Emir. J. Food Agric. 2013. 25 (1): 20-29
doi: 10.9755/ejfa.v25i1.15376
http://www.ejfa.info/

PLANT SCIENCE

Wheat Landraces: A mini review

Abdullah A. Jaradat*

USDA-ARS, 803 Iowa Ave., Morris, MN 56267 USA

Abstract

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 environments. 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. During the last ~50 years, the introduction of high-yielding wheat varieties into, and the structural changes in wheat farming systems in developing countries, led to the loss of genetic diversity and fragmentation of meta-population structures of wheat landraces from large parts of the Fertile Crescent, the center of origin and diversity of wheat landraces. However, the persistence cultivation of some wheat landraces attests to their continued value to farmers, or to their competitive agronomic or nutritional advantage relative to modern varieties. For farmers to continue to grow, select, and manage local wheat landraces, and to reverse the fragmentation of their meta-populations, especially 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. This review provides information on wheat domestication and the origin of wheat landraces; their dynamic on-farm conservation and utilization in improving modern wheat cultivars and reversing the genetic erosion of wheat genetic diversity.

Key words: Wheat, Landrace, Diversity, Fertile Crescent

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 (Zohary and Hopf, 2000). The domestication of wild emmer (*Triticum dicoccoides*), the progenitor of all cultivated wheats (Feldman and Kislev, 2007), 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 (Dvorak et al., 1998). 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 (Jaradat, 2006). 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.

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 (Zeven, 1999). 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 (Belay et al., 1995) to indicate the innovative role of farmer communities in their development and maintenance.

Received 14 March 2012; Revised 07 May 2012; Accepted 06 June 2012; Published Online 24 November 2012

*Corresponding Author

Abdullah A. Jaradat
USDA-ARS, 803 Iowa Ave., Morris, MN 56267 USA

Email: abdullah.jaradat@ars.usda.gov

The genetic structure of wheat landraces is an evolutionary approach to survival and performance (Brown, 2000), especially under arid and semi-arid growing conditions (Jaradat, 1992b). 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 (Masood et al., 2005). 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; therefore, wheat landraces developed multi-locus structures as a result of selection, genetic drift, or fragmentation of their populations (Brown, 2000). 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 (Altieri and Merrick, 1987).

Durum (Jaradat, 2006) and bread wheat landraces (Ehdaie and Waines, 1989a;b) 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 adaptation to low or organic inputs and for resistance to biotic and abiotic stresses. The pure genotypes of high yielding wheat varieties may not have the wide adaptation and the diverse genetic background already present in landraces that they replaced (Ali Deb et al., 1992). 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 (Koshgoftarmanesh et al., 2010) and tolerance to biotic and abiotic stresses (Ehdaie and Waines, 1989b) 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 (Witcomb et al., 1996); also, these landraces harbor genes and gene complexes for quality traits (Zencirci and Karagoz, 2005), tolerance to biotic and abiotic stresses, and adaptation under a wide range of low-input and organic farming systems (Jaradat, 2006).

Wheat Domestication

The domestication of wheat around 10,000 years ago marked a dramatic turn in the development and evolution of human civilization (Willcox, 1998), 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 wheat and other cultivated grasses constitute the domestication syndrome. These were:

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 (Feldman and Sears, 1981), 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.

Molecular genetics and archaeological data have allowed the reconstruction of possible domestication scenarios leading to the development of landraces, old and then modern cultivars (Dvorak et al., 1998; Willcox, 1998). For diploid (2x) *einkorn* and tetraploid *turgidum* (hard) wheat (4x), 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) bread wheat was disseminated around the Caucasian region, then around the Old World. These events, although resulted in wheat domestication, created genetic bottlenecks (Hammer et al., 1996), 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 high yielding cultivars which appear to be associated with loss of some quality traits such as protein content and glutenins quality (Distefeld et al., 2007).

Throughout most of last ~10,000 years, farmers have been behind the development and conservation of wheat genetic diversity (Zeven, 2000). 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. The extinction of traditional farming systems, erosion, or even the aging and exodus of rural population, and more recently, environmental degradation (Mercer and Peralis, 2010), 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 (Hammer et al., 1996; Witcombe et al., 1996) 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 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. Throughout their evolutionary history, wheat crops have been shaped and molded mainly by farmers to meet diverse end uses (Zeven, 2000), cultural practices, and to respond to changing socio-economic and growing conditions (Cox and Wood, 1999). 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 (Dhillon et al., 2004). Wheat landraces generally have both private and public values. Landraces constitute a private good to the farmers who grow them; 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 (Morris and Heisey, 1998). 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 (Zeven, 2000). 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 (Brown, 2000). 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 (Motzo and Giunta, 2007).

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 grains. 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 (Ayed et al., 2010). 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 (Geneç et al., 2005), 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 (Geneç et al., 2005; Distefeld et al., 2007). 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 (Distefeld et al., 2007; Koshgoftarmanesh et al., 2010).

Only a limited number of studies have focused on quality aspects of organic wheat production (Onduru et al., 2002). 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 (Zencirci and Karagoz, 2005). Farm households allocate resources for production of favorite or preferred landraces, expecting benefits to accrue from their subsequent consumption or sale in local markets (Brush and Meng, 1998). 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 (Zencirci and Karagoz, 2005). 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 (Frison et al., 2011). 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.

Conservation and 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 (Frizon et al., 2011). However, a small portion of this diversity is being conserved and used on-farm where it continues to evolve (Brush and Meng, 1998). 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

(Le Boulch et al., 1994; Kebebew et al., 2001). 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 (Brush and Meng, 1998).

Research results indicated 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 would increase 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 (Kebebew et al., 2001). 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 such 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 (Le Boulch et al., 1994).

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 (GRIN, 2011; www.ars-grin.gov). 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, 2011; www.ars-grin.gov) describes collection holdings of the NPGS. The NSGC's *Triticum* spp. collection currently includes the following species and subspecies (Table 1) 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).

Table 1. Wheat species, sub-species and number of accessions available at the Genetic Resources Information Netwrok, USA.
(GRIN, 2011; www.ars-grin.gov).

Wheat species	Sub-species	Number
Triticum aestivum	*aestivum*	44,975
T. aestivum	*compactum*	113
T. aestivum	*macha*	31
T. aestivum	*spelta*	1,295
T. aestivum	*sphaerococcum*	32
T. ispahanicum		7
T. monococcum	*aegilopoides*	918
T. monococcum	*monococcum*	210
T. timopheevii	*armeniacum*	269
T. timopheevii	*timopheevii*	42
T. turgidum	*carthlicum*	95
T. turgidum	*dicoccoides*	921
T. turgidum	*dicoccon*	620
T. turgidum	*durum*	8,403
T. turgidum	*paleocolchicum*	4
T. turgidum	*polonicum*	80
T. turgidum	*turanicum*	107
T. turgidum	*turgidum*	457
T. urartu		210
T. vavilovii		3
T. zhukovskyi		7

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 (Qualset et al., 1997).

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 (Witcombe et al., 1996), 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 (Rijal, 2010); 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 (Almekinders et al., 1994; Zeven, 1999):

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 (Zeven, 1999). 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 association 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 (Baniya et al., 2000).

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 (Bonman et al., 2007).

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 (Newton et al., 2011). 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 (Zeven, 1999). This could result in the loss of certain landrace populations, entire landraces, or, in extreme cases, whole minor wheat species.

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 (Ehdaie and Waines, 1989b). 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 (Jaradat, 1992a; Joshi and Witcomb, 2003).

Conclusions

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 produce 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 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, emphasizing decentralized selection in the target environments with the active participation of local farmers. Wheat breeders, seed producers, farmers and end-users, as stakeholders in participatory 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 ecological and genetic processes. Wheat landraces having multiple home uses are more likely to be conserved and sustainably utilized for the foreseeable future.

Acknowledgments

Thanks to two anonymous reviewers and to the editor of Emirates Journal of Food and Agriculture for their constructive editorial and review comments which contributed to the improvement of this article.

References

Ali Deb, T., P. Monneveux and J. L. Araus. 1992. Adaptation à la sécheresse et notion d'idéotype chez le blé dur. II. Caractères physiologiques d'adaptation. Agronomie 12:381-393.

Almekinders, C., N. Louwaars and G. de Bruijn. 1994. Local seed systems and their importance for an improved seed supply in developing countries. Euphytica 78:207-216.

Altieri, M. A. and L. Merrick. 1987. *In situ* conservation of crop genetic resources through maintenance of traditional farming systems. Econ. Bot. 1:86-96.

Ayed, S., C. Karmous, Y. Trifa, and O. Salma-Ayed. 2010. Phenotypic diversity of Tunisian durum wheat landraces. Afr. Crop Sci. J. 18:35-42.

Baniya, B. K., A. Subedi, R. B. Rana, C. L. Paudel, S. P. Khatiwada, D. K. Rijal and B. R. Sthapit. 2000. Seed supply systems: data collection and analysis. Nepal. In: D. Jarvis, B. Sthapit and L. Sears, (Eds.). pp. 159-164, Conserving agricultural biodiversity *in situ*: A scientific basis for sustainable agriculture International Plant Genetic Resources Institute, Rome, Italy.

Belay, G., T. Tesemma, E. Bechere and D. Mitiku. 1995. Natural and human selection for purple-grain tetraploid wheats in the Ethiopian highlands. Gen. Res. Crop Evol. 42:387-391.

Bonman, J. M., H. E. Bockelman, Y. Jin, R. J. Hijmans and A. Gironella. 2007. Geographic distribution of stem rust resistance in wheat landraces. Crop Sci. 47:1955-1963.

Brown, A. H. D. 2000. The genetic structure of crop landraces and the challenge to conserve them *in situ* on farms. In: S. B. Brush (Ed.). pp. 29-48, Genes in the Field: On-Farm Conservation of Crop Diversity Lewis Publishers, Boca Raton, FL, USA.

Brush, S. B. and M. Meng. 1998. Farmers' valuation and conservation of crop genetic resources. Gen. Res. Crop Evol. 45:139-150.

Dhillon, B. R. Dua, P. Brahmi and I. Bisht. 2004. On farm conservation of plant genetic resources for food and agriculture. Curr. Sci. 87:557-559.

Distefeld, A., I. Cakmak, Z. Peleg, L. Ozturk, A.M. Yazici, H. Budak, Y. Saranga and T. Fahima. 2007. Multiple QTL-effects of wheat *Gpc-B1* locus on grain protein and micronutrient concentrations. Physiol. Plant. 129:635-64.

Dvorak, J., M-C. Lou, and Z-L. Yang. 1998. Genetic evidence of the origin of *Triticum aestivum* L. In: A. B. Damania, J. Valkoun, G. Wlcox and C. O. Qualset (Eds.) pp. 253-251. The origins of agriculture and crop domestication. Proc. Harlan Symp. 10-14 May, 1997. Aleppo, Syria. Published Jointly by ICARDA, IPGRI, FAO, and UC/GRCP.

Ehdaie, B. and J. G. Waines. 1989a. Genetic variation, heritability, and path-analysis in landraces of bread wheat from southwestern Iran. Euphytica 41:183-156.

Ehdaie, B. and J. G. Waines. 1989b. Adaptation of landrace and improved spring wheat genotypes to stress environments. J. Gen. Breed. 43:151-156.

Feldman, M. and M. Kislev. 2007. Domestication of emmer wheat and evolution of free-threshing tetraploid wheat. I. J. Plant Sci. 55:207-221.

Feldman, M. and E. R. Sears. 1981. The wild gene resources of wheat. Sci. American 244:102-112.

Frison, E.A., J. Cherfas and T. Hodgkin. 2011. Agricultural biodiversity is essential for a sustainable improvement in food and nutrition security. Sustainability 3:238-253.

Geneç, Y., J. M. Humphries, G. H. Lyons and R. D. Graham. 2005. Exploring gentypic variation in plant nutrient accumulation to alleviate micronutrient deficiency in populations. J. Trace Elements Med. Biol. 18:319-324.

Hammer, K., H. Knupffer, L. Xhuveli and P. Perrino. 1996. Estimating genetic erosion in landraces-two case studies. Gen. Res. Crop Evol. 43:329-336.

Jaradat, A. A. 1992a. Breeding potential of durum wheat landraces from Jordan I. Phenotypic diversity. Hereditas 116:301-304.

Jaradat, A. A. 1992b. Breeding potential of durum wheat landraces from Jordan II. Differential responses to drought. Hereditas 116:305-309.

Jaradat, A. A. 2006. Phenotypic divergence in the meta-population of the Hourani durum wheat landrace. J. Food Agric. Env. 4:186-191.

Joshi, K. D. and J. R. Witcomb. 2003. The impact of participatory plant breeding (PPB) on landrace diversity: A case study of high-altitude rice in Nepal. Euphytica 134:117-125.

Kebebew, F., Y. Tsehaye and T. McNeilly. 2001. Diversity of durum wheat (*Triticum durum* Desf.) at in situ conservation sites in North Shewa and Bale, Ethiopia. J. Agric. Sci. Cambridge 136:383-392.

Koshgoftarmanesh, A.H., R. Schulin, R.L. Chaney, B. Daneshbakhsh, and M. Afyuni. 2010. Micronutrient-efficient genotypes for crop yield and nutritional quality in sustainable agriculture: A review. Agron. Sust. Dev. 30:83-107.

Le Boulch, V., J. L. David, P. Brabant and C. De Vallavielle-Pope. 1994. Dynamic conservation of variability: responses of wheat populations to different selective forces including powdery mildew. Gen. Sel. Evol. 26:221s-240s.

Masood, M. S., A. Javaid, M. A. Rabbani and R. Anwar. 2005. Phenotypic diversity and trait association in bread wheat (*Triticum aestivum* L.) landraces from Baluchistan, Pakistan. Pak. J. Bot. 37:949-957.

Mercer, K. L. and H. R. Peralis. 2010. Evolutionary response of landraces to climate change in centers of crop diversity. Evol. Appl. 3(5-6):480-493.

Morris, M. L. and P. Heisey. 1998. Achieving desirable levels of crop diversity in farmers' fields: Factors affecting the production and use of commercial seed. In: M. Smale (Ed), Farmers, gene banks and crop breeding: Economics analyses of diversity in wheat, maize, and rice. Norwell, MA: Kluwer Academic Publishers, Inc., and CIMMYT.

Motzo, R. and F. Giunta. 2007. The effect of breeding on the phenology of Italian durum wheats: From landraces to modern cultivars. Eur. J. Agron. 26:462-470.

Onduru, D. D., A. de Hager, E. van der Werf and J. M. Diop. 2002. Participatory on-farm comparative assessment of organic and conventional farmers' practices in Kenya. Biol. Agric. Hort. 19:295-314.

Qualset, C. O., A. B. Damania, A. C. A. Zanatta, and S. B. Brush. 1997. Locally-based crop plant conservation. In: N. Maxted, B. V. Ford-Lloyd and J. G. Hawkes (Eds.) pp. 160-175. Plant genetic conservation: the in-situ approach. Chapman and Hall.

Rijal, D. K. 2010. Role of food tradition in conserving crop landraces on-farm. J. Agric. Env. 11:107-119.

Willcox, G. 1998. Archaeobotanical evidence for the beginning of agriculture in Southwest Asia. In: In: A. B. Damania, J. Valkoun, G. Wlcox and C. O. Qualset (Eds.), pp 25-36.The origins of agriculture and crop domestication. Proc. Harlan Symp. 10-14 May, 1997. Aleppo, Syria. Published jointly by ICARDA, IPGRI, FAO, and UC/GRCP.

Witcombe, J. R., A. Joshi, K. D. Joshi and B. R. Sthapti. 1996. Farmer participatory crop improvement. I. Varietal selection and breeding methods and their impact on biodiversity. Exp. Agric. 32:445-460.

Zencirci, N. and A. Karagoz. 2005. Effect of developmental stages length on yield and some quality traits of Turkish durum wheat [*Triticum durum* L. convar. *durum* (Desf.) MacKey] landraces: influence of developmental stages length on yield and quality of durum wheat. Gen. Res. Crop Evol. 52:765-774.

Zeven, A. C. 1999. The traditional inexplicable replacement of seed and seedware of landraces and cultivars: a review. Euphytica 110:181-191.

Zeven, A. C. 2000. Traditional maintenance breeding of landraces: 1. Data by crop. Euphytica 116:65-85.

Zohary, D. and M. Hopf. 2000. Domestication of plants in the Old World. 2nd edn. Clarendon Press, Oxford, UK.