists have been developed for most crops to provide a means of comparing accessions within a collection based upon standardized morphological, phonological, physiological, biochemical and molecular traits, as well as disease and insect tolerance or resistance. The GRIN system provides information on the availability and amount of seed that can be freely distributed to scientists and farmers in the US and around the world. However, the typically small amount of seed that farmers can obtain from the GRIN system may not satisfy their immediate needs. Moreover, there is a substantial time lag implicated in restoring landrace diversity on the farm from the typically small seed quantities conserved and distributed by genebanks to be immediately used by farmers. Therefore, the continued production of landraces through on-farm conservation ensures timely availability of quality seed, and allows for the dynamic evolution of landraces under diverse agro-ecosystem.

Low-input and organic family farms require reliable sources of producible seed that are well adapted to local farming practices, local food needs, and market conditions. Small farmers who are not able to reproduce and save their own seed on the farm may suffer financially from dependency on the purchase of high-cost commercial seed. Local availability and access to high quality seed are key factors in the efforts to sustain on-farm conservation of wheat landraces. Therefore, to address gaps in the supply side and enhance local seed security, farmers need to restore and strengthen informal seed networks and community seed banks, and seek technical advisory services from traditional seed experts.

Small-scale family farms traditionally save seed of heirloom or local varieties in order to sustain harvests and conserve well-adapted traditional crop varieties. Seed saving can contribute to lower supply costs, more diversified goods, improved human nutrition, and farm self-sufficiency. On-farm seed saving by small farmers is essential in conserving global agricultural biodiversity, in general, and crop diversity, in particular. Recently, however, this effort has been undermined by corporate consolidation of seed markets and the contentious concerns about seed types, sources, and availability. Commercial and large-scale seed industries are constantly developing seeds that represent genetically uniform, high-yielding, and increasingly genetically modified crop varieties. These seed types are of little or no value to organic and low-input farmers; they are usually designed for use in large-scale mechanized farming, and sometimes are packaged with chemical inputs. As modern industrialized farming extends over the global agricultural landscape, the seed industry has become both more technically specialized and increasingly controlled by large corporate firms. The new seed technologies may pose serious and complex economic risks to small farmers; they can become dependent on expensive improved seed varieties and brands that are marketed along with complementary agrochemical packages. In addition, some commercial cultivars may not meet local dietary needs (e.g., gluten-sensitive patients) or market demand (e.g., semolina for traditional confectionery products).

Recreating and structuring local seed systems to simulate a source-sink meta-population model is a first step towards restoring the fragmented meta-population structures of wheat landraces. Through this model, stakeholders can:

1. Identify the unit of analysis (e.g., the farmer as a decision maker and agent of conservation, the field or parcel representing a particular habitat, the landrace, or a seed lot),
2. Incorporate variation among farmers in their practices, knowledge and gender,
3. Quantify patterns of seed exchange among farmers and their impact on the biology parameters of landrace population,
4. Identify the limiting factors that determine distribution and range of a landrace; and,
5. Define the minimum area needed to create a dynamic equilibrium between "colonization" and "extinction" of a landrace meta-population.

The goal of this type of participatory endeavor is empowering the farmers by supporting the formation of groups capable of assessing their own needs and addressing them either directly or through demands on publically-funded research organizations.

Unfortunately, not every smallholder farmer can easily select and save adequate supplies of seed from each harvest. The ability and choice of each farmer to save seed depends on many factors, including availability of labor, technical training and skills in seed conservation, food needs, farm income, and market conditions. Moreover, low income family farms may have limited technical capability and facilities to produce and properly store seed lots, and thus can face risks in conserving and sustaining reliable and high-quality seed supplies for their planting needs.

Traditional farmers periodically resort to replacing seed of their old varieties and landraces with seed from other farmers to combat what they consider as “seed degradation.” This “inexplicable” seed replacement may have its origins in farmers’ belief that homegrown seed degenerates after several generations of re-sowing under the same environmental and edaphic conditions and management practices. Moreover, some farmers are convinced that traditional maintenance breeding may not result in higher yield; therefore, they felt that seed replacement was a better method to maintain productive capacity of their crops. Arguably, seed replacement and avoidance of traditional maintenance breeding by farmers could be attributed to the existing, but mostly unsuspected, negative correlation between yield potential of the landrace and the competitive ability of individual plants within its genetically heterogeneous populations. As seed of many old varieties and landraces disappear across the world and sales of modern improved seed varieties increase exponentially, more low-income farmers may face difficult choices about the type and source of the seeds they utilize.

Landraces and the Future of Wheat Diversity

Durum and bread wheat landraces have been largely replaced, in their centers of diversity by monocultures of pure genotypes. This genetic erosion resulted in significant loss of valuable genetic diversity for quality traits and resistance or tolerance to biotic and abiotic stresses; whereas, the pure wheat genotypes do not have the wide adaptation and the diverse genetic background already present in landraces. Diversity of wheat landrace populations, when structured to build spatial and temporal heterogeneity into cropping systems will enhance resilience to abiotic and biotic stresses. Other resilience sources will include more robust genetic resistances and biochemical response mechanisms derived from landrace genotypes.

The likely loss of landrace populations and the anticipated genetic erosion due to climate change can be likened to the expectation that modern agriculture would inevitably replace landraces with high-yielding cultivars. Genetic diversity can lead to increased productivity of farming systems under a wide range of growing conditions, and more diverse farming systems, generally, are more resilient in the face of perturbations; whereas, diversity among and within crops can maintain or increase soil fertility and mitigate the impact of pests and diseases, thus enhancing food security.

Climate change is expected to differentially affect components of complex biological interactions in modern and traditional wheat production systems. Wheat yield and quality will be affected by climate change directly, and indirectly, through diseases (e.g., stem and leaf rusts) that themselves will change but remain important. These effects will be difficult to dissect and model as their mechanistic bases are generally not well-understood.

The manner with which wheat landraces and their populations in and outside their centers of diversity might respond to climate change will determine their continued productivity, utility, and survival. Phenotypic plasticity, evolution, and gene flow, although each presents its own uncertainty, are possible avenues for surviving shifts in biotic and abiotic conditions caused by climate change. Whether there will be constraints on evolution in response to the abiotic and biotic stresses caused by climate change, modern wheat, but not landrace adaptation may not keep up enough to maintain fitness (i.e., seed production). Wheat plants will probably respond through shifts in morphology (e.g., tillering capacity, leaf area index, green leaf area duration), phenology (e.g., days to anthesis, days to maturity, duration of seed filling period), or development (e.g., rate of leaf emergence based on available growing degree days), which may help maintain fitness. However, phenotypic plasticity and gene flow (mainly through seed exchange) of landraces may not produce fully adapted phenotypes or the necessary genetic variation to combat climate change. Declining yields of landrace populations due to expected climate change would cause great concern to farming families and threatens their livelihoods. In their attempt to maintain yields, farmers would consider changing seed sources and discarding their adapted landrace populations. This could result in the loss of certain landrace populations, entire landraces, or even whole minor wheat species.

Local farmers, as managers of food- and commodity-producing ecosystems, can contribute through local food production and reduction of greenhouse gas emissions along the food supply chain, to food security and environmental health and protection. From an energetic perspective, changes in consumption patterns are particularly important for developed countries. Wheat landraces, based on their nutritional value, when locally-produced can contribute to lower greenhouse gas emissions (0.1 g CO_2 per calorie) as compared to rice (0.43 g CO_2 per calorie), or vegetables (0.57 g CO_2 per calorie). This may encourage local food production and promote food security, farmers' livelihoods, and eventually rural development.

The development of new varieties from wheat landrace populations is a practical strategy to improve yield and yield stability, especially under stress and future climate change conditions. Further enhanced productivity and stability can be achieved through practicing continuous selection within landraces across the marginal production environments, to exploit the constantly released useful adaptive variation. Non-breeding approaches to create demand for landrace products to promote on-farm dynamic conservation and sustainable utilization of wheat landraces include:

1. Raising public awareness regarding current and future value of landraces,
2. Diversity fairs to allow for the exchange of landrace materials and associated indigenous knowledge,
3. Visits among farmers in different localities to share seeds and experiences,
4. Diversity contests to reward farmers who keep special varieties and or conserve the highest diversity, and
5. Recipe development and niche market creation for landrace products. Together, these activities are expected to complement each other and contribute positively towards sustaining on-farm conservation and landrace diversity for the foreseeable future.

Landraces, as an important genetic resource, have been included in international treaties and national decrees that protect and enhance their use in their local environments. However, legislation is needed to make it possible to market landraces as diversified genetic materials. National and international legislation was designed primarily to protect trade and return royalty income to expensively-funded plant breeding programs; as landraces become more attractive to use in local food production and sustainability, legislation changes are needed to facilitate this trend and to promote exportation and exchange of landrace diversity and encourage their use.

Conclusions

Food sovereignty is the basis for forging a free, sovereign society that has the right and the capability to produce its own food and other agro-ecosystem services. Wheat genetic resources contributed to diversify traditional and modern farming systems, and increased their productivity under a wide range of growing conditions. The more diverse the farming systems, the more they are resilient in the face of adverse conditions, thus enhancing food security of local communities. Wheat landraces, as an underutilized but valuable genetic resource in contemporary agriculture, are gaining increasing importance. However, a major part of their diversity is conserved, but not fully utilized, in a network of genebanks in the US and around the world.

A wheat landrace is composed of genetically heterogeneous populations comprising breeding lines and hybrid segregates which have evolved over many generations in a multitude of environments and local farming systems. Genetic erosion of wheat landraces due to replacement with high yielding cultivars could devastate future sustainability of cropping in centers of origin and centers of diversity by reducing the diversity available for future farmer-mediated crop evolution, as well as reducing diversity available for future breeding efforts in the wheat-growing parts of the world; the responses of landraces and farmers who grow them will determine much about the genetic resources available for the world's agriculture. However, the persistence cultivation of some wheat landraces attests to their continued value to farmers or their competitive advantage relative to modern varieties.

Wheat landraces are better adapted than modern cultivars to changing climate conditions and to stress environments due to their population genetic structure, buffering capacity, and a combination of morpho-physiological traits conferring adaptability to stress environments. However, their low yield, as compared to high yielding varieties, could be attributed to their genetic heterogeneity and to inter-plant competition which can be eliminated when a landrace is converted into desirable homozygous genotypes. For farmers to continue to grow, select, and manage local wheat landraces, and to reverse the fragmentation of their meta-populations and eventual genetic erosion in their center of diversity, and allow evolutionary processes that mold landrace diversity to continue, their value should be raised to approximate or exceed the social value of high-yielding wheat varieties. Understanding the different patterns of neutral and adaptive diversity, from the population- to the landrace-level, is essential to explain how landraces conserved on-farm will continue to evolve and how to minimize genetic erosion of this indispensable genetic resource.

New strategies are emerging to develop modern landraces based on multiple crosses and selection from populations of einkorn, emmer, durum, and bread wheat in combination with on-farm site-specific selection and to obtain highly adaptable genotypes for local and regional production. Participatory plant breeding and variety selection practices have emerged as a powerful strategy to merge breeders' knowledge and farmers' selection criteria and indigenous knowledge, emphasizing decentralized selection in the target environments with the active participation of local farmers and other stakeholders. Wheat breeders, seed producers, farmers and end-users, as stakeholders in participatory wheat breeding, are involved in all aspects of research and development of new cultivars. Participatory plant breeding and variety selection are more successful than the classical approach used in high-input breeding programs for improvement in stress-prone environments where sustainability is a high priority. Despite being more complex to carry out, participatory plant breeding not only delivers improved germplasm, but also opens venues of communication and collaboration between farmers and other stakeholders for the benefit of all. Nonetheless, the main challenges of on-farm breeding and conservation of wheat landraces are non-biological, but involve a complex of ethno-anthropological processes, including legal, economic and social factors, superimposed on interacting ecological and genetic processes. Wheat landraces having multiple home uses are more likely to be conserved and sustainably utilized for the foreseeable future.

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