Genet Resour Crop Evol (2008) 55:1185–1195
DOI 10.1007/s10722-008-9319-9

RESEARCH ARTICLE

Morphological spike diversity of Omani wheat

S. Al Khanjari · A. A. Filatenko · K. Hammer · A. Buerkert

Received: 8 November 2007 / Accepted: 3 March 2008 / Published online: 28 March 2008

Abstract Little is known about the diversity of field crops in Oman. The objective of this study therefore was to characterize wheat accessions from this country using individual spikes collected from different wheat cultivation areas. The phenotypic assessment of 15 qualitative and 17 quantitative characters showed variations among Omani wheat landraces. The standardized phenotypic diversity index (H′) was with 0.66 higher for quantitative characters than for qualitative characters (0.52) in tetraploid wheats and with 0.63 and 0.62, respectively, in hexaploid wheats. Overall, the morphological data revealed a surprisingly high diversity among landraces and showed that simple morphological characters can be used for an effective characterization of diversity in Omani wheat.

Keywords Diversity index · Morphological traits · *Triticum aestivum* · *T. aethiopicum* · *T. durum*

S. Al Khanjari · K. Hammer · A. Buerkert (✉)
Institute of Crop Science, University of Kassel, 37213 Witzenhausen, Germany
e-mail: buerkert@uni-kassel.de

S. Al Khanjari
College of Agriculture and Marine Sciences, Sultan Qaboos University, Al Khod, Oman

A. A. Filatenko
Vavilov Institute, 13 Linija, 12, Kv. 7, 199034 St. Petersburg, Russia

Introduction

Wheat is a major globally grown cereal, second largest in total production (FAO 2005). South West Asia is the primary centre of diversity for wheat and barley, and most certainly the region in which wheat was first cultivated about 10,000 years ago (Zohary 1969). In Oman wheat has been cultivated since millenia. The discovery of emmer wheat *Triticum dicoccon* Schrank) in Oman underlines the old presence of wheat cultivation in the country (Hammer et al. 2004; Al Khanjari et al. 2005). Due to its location, Southwest Asia is close to the old wheat growing countries Iran, Ethiopia and Yemen of which the first two are known as major centres of wheat diversity (Vavilov 1964). On the Arabian Peninsula archeological evidence of carbonized rachis and seeds of wheat and other cereals date back to approximately between 5,000 and 3,500 BC (Potts 1993; Willcox and Tengberg 1995).

The evolutionary processes leading to the development of wheat landraces depend on various factors; natural and artificial selection, domestication history and several thousand years of adaptation to cultivation environments. This is one of the invaluable heritages that traditional farmers have given to the world (Hammer 1984; Myers 1994).

The apparent loss of genetic diversity in many crop plants has triggered widespread interest in niche environments from where novel genes often preserved in landraces might provide valuable genes for disease resistance, high protein content, tillering, drought tolerance and other economically desirable attributes (Srivastava and Damania 1989). Therefore, collection, conservation and use of landraces have often been linked to breeding programmes (Brown et al. 1989). Future gains in yield potential will most certainly require exploitation of the largely untapped resources of both domestic and wild crop species (Skovmand et al. 2001; Sneller et al. 2005).

The boundary among wheat species is often difficult to define because of the similarity, crossability and hybrid viability within the groups of different ploidy levels (Mac Key 1966). This is particularly true for closely related cultivated landraces such as the ones from Oman which may share a long history of cultivation and seed exchange. Nevertheless, it is possible to classify wheat landraces in their respective taxonomic species using the accumulated experience codified in the respective formal keys (Hanelt and Hammer 1995; Belay and Furuta 2001).

Morphological markers are often useful classification indicators for crops but require profound taxonomic knowledge and the availability of well elaborated keys. Stalker (1990) suggested that morphological characters can contribute much to the study of relationships among taxa and be used as an initial step in defining systematic relationships, particularly for numerical taxonomy. After visual observation and evaluation, morphological characterization has been successfully used in many studies (Belay et al. 1994; Maxted et al. 1997; Teklu et al. 2005). It is, however, well known that many phenotypic traits are affected by environmental conditions.

Qualitative and quantitative characters of spike parts are frequently used to evaluate and characterize wheat traits as they allow for the estimation of diversity and discrimination of closely related types (Tesemma et al. 1993; Porceddu et al. 1994). Results of initial surveys in the Al Hajar mountains of northern Oman and subsequent characterization of the collected wheat landraces were reported for *T. aestivum* L. by Al-Maskri et al. (2003) and for *T. dicoccon* Schrank by Hammer et al. (2004). The reported findings of *Triticum aestivum* var. *baladseetense* K. Hammer et A. Filat., *T. aestivum* var. *maqtaense* A. Filat. et K. Hammer and *T. dicoccon* Schrank ssp. *asiaticum Vav.* var. *haussknechtianum* A. Schulz were extremely interesting. Subsequent more thorough surveys revealed an additional four scientifically new *aestivum* varieties and three tetraploid wheats which will be published in a separate paper.

Given the very limited information available on tetraploid wheats from Oman the objective of this study was to characterize landrace accessions collected during 2003 in a large number of ecosystems across the country using individual spike characters (Al Khanjari et al. 2005).

Materials and methods

The characterization was undertaken on non-replicated landrace material collected from each farmer's field of which one head from each botanical variety comprising the landrace was further analyzed [tables of the material used are presented by Al Khanjari et al. (2007a) for the tetraploid wheats and by Al Khanjari et al. (2007b) for the hexaploid ones]. A similar approach was used previously to characterize morphological and agronomical traits of bread wheat elsewhere (Hede et al. 1999; DeLacy et al. 2000).

Morphological description

Heads were visually classified following the standard procedure developed at the Vavilov Institute in St. Petersburg, Russia (Dorofeev et al. 1979). The 15 qualitative characters were: spike shape, spike awns, direction of the awns, colour of the awns, rudeness of the awns, roughness of the awns, sector hairiness, glume hairiness, sector thickness of hairiness density, glume shape, glume shoulder shape width, glume colour, glume rigidity, keel tooth roughness and grain colour. The following 17 quantitative characters were determined: spike width (mm), spike length (cm), spikelet number per spike, number of sterile spikelets at the base, length of the first awn (cm), length of the second awn (cm), spikelet length (mm), spikelet width (mm), number of grains per spikelet, sector length (mm), glume length (mm), lemma length (mm), palea length (mm), keel tooth length (mm), grain length (mm), grain width (mm), grain height (mm) and spike density.

Statistical analysis

Each character was categorized into specific class states. The 15 qualitative and 17 quantitative characters were assigned to classes ranging from 1 to 7, and analyzed using the Shannon–Weaver diversity index (H; Shannon and Weaver 1949) as defined by Jain et al. (1975) to calculate phenotypical variation of each accession:

$$H = -\sum_{i=1}^{n} P_i \ln P_i$$

where n is the number of phenotypic classes for a character and P_i is the genotype frequency or the proportion of the total number of entries in the ith class.

H was standardized by converting it to a relative phenotypic diversity index (H′) after dividing it by $H_{\max} = \log_e^{(n)}$

$$H' = -\sum_{i=1}^{n} P_i \ln P_i / H_{\max}$$

Using NTSYS PC software vers. 2.11 (Rohlf 2002) a multivariate analysis was performed to discriminate accessions with cluster and principal component analysis ordination using similarity, after standardization, according to the procedure of Sokal and Sneath (1963). The first and second principal component scores were plotted to generate the two-dimensional model that indicated differences among characters.

Results and discussion

Morphological diversity

Tetraploid races

In general, tetraploid wheat landraces had a high H′ with, however, lower values in qualitative than in quantitative characters. Generally, in all characters of the Omani tetraploid wheat landraces, the Shannon–Weaver diversity index was lower than reported previously (diversity index of 0.71, 0.81 and 0.87) by Jain et al. (1975), Negassa (1986a) and Firdissa et al. (2005), respectively. Observations indicate that a landrace's character variation depends on the farmers' regional preference. As reported previously for wheat from Ethiopia, the center of wheat diversity closest to Oman, total phenotypic variation was highest among populations and lowest among regions (Bekele 1984; Negassa 1986b; Belay 1997).

Hexaploid races

Polymorphisms in spike length, glume shape, glume hairiness and grain colour were observed among the 210 individual spikes indicating considerable diversity among landraces. Over all accessions H′ was 0.63 for quantitative and 0.62 for qualitative traits (data not shown). These values were lower than those reported by Bechere et al. (1996) and Firdissa et al. (2005) for Ethiopian wheat where respective H′-values were 0.70 and 0.71.

For qualitative characters average H′-values between regions within districts ranged from 0.29 in glume shape to 0.83 in spike shape. For quantitative characters average H′-values between regions within districts ranged from 0.35 in grain height to 0.87 in sector length (Tables 1 and 2).

For qualitative traits between-district H′ was highest in Dakhilia (0.69) and lowest in Sharqia (0.57). Similar results were obtained for quantitative characters for which between-district H′ was highest in Sharqia (0.72) and lowest in Dhahira (0.66). However, within-district H′ strongly depended on the observed character. In Dakhilia H′-values ranged from monomorphic in awn roughness over sector hairiness with 0.5 to spike awns with 0.97. In Sharqia H′-values ranged from monomorphic in the direction of the awns and glume shape to awn rudeness of 0.96.

For qualitative characters overall within-district diversity was highest in Ibri-Dhahira (0.72), followed by the South Batinah (0.71). Lowest H′-values were found in Taeen-Sharquia (0.30; Table 1). For quantitative characters South Batinah had the highest overall within-district H′ (0.78) followed by the Dank-Dhahira region (0.74). With 0.58 the lowest H′-value was found at Bahla-Dakhilia (Table 2). The data thereby demonstrate the importance of within-district diversity compared to between-region diversity for overall H′ in Omani hexaploid wheat.

The outcome of our study confirms earlier work on wheat diversity showing that total phenotypic variation was lower within than among regions (Bekele 1984; Bechere et al. 1996; Pecetti and Damania 1996). For tef (*Eragrostis tef* (Zucc.) Trotter), however, Kebebew et al. (2003) reported for all measured traits a similarly large variation among populations regardless of the geographic unit.

Table 1 Estimation of the standardized Shannon–Weaver diversity index (H′) for 15 qualitative characters of hexaploid wheat races among regions within four districts of Oman

Qualitative character	Region											
	YDH	DDH	IDH	SOBT	CEBT	NOBT	BDK	HDK	MSH	TSH	WBK	Average
Spike shape	0.89	0.82	0.74	0.88	0.68	0.79	0.95	0.86	0.94	0.73	0.81	0.83
Spike awns	0.74	0.87	0.70	0.90	0.44	0.89	0.00	0.70	0.87	0.83	0.91	0.71
Direction of the awns	0.63	0.95	0.81	0.86	0.47	0.70	0.00	1.00	0.00	0.00	0.00	0.49
Colour of the awns	0.99	0.85	1.00	1.33	0.00	0.99	0.00	0.93	0.65	0.65	0.92	0.76
Rudeness of the awns	0.92	0.97	0.84	0.86	0.30	0.22	0.00	1.00	0.92	0.00	0.92	0.63
Roughness of the awns	0.39	0.44	0.92	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.34
Hairiness of the glume	0.80	0.77	0.79	0.90	0.92	0.86	0.82	0.42	0.00	0.65	0.84	0.71
Sector hairiness	0.48	0.59	0.81	0.94	0.81	0.68	0.00	0.34	0.95	0.65	0.60	0.62
Sector thickness of hairiness density	0.37	0.29	0.61	0.00	0.67	0.18	0.00	0.92	0.00	0.00	0.35	0.31
Glume shape	0.51	0.77	0.18	0.55	0.00	0.17	0.00	0.99	0.00	0.00	0.00	0.29
Glume shulder shape width	0.24	0.72	0.72	0.83	0.44	0.67	0.88	0.34	0.96	0.00	0.72	0.59
Glume colour	0.24	0.77	0.65	0.83	0.75	0.80	0.95	0.34	0.89	1.00	0.66	0.72
Glume rigidity	0.19	0.32	0.48	0.00	0.00	0.21	0.95	0.78	0.54	0.00	0.35	0.35
Keel tooth roughness	0.62	0.59	0.57	0.00	0.68	0.47	0.00	0.90	0.54	0.00	0.35	0.43
Grain colour	0.79	0.82	0.98	0.81	0.00	0.41	0.67	0.85	1.00	0.00	0.95	0.66
Average	0.59	0.70	0.72	0.71	0.41	0.54	0.35	0.69	0.62	0.30	0.56	

Regions are abbreviated as: YDH = Dhahira (Yanqul), DDH = Dhahira (Dank), IDH = Dhahira (Ibri), SOBT = South Batinah, CEBT = Centre Batinah, NOBT = North Batinah, BDK = Dakhilia (Bahla), HDK = Dakhilia (Al Hamra), MSH = Sharqia (Maqta), TSH = Sharqia (Taeen), WBK = Wadi Bani Khalid (see also Fig. 1)

Frequency distribution

Tetraploid races

The phenotypic distribution showed considerable variation in spikes. The spike shape was very polymorphic and mostly cylindrical. The highest frequency distribution was observed in the sector hairiness (97%) and awn roughness (89%). Sector hairiness was mostly very dense with rough awns. The awn direction was mostly parallel to slightly straight with a frequency of 73%. The awn colour was dominantly black with a frequency of 88% and most of the farmers prefering the black colour. They also preferred straight and rough awns stating that these characters protected the wheat from bird damage. The glume shape was mostly oblong-oval with a frequency of 88% and the glume colour ranged from white to straw-coloured with a frequency of 67%.

The function of the glume hairiness is to protect the glume from insects and to prevent diseases (Warham 1988). However, its adaptive nature is not clear (Jain et al. 1975). The study indicates a wide variation in the amount of hairiness, ranging from less dense (weak) to more dense (intermediate) with respective frequencies of 34.62 and 50%. The result agrees with previous findings by Bekele (1984) and Firdissa et al. (2005) in Ethiopian wheat that indicated polymorphism in glume hairiness. But it contradicts Bechere et al. (1996) and Belay (1997) who reported a higher frequency of Ethiopian wheat landraces without hairiness. Tesemma et al. (1991) also observed monomorphism for glume pubescence and Bechere et al. (1996) reported glabrous glumes in many of their landraces.

Glume shape was more frequent among all characters with 88% having a oblong-oval glume shape, followed by a glume colour which ranged from white to straw-coloured with a frequency of 67%. Seed colour was widely distributed in most of the landraces. The colour ranged from red to brown with red being dominant (81%). This is in agreement with previous studies of tetraploid wheats (Bekele 1984; Bechere et al. 1996; Firdissa et al. 2005) in which brown seed colour (dark red) was predominant.

The majority of the spikelets had five flowers, ranging from three to four fertile flowers and a few of them were sterile. The number of spikelets per spike

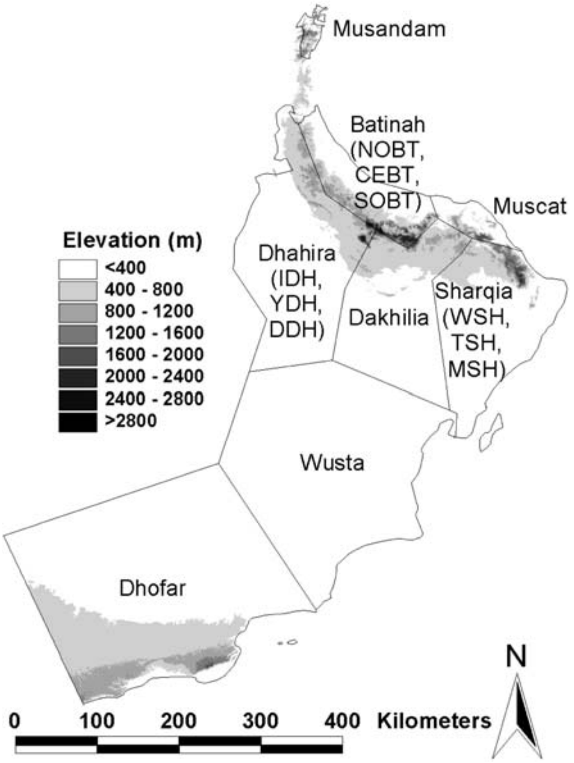

Fig. 1 Map of Oman indicating the districts where the wheat landraces were collected

averaged 23 and the compact spikes were generally well filled with grains. Most spikes had an intermediate density and lax, very dense spike types were rarely recorded in the landraces of this study. Spike traits were polymorphic ranging from low density to moderately dense (72%), lax (18%) and only 5% very dense. Similar results indicating the predominance of dense spike types in all the Ethiopian regions were reported by Bechere et al. (1996) and Negassa (1986a).

Today most of the traditional Omani mountain farmers prefer large, full spikes, black awns, long straight awns and tasty grains for home consumption. The awns of our accessions varied in length. In most landraces longer awns predominated with a frequency of 63% for the first awns and 44% for the second ones. Tetraploid wheats tended to have the lower frequencies of short and intermediate awn lengths. This confirms earlier findings in Ethiopian tetraploid wheats where long awns were predominant in most of the landraces (Tamiru 1999; Firdissa et al. 2005).

Hexaploid races

The cylindrical spike shape (42%) had the highest frequency in the Dakhilia district followed by the Batinah, Sharqia and Dhahira districts with club and spindle spike shapes. Most of the sector hairiness was very dense with rough awns. Glume shape was mostly oblong-oval monomorphic in Sharqia and Dakhilia. Glume rigidness was lowest in Dakhilia and highest in Batinah (97%). Most glumes were white to straw-coloured in Dakhilia (71%) and in Dhahira (54%).

Our study indicated a wide variation in the amount of hairiness. About 79% of the glumes were hairy in Dakhilia, compared to 62% in Dhahira and in all districts most spikes were dense. This finding agrees with reports by Bekele (1984) and Firdissa et al. (2005) showing polymorphism in glume hairiness for Ethiopian wheat but contradicts Bechere et al. (1996) and Belay (1997) who reported higher frequencies of glumes without hairs in Ethiopian wheat landraces. Tesemma et al. (1993) also observed monomorphism for glume pubescence and Bechere et al. (1996) reported glabrous glumes in many of the tetraploid Ethiopian wheat landraces of his study.

An oblong glume shape (95%) characterized all accessions from the Batinah (95%) over the Dhahira (85%) to the Dakhilia (71%). In most landraces grain colour varied widely. It ranged from white to red or brown-red, whereby the white grain colour dominated in Dakhilia (58%), followed by red 57% in Batinah, 40% in Sharqia and 38% in Dhahira. These results are in contrast to previous ones from Ethiopian wheat in which a brown or dark red seed colour predominated (Firdissa et al. 2005).

Spike traits were polymorphic ranging from low to moderate density. For grain height an average frequency of 83% was found in Dakhilia, 83% in Sharqia, 98% in Batinah and 91% in Dhahira.

The majority of spikelets had six flowers with four to five being fertile. This led on average to 23.5 spikelets per spike. Spikes tended to be compact, well filled with grains and had an average size of 7 cm. The majority of spikes were intermediate to dense and lax spike types were rare. Spike traits were polymorphic ranging from moderate to dense with frequencies of 34% in Dakhilia and Sharqia, 53% in Batinah and 58% in Dhahira. Similar results were reported for Ethiopian wheats by Bechere et al. (1996) and Negassa (1986a).

Table 2 Estimation of the standardized Shannon–Weaver diversity index (H′) for 17 quantitative characters of hexaploid wheat among regions within four districts of Oman

Character	Region											
	YDH	DDH	IDH	SOBT	CEBT	NOBT	BDK	HDK	MSH	TSH	WBK	Average
Spike length (cm)	0.65	0.64	0.65	0.85	0.68	1.00	0.82	0.71	0.50	0.79	0.80	0.74
Spike width (mm)	0.78	0.88	0.85	0.78	0.91	0.89	0.82	0.71	0.89	0.79	0.57	0.81
Number of spikelets per spike	0.91	0.90	0.76	0.84	0.55	0.78	0.75	0.67	0.55	0.74	0.92	0.76
Number of sterile spikelets	0.67	0.56	0.56	0.60	0.55	0.54	0.00	0.52	0.46	0.50	0.56	0.50
Length of first awn (cm)	0.52	0.65	0.54	0.63	0.50	0.74	0.00	1.00	0.00	0.65	0.00	0.48
Length of second awn (cm)	0.99	0.73	0.81	0.92	0.99	0.83	0.00	0.81	0.92	0.00	0.92	0.72
Spikelet length (mm)	0.66	0.77	0.72	0.83	0.44	0.97	0.95	0.34	0.95	0.92	0.73	0.75
Spikelet width (mm)	0.86	0.82	0.93	0.99	0.85	0.97	0.82	0.90	0.54	1.00	0.80	0.86
Number of grains per spikelet	0.44	0.52	0.47	0.95	0.55	0.35	0.00	0.55	0.00	0.92	0.00	0.43
Sector length (mm)	0.56	0.96	0.94	0.94	0.69	0.77	0.98	0.90	0.95	0.94	0.95	0.87
Glume length (mm)	0.88	0.98	0.93	0.94	0.95	0.85	0.54	0.95	0.60	0.92	1.00	0.87
Lemma length (mm)	0.86	0.87	0.92	0.83	0.94	0.74	0.98	0.64	0.54	0.92	0.88	0.83
Palea length (mm)	0.70	0.72	0.94	0.83	0.69	0.75	0.82	0.69	0.95	0.63	0.69	0.76
Keel tooth length (mm)	0.75	0.76	0.80	0.65	0.99	0.69	0.81	0.90	0.82	0.46	0.45	0.73
Grain length (mm)	0.55	0.40	0.61	0.49	0.48	0.56	0.81	0.54	0.60	0.41	0.00	0.50
Grain height (mm)	0.82	0.77	0.53	0.44	0.00	0.00	0.00	0.00	1.00	0.00	0.28	0.35
Grain width (mm)	0.60	0.62	0.41	0.69	0.52	0.69	0.81	0.34	0.95	0.00	0.57	0.56
Average	0.72	0.74	0.73	0.78	0.66	0.71	0.58	0.66	0.66	0.62	0.60	

Regions are abbreviated as: YDH = Dhahira (Yanqul), DDH = Dhahira (Dank), IDH = Dhahira (Ibri), SOBT = South Batinah, CEBT = Centre Batinah, NOBT = North Batinah, BDK = Dakhilia (Bahla), HDK = Dakhilia (Al Hamra), MSH = Sharqia (Maqta), TSH = Sharqia (Taeen), WBK = Wadi Bani Khalid (see also Fig. 1)

Multivariate analysis of phenotypic characters

Tetraploid races

The first four principal components in the PCA of the 15 qualitative characters accounted for 24.8, 15.4, 12.0 and 10.8% of the total variation, respectively and together explained 63.0% of the total variation among the 39 tetraploid wheat landraces (Table 3). Glume rigidity, glume shape, spike awns and awn rudeness were the most important characters contributing to the first principal component. To the second principal component, sector hairiness density, directions of the awns, sector hairiness and glume colour contributed significantly, whereas for the third principal component glume hairiness, glume shoulder shape, colour of the awns and keel tooth characters were the most important characters, and to the fourth principal component grain colour and awn roughness contributed most.

For the 17 quantitative characters the Eigenvalues of the first four principal components together explained 56% of the total variation among the wheat landraces (Table 4). They accounted for 26.5, 15.6, 7.5 and 6.7% of the total variation, respectively. Following the interpretation of Johnson and Wichern (1988) grain height, grain number, grain length, grain width, spike length and glume length were the most important characters contributing to the first principal component. Spikelet width, sterile flower number per spike, palea length and keel tooth length contributed significantly to the second principal component. For the third principal component, spike density and spikelet length were important and to the fourth principal component the number of spikelets per spike and lemma length contributed most.

The principal component analysis also showed that the distributions of the measured characters were scattered in all four quadrants (Fig. 2). The first principal component was the most important in

Table 3 Eigenvalue, Eigenvector and scores of the four first factors retained from the principal component analysis (PCA) analysis of 15 qualitative characters performed on a collection of tetraploid wheat landraces from Oman

Character	PCA1	PCA2	PCA3	PCA4
Spike shape	0.14	0.26	0.13	0.15
Spike awns	**−0.77**	−0.11	−0.11	0.30
Direction of the awns	−0.13	**−0.69**	0.45	0.01
Colour of the awns	−0.49	0.26	0.50	0.22
Awn roughness	**−0.81**	0.24	0.07	0.26
Awn rudeness	−0.58	−0.23	0.22	−0.60
Sector hairiness	−0.47	**0.66**	−0.28	0.41
Glume hairiness	0.32	0.35	0.72	0.11
Sector hairiness density	−0.12	**−0.85**	0.13	0.28
Glume shape	**0.81**	0.12	0.10	0.11
Glume shoulder shape	−0.18	−0.12	−0.57	−0.06
Glume colour	−0.18	**0.47**	0.30	−0.45
Glume rigidity	**−0.89**	−0.05	0.06	−0.22
Keel tooth	−0.08	−0.03	0.49	0.31
Grain colour	−0.03	0.22	0.06	−0.63
Eigenvalue	3.72	2.32	1.80	1.62
Total variance (%)	24.78	15.44	12.02	10.78
Cumulative variance (%)	24.78	40.22	52.25	63.03

Table 4 Eigenvalue and scores of the four first factors retained from the principal component (PCA) analysis of 17 quantitative characters performed on a collection of tetraploid wheat landraces from Oman

Character	PCA1	PCA2	PCA3	PCA4
Spike length	0.74	0.30	0.14	0.17
Spike width	−0.29	0.71	0.23	0.15
Number of spikelets per spike	−0.06	−0.17	−0.30	0.56
Sterile flower number per spike	−0.29	0.61	−0.41	−0.03
First awn length	0.11	−0.59	−0.15	0.22
Second awn length	−0.20	−0.43	−0.26	0.30
Spikelet length	−0.03	0.29	−0.40	−0.22
Spikelet width	0.28	−0.28	0.09	−0.44
Grain number	0.87	0.16	0.01	0.12
Lemma length	0.29	−0.27	−0.02	−0.52
Glume length	0.71	0.20	0.20	0.14
Palea length	0.10	0.58	0.05	0.15
Keel tooth length	0.23	0.43	0.24	−0.10
Grain length	0.86	0.03	−0.22	0.00
Grain width	0.74	0.29	−0.34	0.01
Grain height	0.94	−0.31	−0.20	−0.02
Spike density	0.29	−0.34	0.62	0.23
Eigenvalue	4.52	2.64	1.28	1.14
Total variance (%)	26.56	15.55	7.52	6.71
Cumulative variance (%)	26.56	42.12	49.64	56.35

separating the accessions. Spike width and sterile flower numbers which were the most important characters for the second principal component were located in the first quadrant (above, left).

The landraces from the Musandam area came from the most northern part of Oman, where—in contrast to all other ecosystems of the country—rainfed agriculture predominates. It is thus understandable that they cluster in one distinct subgroup of the fourth quadrant with the botanical varieties *T. aethiopicum* Jakubc. var. *pilosinigrum* (Vav.) A. Filat. (Oman Triticum, OMTRI, 232), *T. aethiopicum* var. *comitans* (Vav.) A. Filat. (OMTRI 233), *T. durum* Desf. var. *pseudorubripubescens* (Vav.) A. Filat. (OMTRI 236), *T. aethiopicum* var. *comitans* (OMTRI 234) and *T. aethiopicum* var. *tchertchericum* (Vav.) A. Filat. (OMTRI 235).

T. durum Desf. var. *affine* Koern. (OMTRI 198), isolated in the first quadrant, was only found at the rather isolated Wadi Bani Kharus in the southern Batinah, which is also reflected in its specific position in the dendrogram.

In the third quadrant (up, right) were OMTRI 197 from Khabura and OMTRI 228 from Sohar, while varieties from the Batinah district closely clustered in a different subgroup of the third quadrant.

The cluster analysis of the phenotypic distance of the quantitative characters of the 39 tetraploid wheat accessions from Oman shows distinct groupings (Fig. 3) and yielded similar results as the principal component analysis. Both analyses also produced similar results in placing *T. aethiopicum* var. *hajirense* (nom. nud.) (OMTRI 203) from the southern Batinah area in an isolated subgroup with OMTRI 215, a yet unclassified accession.

Hexaploid races

In quantitative characters the first four principal components accounted for more than 99% of the

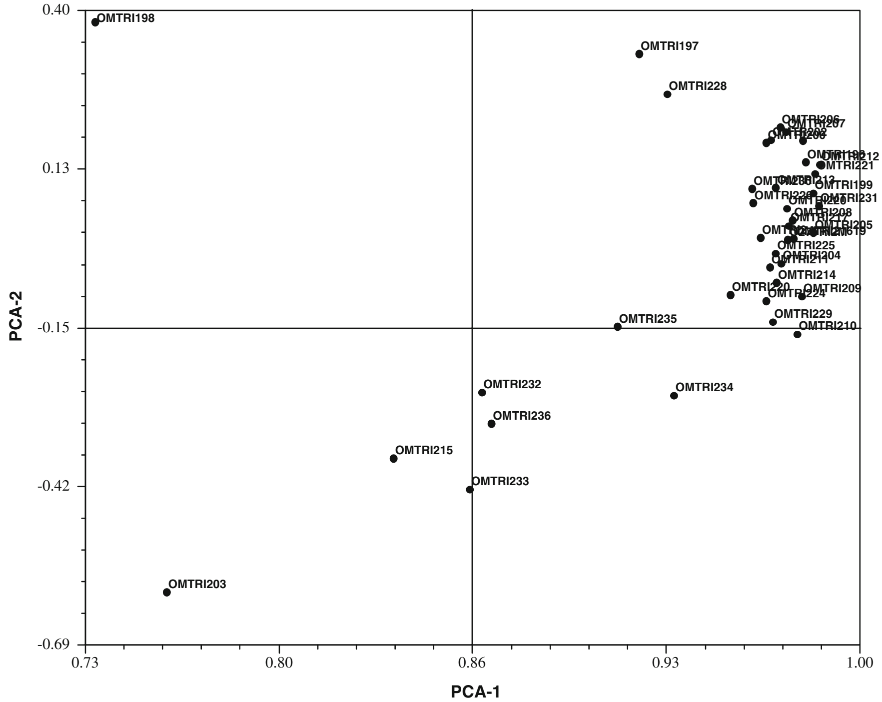

Fig. 2 Scattergram showing the results of a principal component analysis (PCA) of 17 quantitative characters of tetraploid wheat landraces from Oman named according to the OMTRI (Oman Triticum) catalogue established by the authors

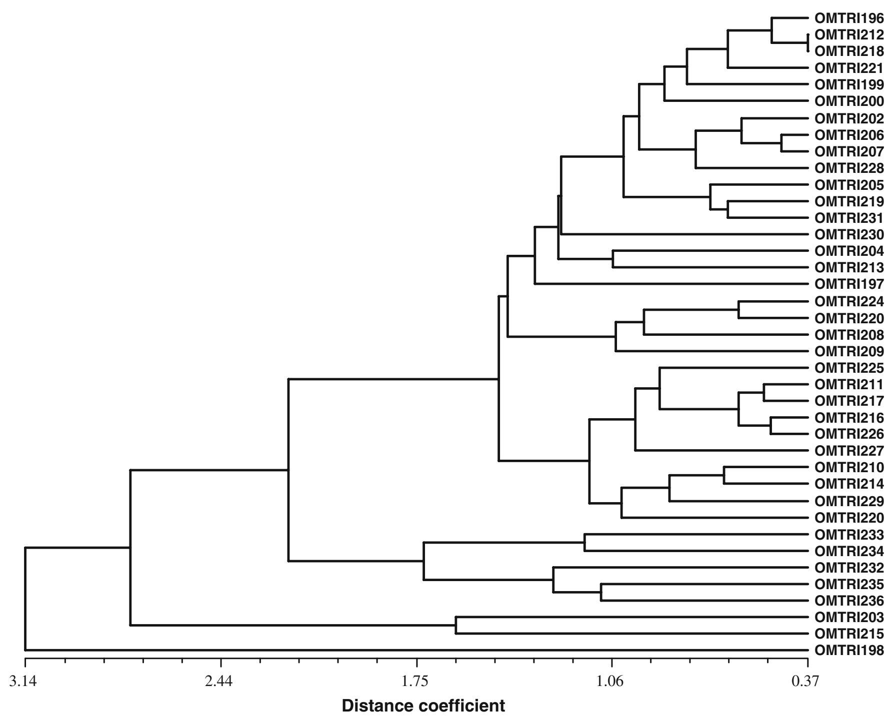

Fig. 3 Dendrogram showing the results (phenotypic distance) of a cluster analysis of 17 quantitative characters of tetraploid wheat landraces from Oman

total variation (Table 5). The dendrogram constructed to describe the relationship among the landraces (Fig. 4) divided the accessions into two main groups, in which the first group contained only accessions from Ibri and the second one comprised a first subgroup with the three subgroups

Table 5 Eigenvectors, Eigenvalues, total variance and cumulative variance of the first four principal components (C1–C4) of 17 quantitative characters of 210 hexaploid landraces across 11 regions of Oman

Region	C1	C2	C3	C4
Khabura Centre Batinah	0.97	0.01	0.02	0.01
South Batinah	0.96	0.03	0.03	0.18
Sohar North Batinah	0.95	−0.30	0.13	−0.01
Al Hamra	0.96	−0.06	−0.08	0.00
Bahla	0.91	0.15	−0.38	−0.14
Al Raky	0.99	−0.04	−0.06	0.01
Taeen	0.88	0.48	0.28	0.00
Maqta	0.95	0.13	−0.05	0.14
Ibri	0.10	1.05	−0.02	−0.04
Dank	0.90	−0.22	0.15	−0.31
Yanqul	0.98	−0.24	−0.04	0.11
Eigenvalue	8.95	1.58	0.28	0.18
Total variance (%)	81.36	14.33	2.53	1.61
Cumulative total variance (%)	81.36	95.69	98.23	99.84

of South Batinah, Taeen and Sohar (North Batinah). Within the second subgroup was Bahla (Dakhilia) and Yanqul (Dhahira) but there was no discrimination among accessions from Dank (Dhahira) and Khabura (Centre Batinah). The third sub-subgroup comprised the accessions of Maqta, Al Raky (Sharqia) and Hamra (Dakhilia).

Neither the cluster nor the principal components analysis of the 17 recorded quantitative traits revealed consistent relationship within or among districts. Similar results were found in barley by Molina and La Cruz del Campo (1977). There is no clear reason why accessions from Ibri appear to be rather isolated in one group although the topographically open nature of the Dhahira region should have facilitated germplasm exchange among farmers within this region and with neighbouring districts.

Conclusions

In general, the studied Omani wheat landraces showed a surprisingly high diversity which could be a result of evolutionary processes allowing for species mixtures and outcrossing after a long joint cultivation history. This would require introgression across different ploidy levels, thus leading to increased polymorphism in the landraces.

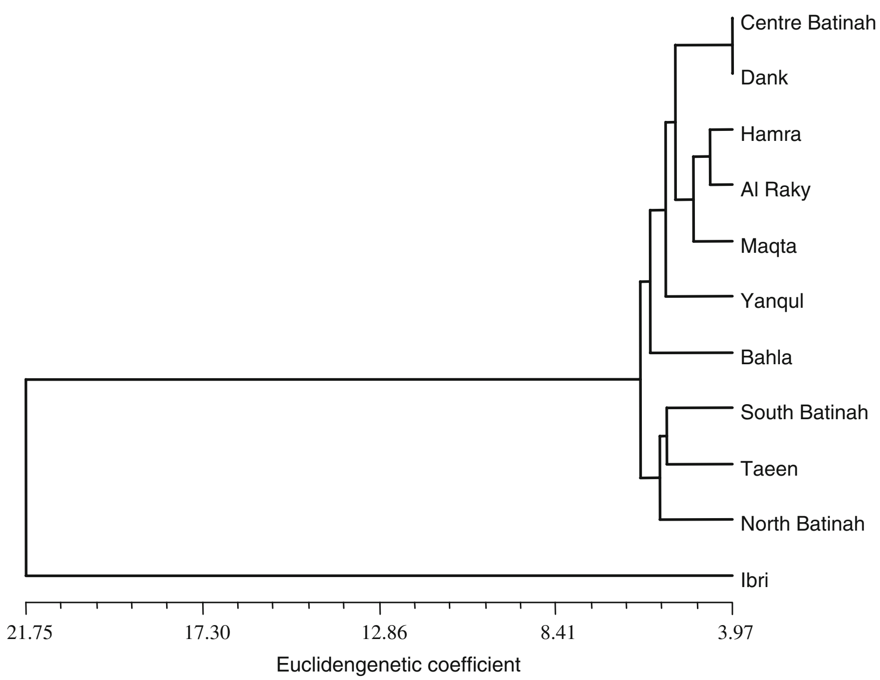

Fig. 4 Dendrogram showing the clustering patterns in phenotypic variation of 17 quantitative characters of hexaploid wheat accessions from 11 regions of Oman

Acknowledgements The authors would like to thank the Royal Air Force of Oman and the Ministry of Agriculture and Fisheries for infrastructural support during the field part of this study and Sultan Qaboos University, Oman and the Deutsche Forschungsgemeinschaft (DFG, BU1308) for partial funding.

References

Al Khanjari S, Hammer K, Buerkert A, Khan I, Al-Maskri A (2005) A survey of wheat landraces in Oman. Plant Genet Resour Newsl (FAO-IPGRI, Rome Italy) 141:7–10

Al Khanjari S, Hammer K, Buerkert A, Röder MS (2007a) Molecular diversity of Omani wheat revelead by microsatellites: 1. Tetraploid landraces. Genet Resour Crop Evol 54:1291–1300

Al Khanjari S, Hammer K, Buerkert A, Röder MS (2007b) Molecular diversity of Omani wheat revelead by microsatellites: II. Hexaploid landraces. Genet Resour Crop Evol 54:1407–1417

Al-Maskri A, Nagieb M, Hammer K, Filatenko AA, Khan I, Buerkert A (2003) A note about *Triticum* in Oman. Genet Resour Crop Evol 50:83–87

Bechere E, Belay G, Mitiku D, Merker A (1996) Phenotypic diversity of tetraploid wheat landraces from northern and north-central regions of Ethiopia. Hereditas 124:165–172

Bekele E (1984) Analysis of regional patterns of phenotypic diversity in the Ethiopian tetraploid and hexaploid wheats. Hereditas 124:165–172

Belay G (1997) Genetic variation, breeding potential and cytogenetics profile of Ethiopian tetraploid wheat (*Triticum turgidum* L.) landraces. Ph.D. thesis, Swedish University of Agricultural Sciences, Uppsala

Belay G, Furuta Y (2001) Zymogram patterns of a-amylase isozymes in Ethiopian tetraploid wheat landraces: insight into their evolutionary history and evidence for gene flow. Genet Resour Crop Evol 48:507–512

Belay G, Merker A, Tesemma T (1994) Cytogenetic studies in Ethiopian landraces of tetraploid wheat (*Triticum turgidum* L.) I. Spike morphology vs ploidy level and karyomorphology. Hereditas 121(1):45–52

Brown AHD, Frankel OH, Marshall DR, Williams JT (1989) The use of plant genetic resources. Cambridge University Press, Cambridge

DeLacy IH, Skovmand B, Huerta J (2000) Characterization of Mexican wheat landraces using agronomically useful attributes. Genet Resour Crop Evol 47:591–602

Dorofeev VF, Filatenko AA, Migušova EF, Udačin RA, Jakubciner MM (1979) Wheat, vol 1. In: Dorofeev VF, Korovina ON (eds) Flora of cultivated plants. Leningrad (St. Petersburg), Russia. Kolos (in Russian), 346 pp

FAO (2005) Special report: FAO/WFP Crop and food supply assessment mission to Ethiopia. Rome

Firdissa E, Bekele E, Belay G, Börner A (2005) Phenotypic diversity in tetraploid wheats collected from Bale and Wello regions of Ethiopia. Plant Genet Resour 3:35–43

Hammer K (1984) The domestication syndrome (in German). Kulturpflanze 32:11–34

Hammer K, Filatenko AA, Alkhanjari S, Al-Maskri A, Buerkert A (2004) Emmer (*Triticum dicoccon* Schrank) in Oman. Genet Resour Crop Evol 51:111–113

Hanelt P, Hammer K (1995) Classifications of intraspecific variation in crop plants. In: Guarino L et al (eds) Collecting plant genetic diversity. Technical Guidelines, pp 113–120

Hede AR, Skovmand B, Reynolds MP, Crossa J, Vilhelmsen AL, Stølen O (1999) Evaluating genetic diversity for heat tolerance traits in Mexican wheat landraces. Genet Resour Crop Evol 46:37–45

Jain SK, Qualset CO, Bhatt GM, Wu KK (1975) Geographical patterns of phenotypic diversity in a world collection of durum wheat. Crop Sci 15:700–704

Johnson RA, Wichern DW (1988) Applied multivariate statistical analysis. Prentice-Hall, Englewood Cliffs

Kebebew A, Merker A, Tefera H (2003) Multivariate analysis of diversity of tef (*Eragrostis tef* (Zucc.) Trotter) germplasm from western and southern Ethiopia. Hereditas 138:228–236

Mac Key J (1966) Species relationship in *Triticum*. Proceedings of the 2nd International Wheat Genetics Symposium, Hereditas 2:237–276

Maxted N, Ford-Lloyd BV, Hawkes JG (1997) Complementary conservation strategies. In: Maxted N, Ford-Lloyd BV, Hawkes JG (eds) Plant genetic conservation. Chapman and Hall, London, pp 15–39

Molina C, La Cruz del Campo JL (1977) Numerical taxonomy as an aid to barley germplasm collection. Barley Genet Newsl 7:45–50

Myers N (1994) Protected areas – protected from a greater what? Biodivers Conserv 3:411–418

Negassa M (1986a) Estimates of phenotypic diversity and breeding potential of Ethiopian wheats. Hereditas 104: 41–48

Negassa M (1986b) Patterns of diversity of Ethiopian wheats (*Triticum* spp.) and a gene center for quality breeding. Plant Breed 97:147–162

Pecetti L, Damania AB (1996) Geographical variation in tetraploid wheat (*Triticum turgidum* ssp. *turgidum* convar. *durum*) landraces from two provinces in Ethiopia. Genet Resour Crop Evol 43:395–407

Potts D (1993) Rethinking some aspects of trade in the Arabian Gulf. World Archaeol 24:423–439

Porceddu E, Perrino P, Olita G (1994) Preliminary information on an Ethiopian wheat germplasm collection mission. Symposium on genetics and breeding of durum wheat Washington State University, Pullman

Rohlf FJ (2002) Numerical taxonomy and multivariate analysis system. NTSYS version 2.11a. Applied Biostatistics Inc., New York

Shannon CE, Weaver W (1949) The mathematical theory of communication. University of Illinois Press, Urbana

Skovmand B, Reynolds MP, Delacy IH (2001) Mining wheat germplasm collections for yield enhancing traits. Euphytica 119:25–32

Sneller CH, Nelson RL, Carter TE, Cui Z (2005) Genetic diversity in crop improvement: the soybean experience. J Crop Improv 14:103–144

Sokal RR, Sneath PHA (1963) Principles of numerical taxonomy. Freeman, San Francisco, 359 pp

Srivastava JP, Damania AB (1989) Use of collections in cereal improvement in semi-arid areas. In: Brown AHD, Frankel OH, Marshall DR Williams JD (eds) The use of plant genetic diversity and genetic resources. Cambridge University Press, Cambridge, pp 88–104

Stalker HT (1990) A morphological appraisal of wild species in section *Arachis* of peanuts. Peanut Sci 17:117–122

Tamiru M (1999) Morphological and molecular diversity in durum wheat (*Triticum durum* Desf.) landraces of North Shewa. MSc. Thesis, Addis Ababa University, Addis Ababa

Teklu Y, Hammer K, Röder MS (2005) Comparative analysis of diversity indices based on morphological and microsatellite data in tetraploid wheats. J Genet Breed 59: 121–130

Tesemma T, Belay G, Worede M (1991) Morphological diversity in wheat landrace populations from central highlands of Ethiopia. Hereditas 114:172–176

Tesemma T, Becker HC, Belay G, Mitiku D, Bechere E, Tsegaye S (1993) Performance of Ethiopian tetraploid wheat landraces at their collection sites. Euphytica 71:221–230

Vavilov NI (1964) World resources of cereals, legumes, flax cultivars and their utilization in breeding. Wheat. Nauka, Moscow (in Russian)

Warham EJ (1988) Screening for karnel bunt (*Tilletia indica*) resistance in wheat, triticale, rye and barley. Can J Plant Path 10:57–60

Willcox G, Tengberg M (1995) Preliminary report on the archaeobotanical investigations at Tell Abraq with special attention to the chaff impressions in mud brick. Arab Archaeol Epigr 6:129–138

Zohary D (1969) The progenitors of wheat and barley in relation to domestication and agricultural dispersal in the old world. In: Ucko PJ, Dimbleby GW (eds) The domestication and exploitation of plants and animals. Duckworth, London, pp 47–66