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RESEARCH ARTICLE

Diversity and sustainability of wheat landraces grown in Uzbekistan

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Abstract

Development of new wheat cultivars combining good local adaptation, disease resistance and grain quality represents an important strategy component for national food security. Uzbekistan was identified by N. Vavilov as important center of wheat diversity. An inventory of landraces was conducted in 2010–2013 in western Tien-Shan Mountains to survey, collect, and characterize old wheats still grown by farmers. Thirty landraces were collected from 17 villages in Jizzakh, Kashkadarya and Surkhandarya Regions. The material went through spike selection, head-rows, un-replicated trials in Tashkent, Uzbekistan (2012–2015), and replicated trials in Konya, Turkey (2018–2019). Landrace diversity was described using spike morphological traits and DNA profiles as reflected by single nucleotide polymorphism. A socioeconomic survey demonstrated that wheat landraces are grown in remote mountain communities by subsistence farmers despite having access to modern cultivars, and both are frequently grown together. The main reasons for the maintenance of landraces are: (1) large grain with excellent bread-making quality and suitability for home-baking; (2) specific adaptations allowing stable and reliable yield; and (3) straw yield and quality. Similar genomic profiles shared by some landraces from remote regions of Uzbekistan and neighboring Tajikistan demonstrated their common origin and are indicative of seed exchange between farmers. Agronomic characterization demonstrated the resilient nature of their adaptation based on spring and facultative growth habit and superiority of some landraces for grain yield and its components compared to local checks. Viable options for maintaining and expanding on-farm wheat diversity include their improvement through selection and breeding, market development, variable incentives, and capacity building. For the first time, this paper presents results of a unique 10-year study in Uzbekistan on social conditions in the areas where wheat landraces are grown, analyses the diversity of these landraces, evaluates agronomic characteristics, and discusses the sustainability options for on-farm wheat landraces use and conservation.

Keywords Wheat · Local varieties · Grain yield · Growth habit · Molecular markers

1 Introduction

Uzbekistan is a double landlocked country in Central Asia with the population of 33.4 M people and arable land of 4 Mha (http://www.fao.org/faostat). Wheat is a major food crop with the total area of 1.4 Mha and average grain yield 4.5 t/ha. Consumption of bread and other wheat products in Uzbekistan is one of the highest in the world and exceeds 200 kg per person per year. Despite substantial production gains in wheat (Khalikulov et al. 2016), the country still depends on imports equivalent to 15–20% of its crop production to meet the growing demand for grain. The processing industry recognizes the low quality of local wheat, but the land use policy prioritizes production quantity, so wheat of better quality is imported to improve flour (Kienzler et al. 2011; http://www.fao.org/giews/countrybrief/country.jsp?code=UZB). Around 70% of wheat is cultivated in irrigated production systems in rotation with cotton, maize, rice, and other summer crops including legumes and vegetables. Rainfed production areas are situated in the foothills of Turkestan and Gissar Ranges of the Tien-Shan Mountains, primarily in Jizzakh, Kashkadarya, and Surkhandarya Regions, with

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precipitation ranging from 250 to 500 mm depending on the altitude. The cropping systems are predominately based on cereals.

Lack of irrigation water and other inputs, and high temperatures represent major constraints for irrigated wheat production, whereas drought, cold, and heat are the main abiotic stresses limiting wheat yield in rainfed production. Wheat diseases and pests substantially reduce grain productivity requiring application of crop protection chemicals. Stripe rust represents a major challenge for wheat production both under irrigated and rainfed conditions reducing the grain yield by 16–24% in susceptible cultivars (Sharma et al. 2016). Until recently, wheat cultivars grown in Uzbekistan were mainly imported as seed from Russia and occupied substantial areas of the country. Although being high yielding and responsive to irrigation and other inputs, Russian cultivars were late maturing and susceptible to stripe rust (Sharma et al. 2013). Development and promotion of new winter wheat cultivars in Uzbekistan combining good local adaptation, disease resistance, and grain quality represent an important strategy component for national food security.

A history of wheat breeding in Uzbekistan was compiled by Khalikulov et al. (2016). Wheat breeding in Uzbekistan goes back to 1909, when the Experimental Station of Turkestan collected local wheat germplasm. The most common wheat landraces of that time were Sary Magiz, Ala-Biruk, Kyzyl bugday, Nar-Kyzyl and Ak bugday. In 1932, wheat breeding was established at Gallyaaral Town where winter temperatures fell to −44°C, and summer temperatures reach 52–56°C. A number of cultivars released in the 1940s were based on selections from landraces. A success of Central Asian breeding, the cultivar Kyzyl-Shark, was developed in the Uzbek Research Institute of Grain at Gallyaaral and released in 1951. Landrace Hivinka was important for Central Asia and Russia breeding contributing to a number of cultivars developed in Saratov, Russia including mega-cultivars covering millions of hectares. During the 1950s to 1980s, few cases of irrigated wheat cultivation were in the country. Hence, wheat breeding was only conducted for rainfed areas at the institute in Gallyaaral. Since independence in 1991, several wheat breeding and research programs with clear focus on yield potential under irrigation were established in Andijan, Tashkent, Karshi and other regions. International cooperation with CIMMYT and ICARDA has made an important contribution resulting in development and adoption of new winter wheat cultivars (Morgounov et al. 2019).

N. Vavilov recognized the importance of Central Asia and Uzbekistan as a region of crop diversity and established genetic resources station in Tashkent in 1924 as Central Asian branch of St. Petersburg Institute of Applied Botany, presently Vavilov Institute (Mavlyanova et al. 2005). The station's first task was survey and collection of crops and their wild relatives in Central Asia. After independence, the station was transformed into Uzbek Research Institute of Plant Industry (Plant Genetic Resources Research Institute since 2020) and now houses a germplasm collection with over 16,000 accessions of cereals. N. Vavilov made the first collection of wheat landraces in Khiva Oasis in lower Amu-Darya River in 1925 (Zuev 2008). Currently, 33 accessions from his collection are maintained at the Vavilov Institute. His colleague, V. Kobelev, continued wheat collection in southeastern Uzbekistan in 1926–1928. Another wheat collection was made by the Tashkent Branch of Vavilov Institute in 1949–1950. In 1965–1971, Vavilov Institute made extensive expeditions and collections across Uzbekistan (Udachin and Shakhmedov 1984). The accessions from all these collections are maintained at the Vavilov Institute. According to Genesys database (https://www.genesys-pgr.org), a substantial number of wheat landrace accessions from Uzbekistan are conserved at the following Institutes: Vavilov Institute (333), ICARDA (201), USDA (50) and CIMMYT (32).

Since independence, several germplasm collection expeditions took place in Uzbekistan (e.g., Pistrick and Mal'cev 1998; van Soest et al. 1998) but none of them targeted wheat. Following successful inventory of wheat landraces in Turkey starting in 2009 (Morgounov et al. 2016), a similar activity was initiated in Uzbekistan. In 2010, an expedition and collection of wheat landraces was conducted in western Turkestan and Gissar Ranges of Tien-Shan Mountains by the Institute of Plant Genetics and Experimental Biology. In 2013, the undertaking was repeated and reached remote villages in the Surkhandarya Region. Overall, 30 wheat landraces were collected from Jizzakh, Kashkadarya, and Surkhandarya Regions. The results of the survey and collections were detailed by Baboev et al. (2015). Preliminary evaluations demonstrated variation among the collected wheat landraces including grain yield, 1000-kernel weight and gluten content, with several lines exceeding the check cultivar for different traits (Baboev et al. 2017). The collected wheat landraces were further studied in Uzbekistan and in Turkey in 2016–2019 using modern phenotyping and genomic tools. This paper provides the first description of the social and environmental conditions of the areas where wheat landraces are grown, analyzes their diversity using genomic tools, evaluates agronomic characteristics based on field experiments, and discusses the sustainability options for on-farm wheat landraces use and conservation.

2 Material and methods

2.1 Wheat landraces collection and evaluation in Uzbekistan, 2012–2015

The collections sites in Uzbekistan were determined based on preliminary communication with researchers, local administrators, and farming communities on the likelihood of finding wheat landraces. Wheat accessions were collected from 17 villages situated in eight districts and three administrative regions (Table 1, Fig. 1). Overall, 30 wheat landraces were collected. All the collections were made in July–August in the field by harvesting a random sample of around 100 spikes across the field. Collection was accompanied by socioeconomic survey of 20 farmers growing the landraces. The survey comprised around 50 questions of household nature, agronomic practices, and utilization of wheat landraces (Table S1). Many spike samples represented mixtures of different wheat and other crops (e.g., barley and rye). For this reason, the samples were divided into similar groups based on spike morphological traits: glume color and pubescence, presence of awns and grain color. The combination of these highly inherited traits defines the botanical variety (or morphotypes) as described by Zuev et al. (2013) and presented in Table S2. After classification and grouping of morphotypes, 20 spikes were selected from each landrace for planting representing the whole diversity of the landrace. They were planted as head-rows, described and evaluated for morphological and agronomic traits. The selection from the head-rows targeted

Table 1 Geographic location and description of wheat landraces collected in Uzbekistan

Catalogue #	Region	Village, District	Latitude	Longitude	Elevation, masl	Landrace name	Planting season	Botanical variety of main component
2010 collection								
1	Surkhandarya	Duoba, Boysun	38.32121	67.38181	1391	Kzyl bugday	March	*erythrospermum*
2			38.32025	67.36594	1431	Kzyl bugday	March	*erythrospermum*
3		Kurgancha, Boysun	38.37921	67.41462	1633	Kzyl bugday	March	*erythrospermum*
4		Gumatak, Boysun	38.35699	67.37737	2136	Kzyl bugday	March	*erythrospermum*
5			38.35986	67.07070	2174	Kzyl bugday	March	*erythrospermum*
6			38.35057	67.42538	2143	Kzyl bugday	March	*erythrospermum*
7		Pulhokim, Boysun	38.16484	67.38905	1050	Boboky	October	*erythrospermum*
8	Kashkadarya	Guldara, Yakkabog	38.78582	66.81014	1159	Ak bugday	March	*greacum*
9			38.77369	66.82451	1270	Greacum	March	*greacum*
10		Terakly, Yakkabog	38.75540	66.81783	1634	Surkhak	November	*erythrospermum*
11			38.75934	66.82558	1500	Ak bugday	November	*greacum*
12		Navruz, Yakkabog	38.90100	66.64225	585	Korakiltik [a]	November	*pseudo-leucurum*
13		Kuga, Kamashi	38.66376	66.92626	2249	Ak bugday	March	*greacum*
14			38.63243	66.94461	1988	Ak bugday	March	*greacum*
15		Kzyltom, Kamashi	38.61663	66.93731	1753	Tuyatish	March	*erythrospermum*
16		Kuga, Kamashi	38.64701	66.93114	1731	Kzyl bugday	March	*erythrospermum*
17		Kzyltom, Kamashi	38.66376	66.92626	2249	unnamed	March	*erythrospermum*
18			38.65243	66.90205	2147	unnamed	March	*erythrospermum*
19			38.59266	66.91480	1317	Ak bugday	March	*greacum*
20	Jizzakh	Muzbulok, Bakhmal	39.71376	68.12882	1520	Ak bugday	October	*greacum*
21		Zartepa, Bakhmal	39.70017	68.19329	1763	Surkhak	March	*erythrospermum*
22		Yonbosh, Galla-Aral	40.12471	67.41983	1449	Ak bugday	November	*greacum*
23		Lalmikor, Galla-Aral	39.93540	67.45574	740	Ak bugday	November	*greacum*
2013 collection								
24	Surkhandarya	Khodja Osmin, Saryazia	38.61500	67.58411	2008	Pashmak	October	*greacum*
25			38.60202	67.56589	1650	Khivit	August	*greacum*
26			38.57685	67.58622	1558	Kzyl bugday	March	*erythrospermum*
27		Chinar, Altinsay	38.33086	67.65667	1301	Greacum	October	*greacum*
28		Pas Machay, Uzun	38.31318	67.04989	1289	Muslimka	October	*erythrospermum*
29			38.58531	67.57554	1615	Kayraktash	March	*greacum*
30		Changar-dak, Uzun	38.49779	67.69071	957	Kzyl shark	October	*erythrospermum*

[a] Durum wheat

maintaining the whole diversity of the collection. Overall, planting of 20 spikes from each of the 30 collected landraces resulted in 600 headrows. They were subjected to further selection resulting in 60 distinct landraces lines.

The process of describing the morphological and agronomic diversity took place in the experimental field of the Institute of Plant Genetics and Experimental Biology in Tashkent in 2011–2015 (41.23°N; 69.26°E). The following traits were recorded: number of days to heading, plant height, disease resistance, grain yield, and spike morphology. A field fallowed in the preceding year was used and regular agronomy was applied including herbicide control in spring and nitrogen application with 80 kg/ha (active matter). The head-rows were planted as a 1-m single row with 30 cm between rows. Selected head-rows were planted in 2-m^2 plots without replication in the 2012–2015 seasons and evaluated for agronomic traits. Overall, 60 lines selected from all the collected wheat landraces were integrated into one nursery and transferred to Haymana Station of Central Field Crop Research Institute, near Ankara (39.36°N; 32.39°E), Turkey for the 2015–2016 season. These were planted as 1-m single rows under dry rainfed conditions following a fallow. Due to poor establishment, the material evaluation in 2016 was limited, so the experiment was repeated in 2017 at the same site. In addition to morphological traits, plant height and reaction to stripe rust were recorded.

2.2 Application of DNA markers for diversity analysis

All 60 lines originating from Uzbek landraces were genotyped using a selected set of 63 KASP markers covering all chromosomes (Table S3). These KASP markers were selected based on SNPs included in the Illumina wheat 90K iSelect genotyping assay (Wang et al. 2014) to represent the diversity of all wheat chromosomes and their arms. Diversity analysis was conducted using SNP markers in the CIMMYT wheat molecular breeding laboratory in Mexico using standard conditions as described in Dreisigacker et al. (2016). Using the combination of botanical variety or morphotype (Table 2S); phenotypic (plant height, days to heading, disease reaction) and genotypic data (assignment to clusters based on 63 KASP markers), 26 unique distinct lines were identified. A set of 14 lines representing all regions, morphotypes, agronomic traits diversity and KASP markers profiles was further selected from these 26 lines. This set of 14 Uzbek wheat landraces was genotyped at higher density using an Illumina Infinium 25K wheat SNP array (TraitGenetics GmbH, Gatersleben, Germany) resulting the identification of 21,186 diverse SNP markers. In addition to Uzbek wheat landraces, 30 wheat landraces from Tajikistan collected in 2013–2014 (Husenov et al. 2021) were genotyped with the same platform. The Uzbek landraces data from 63 KASP markers and Illumina SNP chip data for the 14 Uzbek and 30 Tajik wheat landraces were independently used to calculate the kinship between the

Fig. 1 Location of wheat landraces collection sites in Uzbekistan: 1 Jizzakh region; 2 Kashkadarya region; 3 Surhandarya region

genotypes. The kinship matrix was estimated from the SNP data as the average allele sharing between the genotypes. Kinship values from pairwise comparison were utilized for clustering the genotypes. R Studio version 3.4 (R Core Team 2017) was used for the genomic analysis.

2.3 Wheat landraces evaluation in Turkey, 2018–2019

The set of 14 landraces was phenotyped for common agronomic traits (plant height, days to heading, grain yield and its components) in 6-m^2 plots without replication under rainfed conditions at the Bahri Dagdas International Agricultural Research Institute in Konya (37.51°N; 32.33°E), Turkey in the 2017–2018 season. The phenotyping was repeated at the same rainfed site with two replicates using alpha-lattice design in the 2018–2019 season. Agronomic traits and yield components were evaluated following the methods of Pask et al. (2012). In addition, the material was evaluated for stripe rust resistance at the Haymana Station of Central Field Crop Research Institute, Turkey and for leaf rust resistance at the Maize Research Station, Sakarya (40.43°N; 30.22°E), Turkey in 2019. Artificial inoculation with the mixture of local pathotypes as described by Pask et al. (2012) was used at both sites and led to high disease pressure. Growth habit was evaluated by planting the material in late April when the minimum daily temperatures exceeded 10°C. The genotypes coming to head were classified as spring types while the entries remaining at tillering stage were classified as winter types. Facultative types were also identified as heading substantially later that spring types. Weather conditions in Konya in 2018 were characterized by lack of moisture prior to heading resulting in drought and yield reduction. In 2019, the precipitation was sufficient; the plants grew tall and lodged during maturity. Statistical analysis of the field data was limited to ANOVA of agronomic traits from replicated experiments in Tashkent and Konya using Microsoft Excel software.

3 Results and discussion

3.1 Where, how and why the wheat landraces are grown

Prior to the expedition and collection mission, the main questions in relation to wheat landraces were: who is growing what, where, how and why. Wheat landraces occupy only a small area of Uzbekistan in the mountains bordering Tajikistan in Jizzakh, Kashkadarya, and Surkhandarya Regions (Table 1, Fig. 1). The altitude of most of the villages and collection sites exceeded 1000 masl and seven fields were located above 2000 masl. The villages where the wheat landraces are grown were remote with average distance to markets exceeding 40 km (Table 2). Considering the quality of the rural roads, it is difficult to have access to the new seeds and other inputs as well as to sell grain and agricultural products. It appears that mostly subsistence farmers grow landraces. The size of the settlements surveyed varied from small with 40 families to large ones with 1800 families. The average age of the farmers who grow landraces was around 50 years old. Only in two villages that farmers did grow wheat landraces exclusively, whereas in most villages, the proportion of the area planted to wheat landraces varied from 1 to 50% of all wheat including modern cultivars. The farmers grow the landraces from generation to generation using their own seed. The grain from the landraces is used for clay tandoor oven bread normally baked at home as described by Ranum et al. (2006). The survey identified three main reasons for the maintenance of landraces: (1) large grain with excellent bread-making quality and suitability for home baking including taste and shelf life; (2) specific adaptations allowing stable and reliable yield in harsh highland environments including spring planting; and (3) straw yield and quality as animal feed, fuel mixed with cattle manure and construction material. Depending on the region, the villagers were primarily engaged in forestry, raising livestock, and forage grasses. However, farmers grow landraces such as Boboky, Kzyl bugday, Kayraktash, Ak bugday, Korakiltik, and others every year in the smaller fields whereas larger fields are used for old commercial wheat cultivars such as Intensivnaya and Krasnovodopadskaya.

The farmers growing wheat landraces apply simple extensive production methods. Depending on the region and altitude, planting takes place in autumn or spring. Even when planted in autumn, the seed could stay in the soil without germination till spring. The landraces may be planted continuously or rotated with safflower or chickpea. Tillage including plowing is practiced. For small fields, farmers mainly engage in hand planting or broadcasting with a fertilizer spreader followed by harrowing. Phosphorus fertilizer (P30) is applied at planting and nitrogen is applied in spring (N20-40) depending on the rainfall. No herbicides or fungicides are applied during the season and the fields are quite weedy.

Until recently, wheat production in Uzbekistan and especially in irrigated areas was a strategic food security commodity highly regulated by the government. Prior to planting, the plan and orders would be issued on which cultivar to be planted where, when, and how, and what inputs to be provided and yield obtained (Babakholov et al. 2018). The situation was a little more flexible for the rainfed areas. For this reason, there was no scope for old wheat landraces to be grown in commercial private or cooperative farms. However, they were conserved, maintained, and used by farmers in remote mountain communities which were beyond the reach of the state agricultural planning system. The main drivers for farmers to grow wheat landraces in Uzbekistan were not concern for maintenance of global agrobiodiversity but their adaptation to local conditions and the use of the grain and straw in their

Table 2 Socioeconomic survey of villages growing wheat landraces in Uzbekistan (2010 and 2013)

Region	District	Village	Number of families	Distance to market, km	Average age of farmer	Main reason to grow wheat landraces	Village wheat area, ha	Village landrace area, ha	Years of landrace cultivation
Jizzakh	Bakhmal	Muzbulok	300	50	45	Quality, yield	1500	800	>50
		Zartepa	70	60	45	Quality	2500	2500	>50
	Galla-Aral	Yonbosh	120	20	50	Quality, drought	7000	1000	30
		Lalmikor	1800	25	50	Quality, drought	500	250	>50
Kashkadarya	Yakkabog	Guldara	300	45	45	Quality, yield, straw	100	30	Forever
		Terakly	45	50	50	Quality	50	50	Forever
		Navruz	150	9	50	Quality	2500	20	Forever
	Kamashi	Kuga	80	60	50	Quality, yield, straw	50	20	Forever
		Kzyltom	40	50	50	Quality	60	15	Forever
		Kzyltepa	75	80	50	Quality	200	50	Forever
Surkhandarya	Boysun	Duoba	70	35	50	Quality	500	100	80
		Kurgancha	220	45	50	Quality, straw	230	130	100
		Gumatak	70	33	60	Quality, straw	150	20	>100
		Pulhokim	680	25	50	Quality, drought	500	50	50
	Saryazia	Khodja Asmin	700	80	45	Quality, cold, straw	100	1	Forever
	Uzun	Changardak	100	50	50	Quality, straw	100	3	Forever

houses. Strong traditions also contributed to keeping landraces. Wheat landrace inventory conducted in Turkey in 2009–2014 (Kan et al. 2015) and in Tajikistan in 2013–2014 (Husenov et al. 2015) demonstrated quite similar results: remote mountainous communities continue to grow diverse wheat landraces from generation to generation despite the access to modern cultivars and technologies. Recent surveys and studies in Afghanistan, Iran, and Turkey demonstrated a gender dimension to on-farm wheat landraces diversity (https://www.wheatlandraces.org/information#project-reports). Individual and group interviews with more than 400 rural women involved in farming, especially older generations, indicated that these women possess great knowledge of landraces and have an important role in deciding what crops are planted on their land. At least 50% of responders indicated that their voice in selection of the seed for planting is considered. This is very logical as these women are the ones who mostly deal with the daily food preparation and weekly bread baking. McNamara and Wood (2019) studied food choice in neighboring Tajikistan and concluded that women believe in health benefits of local homegrown products versus imported or industrially produced with high inputs. Feminization of agriculture has been an obvious tendency in Central Asia due to migration of rural men as labor (Mukhamedova and Wegerich 2018). Any strategy for conservation and expansion of on-farm wheat diversity needs to take into account the role of women in household decision-making.

3.2 Morphological and genomic diversity of wheat landraces

Description of the landraces and identification of the unique genotypes associated with a specific farming community and an identified name was a difficult task. Firstly, 10 out of 30 collected landraces were mixtures of different wheat morphotypes easily identified by spike color or awns. Secondly, some landraces with the same name originating from different regions and villages were quite different morphologically or genomically. Thirdly, phenotypically similar landraces may have different origin and names. Diversity of the landraces was initially described using spike morphology traits and botanical variety (Table S2). This approach was developed by Vavilov (1966) and was widely used by Russian scientists in the early 1900s to describe numerous wheat collections including in Central Asia. The main assumption of this approach is conservative inheritance of spike traits (glume color and pubescence, presence of awns, and grain color) for self-pollinated species like wheat in the absence of artificial crosses. The extent of the diversity was judged by the number of botanical varieties identified. For instance, Vavilov Institute collections in 1965–1971 in southeastern Uzbekistan, which coincides in area with the present collection, identified 15 botanical varieties including both bread and durum wheat (Zuev 2008). The collection in 2010 and 2013 identified only three botanical varieties of bread wheat (*erythrospermum, greacum,* and *ferrugineum*) and one durum wheat (*pseudo-leucurum*) (Table 3).

In this study, identification of the unique lines originating from the collected wheat landrace was based on name, geographic origin, botanical variety, plant height, and KASP markers profile. As a result, 30 lines from wheat landraces were identified representing the diversity of the collection (Table 3). The cluster analysis using kinship calculated based on the 63 KASP markers demonstrated the relationship between landraces from different regions (Fig. 2). The Cluster 4 consists of five almost identical genotypes, Surkhak from Jizzakh Region and four Kzyl bugday landraces from Kashkadarya and Surkhandarya Regions. Overall, Cluster 4 also included closely related Ak bugday and Pashmak (both from the Jizzakh Region), Tuyatish (Kashkadarya) and Muslimka (Surkhandarya). This close relationship of wheat landraces with different names from different relatively isolated regions signifies their common origin and exchange of seed among farmers. Durum wheat landrace Korakiltik had a unique KASP markers profile distinguishing it from the other landraces in Cluster 1. Cluster 2 included several Ak bugday lines from the three regions represented by botanical varieties *greacum* and *erythrospermum*. Cluster 3 was relatively diverse and included 10 landraces with different names originated in different provinces, but all classified as *erythrospermum* botanical variety. As reported previously (Dreisigacker et al. 2005), it appears that similarity of the landraces based on DNA diversity is not related to their name and geographical origin. Even morphologically similar landraces can be distinguished when classified by genomic profile.

For the detailed phenotyping and evaluation, a set of 14 Uzbek wheat landraces was selected to represent the existing diversity (selected lines are highlighted bold in Table 3 and Fig. 2). High density Illumina SNP chip data was obtained for these 14 landraces along with the core set of 30 Tajik wheat landraces collected in 2013–2014. The resulting SNP data was used to calculate the kinship and conduct joint cluster analysis to find the relation between the landraces from the two countries (Fig. 3). Tajik landraces collection and survey was described by Husenov et al. (2015, 2021). The cluster analysis results demonstrated both similarity and diversity of landraces from the two countries. Group 4 comprised very similar wheat

Table 3 Distinct wheat landraces collected in Uzbekistan in 2010 and 2013

Region	District	Village	Landrace ID	Name	Bot. variety	DNA cluster	Height (cm)
Jizzakh	Bakhmal	Muzbulak	216-UzCL-15-35	**Ak bugday**	*erythrospermum*	2	94
		Zartepa	218-UzCL-15-47	Surhak	*erythrospermum*	4	94
			217-UzCL-15-46	**Surhak**	*erythrospermum*	3	86
	Gallaaral	Lalmikor	222-UzCL-15-17	Ak bugday	*greacum*	2	77
		Yonbosh	221-UzCL-15-49	Ak bugday	*erythrospermum*	4	83
Kashkadarya	Kamashi	Kuga	208-UzCL-15-9	Kzyl bugday	*erythrospermum*	4	102
			204-UzCL-15-30	**Ak bugday**	*greacum*	2	80
			202-UzCL-15-27	**Ak bugday**	*erythrospermum*	2	96
		Kzyltom	205-UzCL-15-53	**Tuyatish**	*erythrospermum*	4	103
			206-UzCL-15-36	**Tuyatish**	*erythrospermum*	3	98
			212-UzCL-15-44	**Nameless**	*erythrospermum*	3	87
	Yakkabog	Navruz	200-UzCL-15-14	Korakiltik	*pseudo-leucurum*	1	92
		Terakly	196-UzCL-15-40	Surkhak	*erythrospermum*	3	83
			199-UzCL-15-32	**Surkhak**	*greacum*	2	82
Surkhandarya	Boysun	Duoba	175-UzCL-15-7	**Kzyl bugday**	*erythrospermum*	3	74
			174-UzCL-15-6	**Kzyl bugday**	*erythrospermum*	3	84
			177-UzCL-15-26	Kzyl bugday	*erythrospermum*	3	96
		Gumatak	184-UzCL-15-4	Kzyl bugday	*erythrospermum*	4	100
			185-UzCL-15-5	Kzyl bugday	*erythrospermum*	4	77
			191-UzCL-15-34	Kzyl bugday	*erythrospermum*	3	83
		Kurgancha	180-UzCL-15-1	**Kzyl bugday**	*ferrugineum*	4	73
		Pulhokim	193-UzCL-15-D25	**Boboky**	*erythrospermum*	3	80
	Khodja-osmin	Saryazia	223-UzCL-15-118	**Pashmak**	*erythrospermum*	4	97
			224-UzCL-15-119	Khivit	*erythrospermum*	3	89
	Uzun	Changar-dak	229-UzCL-15-117	Kzyl shark	*erythrospermum*	2	73
		Pas machay	227-UzCL-15-D36	**Muslimka**	*erythrospermum*	4	100

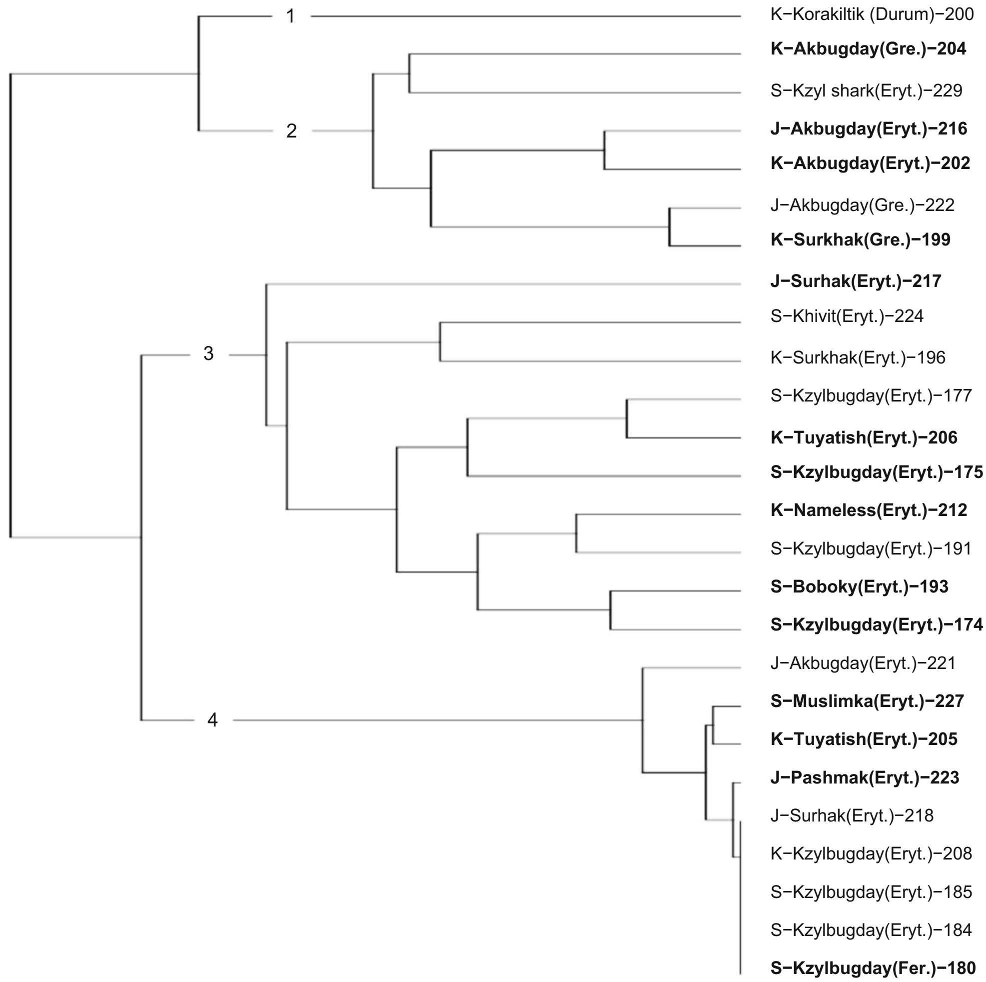

Fig. 2 Cluster analysis of 30 Uzbek landraces using 63 KASP markers. For each genotype first letter identifies the region: J, Jizzak; K, Kashkadarya; and S, Surkhandarya. Botanical variety is abbreviated in brackets: Eryt, *erythrospermum;* Fer, *ferrugineum;* Gre, *greacum.* The 2017 entry number is in the end of ID. Bold script identifies the lines selected for detailed agronomic characterization in Turkey

landraces from Uzbekistan Surkhandarya (Boboky, Kzyl bugday and Muslimka) and Kashkadarya (Tuyatish) regions and Tajik landraces from Shahristan (Uruklii bahori), Zerafshan valley (Surkhak) and Khatlon region (Shikhaki boboi). Common genomic profile shared by these landraces collected from distant and isolated locations indicated their close relatedness probably due to seed exchange between the farmers in the past. Group 1 included three Ak bugday landraces from Uzbekistan and several Tajik wheat landraces primarily from Khatlon. Group 2 almost entirely comprised unique Pamir landraces from Tajikistan. Group 3 equally combined Tajik landraces from Rasht Valley and Khatlon Region and Uzbek landraces from all three regions. It appears that country borders do define the spread of genetically similar landraces.

In a related study, Husenov et al. (2021) used high-density SNP array data for evaluation of diversity parameters of 14 Uzbek landraces from the current study, 30 Tajik, and 20 Afghan landraces collected in the last 5–7 years. The SNP polymorphism was the highest in Afghan (85%) and Tajik landraces (72%) and the lowest in Uzbek landraces (58%). The level of heterozygosity and the effective number of alleles maintained in three groups followed the same order as the SNP polymorphism with Uzbekistan group being least diverse. Relatively low genomic diversity of Uzbekistan landraces may be explained by their few number grown across spatially limited, relatively uniform landscape. Whereas Tajik and Afghan landraces were collected from much larger and diverse area.

In the same study by Husenov et al. (2021), the kinship values derived from analysis of the 63 KASP markers and 23,186 SNP markers were compared for each of the 14 Uzbekistan and 30 Tajikistan landraces. For 22 lines (50%), the coefficients of correlation between two genotyping methods exceeded 0.7 indicating strong agreement between the results. For an additional 13 lines (29%) the correlation values varied between 0.5 and 0.7. Overall, application of a larger number of array derived SNP markers data allowed more detailed differentiation between the landraces in regard of their similarity or divergence. However, for the majority of the lines, even the application of a limited number of cost-effective markers provided sufficient differentiation.

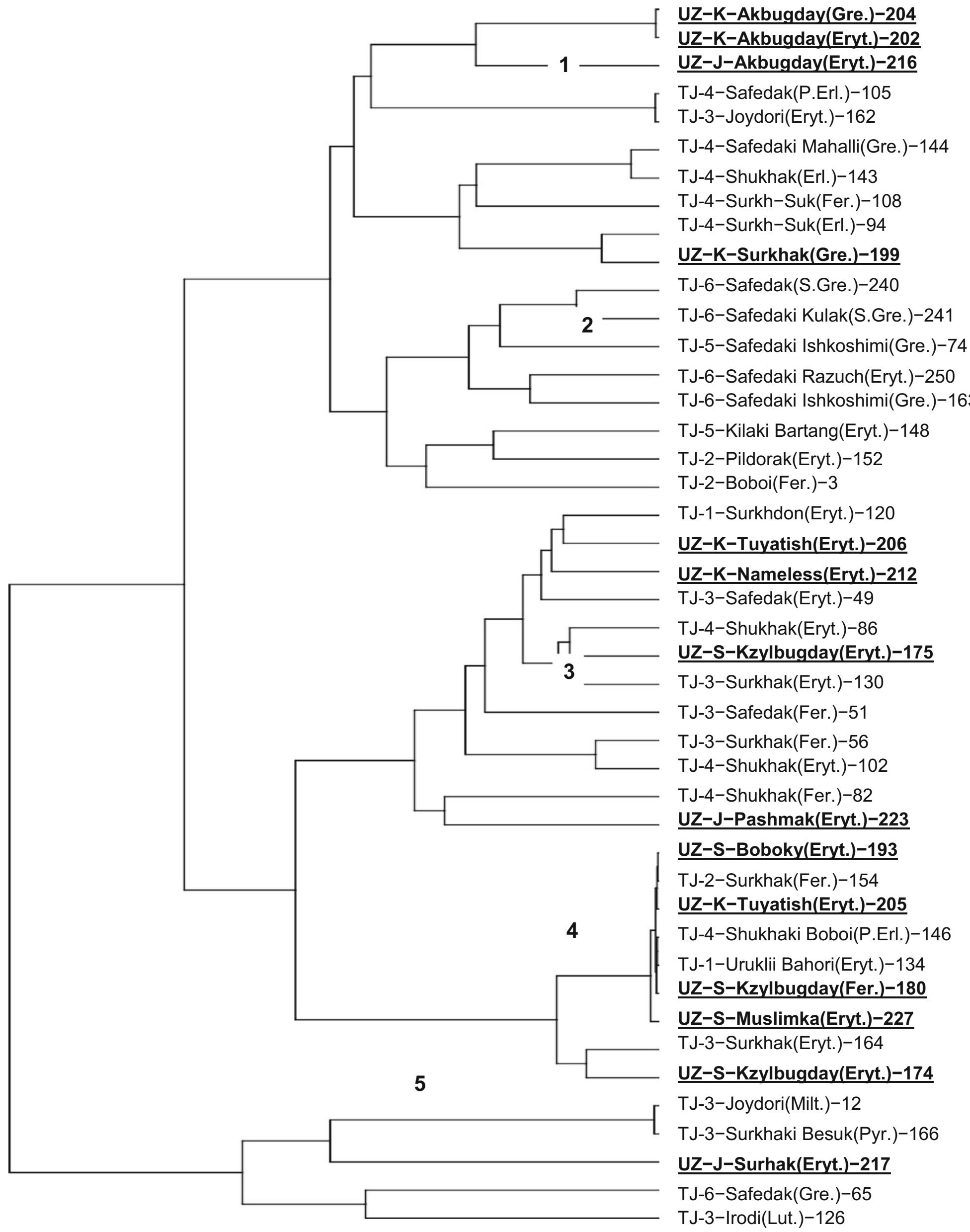

Fig. 3 Cluster analysis of 14 Uzbek (bold and underlined) and 30 Tajik landraces based on SNP array markers. For each entry the first two letters identify the country: TJ, Tajikistan and UZ, Uzbekistan. For Uzbek landraces the next letter identifies the region: J, Jizzak; K, Kashkadarya; and S, Surkhandarya. For Tajik landraces the number after TJ identifies the region of wheat landraces: 1, Shakhristan; 2, Zerafshan; 3, Rasht; 4, Khatlon; and 5 and 6, Pamir. Botanical variety is abbreviated in brackets and followed by the entry number in 2017

3.3 Agronomic evaluation of wheat landraces

The results of the experiments conducted in 2012–2015 at the research institute in Tashkent are presented in Table 4. All the wheat landraces accessed had spring growth habit and, on average, were slightly later than the check cultivars and 200–400-mm taller. The landraces were inferior to the check for grain yield under irrigation. When spring planted without irrigation, several landraces (entries 1 and 2, Kzyl bugday; 7, Surkhak; and 9, Ak bugday) were as high yielding as under irrigation and exceeded the grain yield of the check cultivar by at least 40%. These landraces along with entries 8, 12, 14, and 15 had 1000-kernel weight exceeding 40 g across all years of testing. With the exception of durum wheat landrace Korakiltik, all material had variable degree of susceptibility to leaf and stripe rust.

The set of 14 wheat landraces was field evaluated in Konya, Turkey (1000 masl) in 2018–2019. This material had one more cycle of spike selection from the lines tested in Tashkent and presented in Table 4. The phenotypes of the key agronomic traits are presented in Tables S4 and S5 for 2018 and 2019 seasons separately, and Table 5 gives the average values for the two years. Quite severe heat and moisture stress in 2018 resulted in rapid crop development and the average grain yield was 1947 kg/ha in 2018 versus 2784 kg/ha in 2019. These two contrasting seasons allowed detailed evaluation of the landraces. Except for Surkhak (entry 217) all the material demonstrated spring or facultative growth habit

Table 4 Agronomic performance of lines selected from wheat landraces (2010 collection) under irrigated (Tashkent, 2011–2012; 2013–2014 and 2014–2015 seasons, autumn-planted) and rainfed conditions (Tashkent, 2013 spring-planted)

Landrace	Irrigated, autumn-planted, 2012, 2014–2015				Rainfed, spring-planted, 2013				2012	2014
	Day to heading	Plant height, cm	Grain yield, g/m^2	1000-kernel weight, gr	Day to heading	Plant height, cm	Grain yield, g/m^2	1000-kernel weight, g	Stripe rust, %	Leaf rust, %
Krasnodar 99 (check)	124	75	505	42.0	-	-	-	-	80	90
Tezpisar (check)	-	-	-	-	58	70	297	46.0	-	100
Kzyl bugday:2-6T	123	110	431	45.5	68	110	470	42.7	60	70
Kzyl bugday:3-7T	123	116	492	45.7	68	110	462	43.0	80	60
Kzyl bugday:9-4T	128	113	447	46.6	68	115	262	37.0	80	70
Kzyl bugday:5-4T	128	109	454	47.8	68	110	362	42.5	80	50
Kzyl bugday:11-4T	124	113	386	45.1	68	105	220	37.0	90	100
Ak bugday:7-3T	122	102	368	42.6	60	90	125	30.0	60	70
Surkhak:12-3T	124	110	426	43.3	67	105	410	43.0	50	90
Korakiltik:19-3T	121	111	440	43.3	60	110	285	40.0	0	0
Ak bugday:8-2T	122	105	396	42.3	60	90	420	39.0	80	65
Tuyatish:10-4T	126	121	393	43.7	63	115	301	37.0	40	70
Kzyl bugday:1-4T	123	110	352	44.8	68	110	292	37.0	60	60
Nameless:13-8T	125	111	399	42.8	69	110	360	40.5	80	85
Nameless:14-3T	125	120	438	46.8	68	105	300	35.0	80	75
Ak bugday:16-5T	121	105	435	45.3	60	115	339	44.5	80	70
Surkhak:15-6T	125	113	405	46.1	60	110	302	41.5	60	65
LSD 0.5	n.s.[a]	15	52	n.s.	-	-	-	-	-	-

[a] not significant

allowing a wide variation in planting time. Four Uzbek landraces were significantly later heading compared to local check, cv. Karahan, which is 3–5 days later than commonly grown rainfed cultivars in Turkey. This shows the capacity of Uzbek landraces to develop within the growing opportunity of mountainous regions with cool summers. The landraces lines suffered a variable degree of lodging in 2019 not necessarily related to plant height. All landraces were susceptible to leaf rust but demonstrated relatively high level of resistance to Turkish population of stripe rust. The landrace Boboky (entry 193) out-yielded the check by 18% based on the two years of testing, whereas landraces Ak Bugday (entry 202), an unnamed entry (entry 212) and Muslimka (entry 227) were as high yielding as the check. Two landraces (entry 205, Tuyatish; and entry 180, Kzylbugday) had 1000-kernel weight exceeding 50 g compared to 34 g for the check. Field evaluation of wheat landraces in Uzbekistan and in Turkey demonstrated their superiority in several agronomic traits compared to commonly grown cultivars.

The standard approach to wheat landraces is agronomic characterization followed by incorporation of the traits of interest in breeding of new cultivars, especially those intended for areas subjected to abiotic stresses. The merits of this approach are reconfirmed by the current study. Wheat landraces with superior performance for grain yield and other traits have been identified and their genomic relatedness demonstrated. Baboev et al. (2017) also showed the superiority of these landraces for grain quality including gluten content and composition, concentration of important micronutrients (Fe and Zn) (Buranov et al. 2017). These landraces have already been incorporated into the crossing and selection program in Uzbekistan to develop drought tolerant cultivars.

3.4 Sustainability of wheat landraces in farmer fields

As mentioned above, farmers have little concern for the global value of wheat landraces as genetic resource other than these landraces satisfy their daily needs. One option to keep the wheat landraces and their diversity on-farm is to improve them through selection or crossing program to strengthen the positive traits and to eliminate negative characteristics such as disease susceptibility. This can be easily done using modern breeding tools. In this study, the landrace Kayraktash collected from one village in Surkhandarya region had good drought tolerance, high gluten content, average plant height and moderate resistance to yellow rust. In 2014, this landrace was

Table 5 Agronomic traits of Uzbek wheat landraces tested in Konya, Turkey, 2018–2019

Region	Landrace ID	Local name	Growth habit	Days to heading From Jan.1	Plant height cm	Lodging %	Leaf rust %, infection type	Stripe rust %, infection type	Yield kg/ha	Yield %LC	TKW g
			2019	2018-2019	2018-2019	2019	2019	2019	2018-2019		2018-2019
Local check (LC)		Karahan	F	131	99	0	60S	0	2585	100	33.7
Jizzakh	216-UzCL-15-35	Ak bugday	S	136	103	20	60S	10MR	1787	69	42.3
	217-UzCL-15-46	Surhak	W	133	108	0	50S	0	2228	86	45.9
Kashka-darya	199-UzCL-15-32	Surhak	S	130	115	70	50S	5MR	2548	99	46.8
	202-UzCL-15-27	Ak bugday	S	129	114	60	60S	20MR	2593	100	34.8
	204-UzCL-15-30	Ak bugday	S	129	102	70	40S	10MR	2020	78	45.6
	205-UzCL-15-53	Tuyatish	S	134	108	50	70S	0	1983	77	52.1
	206-UzCL-15-36	Tuyatish	S	135	100	50	40S	TMR	2308	89	49.1
	212-UzCL-15-44	Nameless	F	136	97	70	50S	0	2619	101	45.1
Surhan-darya	174-UzCL-15-6	Kzyl bugday	S	132	100	20	40S	0	2158	83	44.7
	175-UzCL-15-7	Kzyl bugday	F	134	110	20	50S	0	2503	97	43.5
	180-UzCL-15-1	Kzyl bugday	F	137	105	70	60S	0	2203	85	51.3
	193-UzCL-15-D25	Boboky	F	137	114	80	70S	0	3061	118	44.2
	223-UzCL-15-118	Pashmak	S	134	111	50	60S	10MS	2236	87	48.6
	227-UzCL-15-D36	Muslimka	S	133	111	60	50S	0	2651	103	38.4
LSD 0.5				4	5	-	-	-	417	-	7.8

planted on a 0.3 ha of rainfed land near Tashkent and 0.8 t (2.7 t/ha) of seed was harvested. The seeds were cleaned, treated with fungicides and distributed to the villages of Boysun and Altinsay districts (Surkhandarya Region). The farmers willingly and thankfully accepted the seeds. Simple selection from the landrace can result in new cultivars which can go through official testing and certification program. This is under discussion in Turkey and elsewhere where formal rules prevent seed production of landraces as they are not registered cultivars. A major ethical concern is the farmer's rights. The farmers have maintained and improved landraces over generations and then scientists come, collect the seed, make selections and in a few years release new cultivars. Farmers may then have to pay for the seed of these new cultivar-landraces which originated from their own field. Recent review by Dwivedi et al. (2019) addresses this issue from farmer-breeder-chef collaboration perspective. Dennis et al. (2007) studied farmers seed exchange in Uzbekistan and demonstrated that seed is often considered a public good, and therefore no farmer should be excluded from the right to use this seed. Community-level institutions and local customs facilitate the exchange of plant genetic resources and are built around reducing transaction costs for information and planting material.

What are the other options to keep, possibly expand and diversify landraces in the fields of Uzbek farmers? Wheat landraces have received considerable attention in the last few years through the possible health benefit of their grain (Shewry 2018). Two international conferences in Italy in 2018 (https://wheat-landraces.ifoam.bio) and in Turkey in 2019 (https://wheat-health.meetinghand.com) were almost entirely devoted to this subject. There is a documented market driven increase in the area of einkorn in Turkey as the public and food suppliers believe its grain to be healthier than other types of wheat (Yaman et al. 2019). However, this situation is unlikely to develop in Uzbekistan soon since the consumer preferences are quite conservative (Wood et al. 2018) and a market for wheat landraces products has yet to develop.

There is an option of government, national and international donors to support incentives for maintaining agrobiodiversity in Uzbekistan. This is well justified for supporting remote mountainous rural communities that are generally less developed than communities in the lowlands and irrigated valleys. The Food and Agriculture Organization of the United Nations developed guidelines for the conservation and sustainable farmer-owned genetic resources (FAO 2019). This comprehensive document suggests development of national plans for the conservation and sustainable use of landraces consisting of the following components: improving availability of landraces; quality and availability of information; management of landraces including participatory breeding; improved processing; alternatives and modifications to seed certification systems; market creation and promotion, building partnerships and trusts; changing norms; promoting ecological land management practices; payment schemes for ecosystem services. The current status of wheat landraces in Uzbekistan and Tajikistan provides an excellent opportunity for the application of these principles into a plan to conserve and enhance on-farm wheat diversity.

4 Conclusion

Central and West Asia is the center of origin and diversity for wheat (Vavilov 1966). Substantial wheat diversity developed and maintained by the farmers over centuries has undergone dramatic losses in the last 100 years. However, wheat landraces have not been totally eliminated from the production landscape and are still found in Afghanistan, Iran, Turkey, and other countries. Collection of wheat landraces in Uzbekistan and their characterization as presented in this paper proves that this valuable material is still cultivated by the farmers from generation to generation. The grain from the landraces is used for oven bread baked at home. The socio-economic survey identified three main reasons for the maintenance of landraces: (1) large grain with excellent bread-making quality; (2) specific adaptations allowing stable and reliable yield in harsh highland environments including spring planting; and (3) straw yield and quality. Farmers grow landraces such as Boboky, Kzyl bugday, Kayraktash, Ak bugday, Korakiltik, and others in the smaller fields whereas larger fields are used for commercial wheat cultivars.

Application of genomic tools greatly enhanced the capacity of identification of unique landraces and allowed comparison of diversity of landraces from Uzbekistan and Tajikistan. Common genomic profile shared by the landraces collected from distant and isolated locations in two countries indicated their close relatedness probably due to seed exchange between the farmers in the past. Genetic diversity of the landraces evaluated through SNP polymorphism and other parameters was the highest in Afghan and Tajik landraces and the lowest in Uzbek landraces due to their few number grown across limited, relatively uniform landscape. Extensive evaluation of the landraces in Uzbekistan and Turkey identified material with superior performance for grain yield and other traits which have already been incorporated into the crossing and selection program in Uzbekistan to develop drought tolerant cultivars.

Uzbek wheat landraces have proven their value and the recent collection again confirms their wide diversity, benefit for farmers as well as for wheat research community. Concerted efforts by all stakeholders are needed to ensure they are not lost and are managed and cultivated in-situ and conserved ex-situ for future generations. Several avenues have been discussed including landraces improvement, market development and policy interventions. Due to feminization of agriculture in Central Asia any strategy for conservation and expansion of on-farm wheat diversity needs to take into account the role of women in household decision-making.

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Data availability The data generated during the current study are available from the corresponding author on request.

Declarations

Ethics approval and consent to participate The section of the study involving survey of the farmers was approved by the Ethics Committee of the Institute of Plant Genetics and Experimental Biology, Tashkent, Uzbekistan. Informed consent was obtained from all individual participants included in the study.

Consent for publication The authors affirm that farmers participating in the survey provided informed consent for publication of anonymized data.

Conflict of interest The authors declare no competing interests.

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